Late Pleistocene Palaeoenvironmental Reconstruction
Using Sediment Cores from the Bohai Sea, the Huanghai Sea and the Arabian Sea

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Declaration

I certify that the work presented in this thesis is my own work, except where otherwise stated, and has not been submitted for a degree at this, or any other, university.

Hao Chen
To my family.
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Late Pleistocene Palaeoenvironmental Reconstruction
Using Sediment Cores from the Bohai Sea, the Huanghai Sea
and the Arabian Sea

Abstract

This thesis studied 9 sediment cores from the Bohai Sea (JX91-2A and JX91-3B), the Huanghai Sea (JX91-7m and JX91-7G) and the Arabian Sea (cores 1733, 1734a, 1735, 1736 and 1739) through a multi-disciplinary approach including lithostratigraphy, geochemistry, sedimentology, rock magnetism and radiochemistry. The purposes of this study are to retrieve sedimentary records in the above five categories, characterise and compare the virtually different sedimentation processes in the Chinese and Arabian regions, and to reconstruct regional and trans-continental palaeoenvironmental changes since the Late Pleistocene.

High resolution chronostratigraphy and event stratigraphy have been established for the two regions, mainly using radiometric dating ($^{210}$Pb and $^{14}$C), core correlation (XRF major and trace elements and particle size) and historical records, in particular the records of the Huanghe channel switching on the Huanghe delta in the Bohai Sea since 1855 AD and that between the Bohai and Huanghai Seas in the longer term. Spatial and temporal characteristics of the sedimentation processes in the two regions are identified and compared, which show that sedimentation is dominated by fluvial process in the China Seas (the Huanghe River and/or shelf currents), but controlled by aeolian process in the Arabian Sea (the southwest and the northwest monsoons). Based on the geochemical, sedimentological and magnetic analyses of the sediments and terrestrial records, together with statistical analysis (PCA) and modelling, the whole sedimentation procedure from sediment source to sediment erosion, transport, deposition, reworking and redistribution has been explored, and the palaeoenvironments for the two regions have been reconstructed and correlated.

The main conclusions drawn from this study concerning A) the China Seas, B) the Arabian Sea and C) palaeoenvironments in the two regions include:
A1. The Huanghe River plays a key role in the sedimentation in the Bohai and Huanghai Seas, and its well documented channel switching can be directly correlated with the lithological changes in the sediments.

A2. Estuarine turbidity current can be formed in the Bohai Sea in a way different from that in deepwater, owing to the extremely turbid riverwater and highly diluted seawater, but only mass-flow seemed likely in the Huanghai Sea.

A3. Huanghe estuarine sediment in the Bohai Sea can be linked to the recent soil erosion on the Loess Plateau through geochemical and palaeomagnetic indicators, viz. P, Ti, REE and magnetic susceptibility.

B1. Sediments in the western Gulf of Oman (northwest Arabian Sea) are generally of aeolian origin, though coarser sands can be found either as saltation population in nearshore cores or as cyclone deposits on the Murray Ridge.

B2. Monsoonal variations since the Late Pleistocene in terms of both wind strength and wind direction are responsible for the lithological changes in the Arabian sediments directly and biogeochemical changes indirectly through the wind-driven coastal upwelling system in the Arabian Sea.

B3. The northwesterlies might have prevailed in the Arabian Sea in the late Pleistocene and only gave way to the southwest monsoon around 6,000 yr BP, which is seen migrating from India to Arabia in the Holocene.

C1. The Tibetan Plateau, together with the southern slope of the Himalayas and the Persian Plateau, determines the trans-continental palaeoclimate from Afro-Arabia, Indo-Arabia to North China, though they seemed to act at different times.

C2. Palaeoenvironmental changes in the two regions are different and may be influenced by anthropogenic activities in late Holocene, but they can still be correlated through the heat sensitive Himalayan area and Tibetan Plateau.

C3. Palaeoclimate responds to external (earth orbit) forcing via complex feedback mechanisms, in which mid-latitude orographic features (the Tibetan Plateau) may play a significant role by postponing regional deglaciation process, altering the Indian monsoon system and the East Asian monsoon, and causing the wide-spread continental aridity.
Chapter 1. Introduction

- purpose of the chapter
This chapter will introduce the concept of palaeoenvironmental reconstruction (section 1.1), the objectives of this study (section 1.2), the study areas and cruise details (section 1.3), literature review (section 1.4) and the thesis structure (section 1.5).

1.1 Palaeoenvironmental Reconstruction

- what is palaeoenvironmental reconstruction?
The term ‘palaeoenvironmental reconstruction’ first appeared in scientific literature in 1980 (Paul, 1980), and has become more and more popular since then. Palaeoenvironmental reconstruction differs from previous similar studies in that it concentrates not only on individual indicators of palaeoenvironmental changes, but also on the intrinsic relationships (the mechanisms) between these indicators in light of the fact that environmental changes are widely connected and globally correlated. Palaeoenvironmental reconstruction is a comprehensive study which involves a wide range of subjects and covers various geographical locations. Large scale international projects, e.g. DSDP (Deep Sea Drilling Project) and ODP (Ocean Drilling Program), together with tremendous efforts made by the geoscience community world-wide at various levels, have produced large amount of data with the help of advanced technology, and have made detailed palaeoenvironmental reconstruction achievable. Palaeoenvironmental reconstruction from marine sedimentary records has remained as the most productive field so far, mainly because of the completeness of the geological records, the accessibility of the sediments and the importance of the ocean to global environment. Although most of the palaeoenvironmental reconstruction studies are now carried out regionally and based on one or a few disciplines, they will be conducted on a global scale and cover most disciplines eventually.
1.1 Palaeoenvironmental Reconstruction

- the importance of palaeoenvironmental reconstruction

Facing the global warming and deterioration of the global environment, people are working hard to take control of the situation and trying hard to improve the environmental system in which we live. To achieve these ultimate goals, it is a basic requirement to know what had happened in the past and how they had happened. Palaeoenvironmental reconstruction is aimed at answering these questions. Moreover, palaeoenvironmental reconstruction studies can also reveal some processes that are of particular interest to exploring natural resources, e.g. formation of oil-field. Furthermore, palaeoenvironmental reconstruction in Holocene is particularly important for assessing the anthropogenic influences on the environment, and on the other hand, to examine the interaction between environment and human activities. The past is the key to the future. The processes and mechanisms established in palaeoenvironmental reconstruction studies are very valuable for predicting the future environmental changes, and can provide original parameters to and testify the validity of the computerised models designed for this purpose such as in the COHMAP (Co-operative Holocene Mapping Project) (Wright, et al., 1993).

- steps involved

Palaeoenvironmental reconstruction study involves mainly three steps. As palaeoenvironmental reconstruction stresses simultaneous environmental changes in different areas, a reliable chronology is highly required. Only based on this reliable chronology can the correlations of environmental changes in a certain region be established and the mechanisms involved be examined. Therefore chronology is the first fundamental step to take, followed by the second step: recognition of palaeoenvironment indicators and their variations through geological time, which can be done through various measurements and analyses. When these variations from different places in a region are not consistent with each other, the mechanisms behind them need to be worked out, and to be tested throughout the study period, which forms the third step. After the three steps, the palaeoenvironmental reconstruction for this region will be completed and ready to be correlated to other regions or worldwide.
1.2 Objectives

- spatial and temporal limits of this study

In this thesis, the palaeoenvironmental reconstruction will concentrate on two regions, the Chinese region and the Arabian region, and on the time span from the late Pleistocene (14,000 yr BP) to present.

- objectives

Palaeoenvironment studies in these two regions have yielded various long records (especially in the Arabian region in ODP Leg 117) but not in a resolution high enough for detailed late Pleistocene palaeoenvironmental reconstruction (see section 1.4). There is a gap between the long records and contemporary observations, and this study will focus on this temporal gap from the late Pleistocene to present using high resolution sedimentary records from the Bohai and the Huanghai Seas (China) and the Arabian Sea. Rapid changes (at least in the order of 1,000 years) since the late Pleistocene will be stressed on, and relevant mechanisms of the processes involved in the environmental changes will be examined. In addition, as the Chinese and Arabian regions are dominated by two major yet quite different sedimentation processes (fluvial and aeolian), this study will also focus on revealing these particular sedimentation processes under different environments and the consistence and difference between the two types of sediment corresponding to the global (low to mid latitude) and regional environmental changes, and their possible connections since the late Pleistocene.

- 5Ws

These objectives can be achieved through answering the following questions, which can be summarised in the '5Ws': what, when, where, how (literally odd though) and why.

◊ What are the sediments and their physical and chemical compositions?

Studies and measurements in five subjects in Chapter 2, viz. lithology, sedimentology, rock magnetism, geochemistry and radiochemistry, will describe the sediments quantitatively as well as qualitatively in the five aspects.
1.2 Objectives

◊ When are the sediments deposited?
Numerical dating ($^{210}$Pb and $^{14}$C) and chronological studies, including core correlation and historical records, will be applied to establish chronostratigraphy for the two regions in Chapter 3.

◊ Where are the sediments from?
Distance and local sediment sources will be examined in Chapters 3 and 4. The main sediment sources are the Loess Plateau in China and the Arabian deserts and other regional deserts in the Afro-Arabia and Indo-Arabia, though lateral input from previously deposited sediments may also play a role.

◊ How are the sediments transported, deposited, reworked, redistributed and preserved?
Sedimentological and geochemical studies, with the help of other studies, will depict two virtually different transport and depositional processes, the fluvial and aeolian processes for the Chinese region and Arabian region respectively in Chapter 4. Each of the processes may appear differently from low-energy process to high-energy turbidity current (China) and cyclone (Arabia). The sedimentation processes will focus on the present and recent mechanisms in the two regions in Chapter 4.

◊ Why do the sediments have such sequences?
Palaeoenvironmental reconstruction studies in Chapter 5 will show the significance of those sediment sequences and their correlations within and between the two regions. The sediment sequences have actually reflected the regional palaeoenvironmental changes since the late Pleistocene, and the two regions will be connected through the Tibetan Plateau. The interaction between the palaeoenvironmental changes and human activities in the two regions will be studied, in particular that from the mid-Holocene on.
1.3 Background

- main reasons to choose the two regions

Both of the Chinese region and the Arabian region are very sensitive to environmental changes, as generally speaking they are both under the influence of monsoons, which control the basic characteristics of climate in the two regions. The palaeoenvironmental reconstruction in these regions will not only improve our understanding of the environmental systems there, but also contribute to the global palaeoenvironmental reconstruction through the low and mid latitude areas, in particular the Tibetan Plateau (known as Qinghai-Tibetan Plateau officially). As for the Arabian Sea, it is regarded as one of the most productive areas on earth which plays an important part in global carbon cycle and hence is closely associated with global warming. Another important reason to choose these regions is that two recent cruises in the two regions, the Cruise JX91 (1991) in the Bohai and Huanghai Seas and the Leg 17 of R/V Charles Darwin in the Arabian Sea, have provided the sediment cores in the Department of Geology and Geophysics, University of Edinburgh, to make this study possible.

1.3.1 The Chinese Region and the Cruise JX91

The Chinese region

- the Loess Plateau

The Loess Plateau is located in the centre of the North China (Fig. 1.1-1). The Huanghe (Yellow) River, the largest river in the North China, traverses the plateau and gains its unique features in its middle reaches (Ren, et al., 1985). The ‘loess’ means ‘yellowish silt’ in Chinese, which is rich in carbonates and shows abundant high-porosity vertical joints, making it quite erodible. Particle size of the loess ranges mainly from 0.01 mm to 0.05 mm, depending on location, and seldom coarser than 0.1 mm (Ren, et al., 1985). The 300,000 km² Loess Plateau has an average elevation of about 3,000 m above sea-level in a semi-arid to semi-humid region with an annual precipitation of around 500 mm (Ren, et al., 1985, Yuan, 1984, Zhang, et al., 1992), and the hydrology is characterised by well defined dry and wet (mainly July to
October) seasons. Agricultural development on the plateau in the last 2,000 years, among other factors, has largely changed the natural eco-system in North China, where shrinking of forest cover and increasing aridity of land are noticed. Much of the famous 'Silk Road', which thrived around a thousand years ago, is now severely desertified.

The 5464 km long Huanghe River ranks the second only to the Changjiang (Yangtze) River in China, in terms of both drainage area (752,400 km²) and water discharge (48x10⁹ m³/yr) (Ren, et al., 1985). Statistical data show most of the river runoff comes from its upper and middle reaches and most of the sediment from the Loess Plateau. Its annual mean flow at Shaanxian is 1,350 m³/s, and the peak flow of the river can reach as high as 22,300 m³/s (Ren, et al., 1985). The Huanghe River
1.3.1 Background: the Chinese Region and the Cruise JX91

transports around $1.2 \times 10^9$ tons of sediment annually to the Bohai Sea, the world’s second largest after the Ganges-Brahmaputra River (Milliman and Meade, 1983, IOCAS, 1985, Pang and Si, 1980). The yearly average concentration of suspended sediment ranges from 15 g/l to 48 g/l, often around 37.7 g/l at its middle reaches. This is undoubtedly the world’s greatest as compared with the second, 6.7 g/l for the Colorado River (Lisitzin, 1972, Emery and Milliman, 1978, Milliman and Meade, 1983, IOCAS, 1985, Gao, et al., 1989, Li and Finlayson, 1993). The highest sediment concentration recorded in 1977 even reached a staggering 941 g/l during a flood (Chief Editorial Board of Annals of the Yellow River, 1989). The name of ‘Huanghe’, ‘Yellow River’ in Chinese, was given to this river mainly because of the large content of yellowish loess in the riverwater, an exceptional feature of the river.

Fig. 1.3-2 Channel switching on the lower reaches and delta of the Huanghe River in history (after Ren, et al., 1985).

- three consequences: rising riverbed, frequent channel switching and huge modern delta

The extraordinarily high suspension concentration of the Huanghe River consequently results in unusual features in the sediment transport and deposition.
Sediment deposition within the river has been inducing a progressive elevation of the riverbed, making it about 10 m above the surrounding alluvial plain (Liu, 1986). This has caused frequent channel switchings on the lower reaches of the river as well as on the Huanghe River delta in the last 4,000 years as shown in Fig. 1.1-2 (Ren, et al., 1985, Pang and Si, 1979). The large amount of Huanghe suspended sediment has produced a huge delta in the Bohai Sea, and is moving the coastline about 3 km a year seaward (1968 - 1983), claiming a land area of 38.8 km² every year (Liu, 1986).

In fact, only about half of the total river sediment is deposited in the river mouth area to construct the Huanghe delta, and about a quarter in the channel of the lower reaches, and another quarter in the shallow water of the Bohai Sea (Gao, et al., 1989).

The Huanghe River delta, with an area over 3300 km², is a highly constructive delta with no apparent lobes as compared with the so-called bird-foot Mississippi delta. The old Huanghe delta in the Huanghai Sea has been badly eroded (ref. to Fig. 1.2-1).

- the Bohai Sea

The Bohai Sea is an isolated inlet in Northeast China with an average water-depth of 18 m and an average slope of 0° 0' 28" (IOCAS, 1985). Protected by the Shandong Peninsula from the open sea, the Bohai Sea has a quiet depositional environment. The Huanghe riverwater has greatly diluted the seawater, making the salinity near shore below 30%, with a minimum of 22‰ close to the river mouth. The Huanghe River is by far the predominating supplier of sediment to the Bohai Sea, except in the northern Liaodong Bay and some estuarine areas of smaller rivers. In the Huanghe estuary, especially on the sub-aqueous delta, the sediment is found to be so soft and fluid that there is actually no water/sediment interface (IOCAS, 1985). The benthic biological activities are greatly limited as a result of a few factors: fluid bed (hard to settle), turbid water (blocked sunlight), poor nutrition supply (at least highly diluted by loess), high accumulation rate and unstable environment, especially in the Huanghe estuarine area. The current system is mainly of weak tidal current, which can be significantly altered by the runoff of the river. The along-shore current around the Shandong Peninsula carries part of the Huanghe fine-grained sediment from the Bohai Sea to the Huanghai Sea (ref. to Fig. 4.2-1), establishing a modern link between the two in terms of sedimentation (IOCAS, 1985, Qin, et al., 1989).
13.1 Background: the Chinese Region and the Cruise JX91

The Huanghai Sea is a shallow water between China and the Korean Peninsula with an average water-depth of 44 m and an average slope of 0° 01’ 21” (Qin, et al., 1989). It is a marginal sea on a broad continental shelf up to 550 km wide, and its salinity and temperature are close to those of the open sea. Climate of the Huanghai Sea is also seasonised, with cold airflow from north in winter and typhoon from south in summer (Qin, et al., 1989). Sedimentation in the Huanghai Sea is different from place to place. In the south Huanghai Sea, where the cores in this study were taken, surficial suspended matter is mainly controlled by the eddy. One striking feature in this area is the wide-spread high-concentration bottom suspension layer (Qin, et al., 1989), starting from the north Jiangsu Province, where the Huanghe River used to enter the sea and develop its massive delta. This channel switching in 1128 AD must be responsible for the name of the sea, as the 'Huanghai', 'Yellow Sea' in Chinese, was given just at that time (e.g. Qin, et al., 1989, Tan, 1954, Pang and Si, 1979). The Huanghai current system is more complicated than in the Bohai Sea. A branch of the Kuroshio Current, the Huanghai Current, is flowing north through the Huanghai Sea over the Huanghai Trough (Fig. 4.2-1), making an eddy in the south Huanghai Sea associated with the along-shore current flowing down from north (e.g. Qin, et al., 1989, Chen, 1996).

The Cruise JX91

The Cruise JX91 was designated for a Sino-British joint project under British Council (ALCS scheme) and Chinese Academy of Sciences (CAS), aiming at palaeomagnetic SV records and geochemistry and palaeoenvironment of the Bohai Sea and the Huanghai Sea. The cruise was carried out from 1 July to 22 July, 1991 on the R/V Jin Xin No. 2 of the Institute of Oceanology, CAS in Qingdao. Fig. 1.3-3 shows the cruise track and the coring stations (ref. to Chen, 1994 for more detail). Two types of corers were used to recover the sediment cores (Appendixes A1 and A2), a 6m-long Mackereth type corer (Mackereth, 1958), a portable mini Mackereth type corer (1m-long) and a (piston) gravity corer (Zhang, 1979). The Mackereth type corer is driven by compressed air and causes little disturbance to the sediment, except

The Cruise JX91
the sediment surface when mooring, but the mini corer can often recover an undisturbed core with water/surface interface (ref. to Chen, 1994). Gravity corer is notorious for the disturbance caused to the sediment and usually results in a missing top. A piston applied in the sampling tube may help to reduce this effect. The cores recovered during the Cruise JX91 are listed in Table 1-1, among which only the JX91-2A, JX91-3B, JX91-7m and 7G are available for this study.

![Map of the Bohai and Huanghai Seas with cruise track and stations.](image)

Table 1-1 Cores recovered in the Bohai Sea and the Huanghai Sea during cruise JX91

<table>
<thead>
<tr>
<th>Station No.</th>
<th>Research Area</th>
<th>Location</th>
<th>Water Depth (m)</th>
<th>Length of Cores</th>
<th>Cores (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Latitude (N)</td>
<td>Longitude (E)</td>
<td>Mackereth</td>
<td>Piston</td>
</tr>
<tr>
<td>1</td>
<td>S.H.S*</td>
<td>36°17'02&quot;</td>
<td>121°51'20&quot;</td>
<td>34</td>
<td>3.71</td>
</tr>
<tr>
<td>2</td>
<td>Bohai Sea</td>
<td>38°23'00&quot;</td>
<td>119°37'00&quot;</td>
<td>27</td>
<td>3.9(2A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.0(2B)</td>
</tr>
<tr>
<td>3</td>
<td>Laizhou Bay</td>
<td>37°25'21&quot;</td>
<td>119°15'21&quot;</td>
<td>10</td>
<td>3.5(3A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.9(3B)</td>
</tr>
<tr>
<td>4</td>
<td>Laizhou Bay</td>
<td>37°45'00&quot;</td>
<td>119°20'00&quot;</td>
<td>11</td>
<td>2.90</td>
</tr>
<tr>
<td>5</td>
<td>S.H.S.</td>
<td>36°05'00&quot;</td>
<td>124°15'00&quot;</td>
<td>76</td>
<td>3.25</td>
</tr>
<tr>
<td>6</td>
<td>S.H.S.</td>
<td>35°06'08&quot;</td>
<td>123°56'00&quot;</td>
<td>78</td>
<td>2.35</td>
</tr>
<tr>
<td>7</td>
<td>S.H.S.</td>
<td>34°39'00&quot;</td>
<td>123°40'00&quot;</td>
<td>71</td>
<td>3.50</td>
</tr>
</tbody>
</table>

*The South Huanghai Sea (the South Yellow Sea)
1.3.2 The Arabian Region and the Leg 17 of R/V Charles Darwin

The Arabian Peninsula and surrounding area
- geography, climate and dust sources
This region falls into the global desert zone in mid-latitude, with a pretty low precipitation, normally less than 150 mm per year in desert areas. Lithofacies in this region is characterised by a wide-spread carbonate sequence and limestones and the Semail ophiolite mainly found in northeast Oman (Bailey, 1981). Around the Arabian Sea is a quite arid region lacking of permanent rivers (wadis only have flash flood), except in the Indus plain and India. The area of interest in this study lies in the northwest Arabian Sea, the Arabian Peninsula and its surrounding area (Fig. 1.3-4), which includes the coastal areas of Pakistan and Makran of Iran, the lowland of Mesopotamia, the Rub al Khali and An Nafud deserts in the Arabian Peninsula, and the coastal areas of the Red Sea and North Africa. Sirocko et al., (1996) found the most important dust source is on the Arabian Peninsula, though in glacial period, areas like the Persian Gulf could also be important (Lambeck, 1996).

Fig. 1.3-4 Map of the Arabian region and distribution of dust sources.
1.3.2 Background: the Arabian Region and the Leg 17 of R/V Charles Darwin

- monsoons
  The Indian Ocean monsoons and Shamal wind are seen playing key roles in this region, transporting dusts from land to sea and acting as a main force in the absence of permanent river in this region, though there may have been small rivers in the past (Fig. 5.3-5). The Indian Ocean monsoons are characterised by seasonal changes: in summer it blows southwesterly at sea and northwesterly in Afro-Arabia, and in winter it mainly blows northeasterly (e.g. Sirocko and Lange, 1991) (Fig. 1.3-5). The monsoons largely control the climate of this region.

![Fig. 1.3-5 Present seasonal surface winds in the Arabian Sea and heat lows on land (modified from Hasternrath and Lamb, 1980).](image)

- the Wahiba Sands: a case study (Winser, 1989)
  The Wahiba Sands (Figs. 1.3-4 and 6) is a representative desert in this region, which is also nearest the study area. It locates at the eastern tip of Oman with a surface area of 9,400 km². The two main sources of sands (0.08 -2.00 mm in diameter) are the mountains and the sea, and the intermediary sources such as the alluvial fans and the wadis. The ocean bed nearby was confirmed to be covered with sandy material which appeared to become increasingly fine offshore and to the north. Roughly half of the sand in many locations is quartz, 30-45 % is carbonate of marine origin (marine organisms), and 10-21 % is of ophiolithic origin. The Wahiba Sands can provide a clue to the palaeoenvironment in this region through the sand dunes, the 'relic of time', which formed 15,000 years ago when the winds were much stronger. Human occupation in the sands can be traced back at least 7,000 years ago.
1.3.2 Background: the Arabian Region and the Leg 17 of R/V Charles Darwin

The Arabian Sea locates at the northern part of the Indian Ocean. The northwest part of the sea between Iran and Oman is also known as the Gulf of Oman (Fig. 1.3-4). As the continental shelf along Iran and Oman is very narrow or almost absent, it is regarded as a deep-sea area. The relief of the continental slope is rather rough, and shallow troughs parallel to the Hajar mountain range are common. The surface current, mainly driven by the monsoons, has a strong seasonal pattern, flowing clockwise in summer and opposite in winter except along the north and the Indian coasts (Wyrtnki, 1973). The intermediate and deep water are flowing to the right of the wind direction (Ekman effect), and produce the most distinct phenomenon in the
1.3.2 Background: the Arabian Region and the Leg 17 of R/V Charles Darwin

Arabian Sea, the coastal upwelling system off Oman, being one of the most productive areas in the world (e.g. Naidu and Malmgren, 1996, Summerhayes et al., 1992). In the past, however, the upwelling system might decouple from the southwest monsoon according to various sedimentary records in this region (Prell and Van Campo, 1986).

**Fig. 1.3-7 Map of the Arabian Sea (Gulf of Oman) and core locations.**

**The Leg 17 of R/V Charles Darwin**
- objectives, cruise date, core locations and cores

The aims of the R/V Charles Darwin Cruise 17 were to examine various aspects of sediments, ranging from highly reducing diatomaceous shelf to hemipelagic sediments, and to gather water column geochemical data and aeolian inputs (Watson, 1989). Tens of box and piston cores were recovered during this cruise from 14th
October to 7th November, 1986 in the northwest Arabian Sea (ref. to Watson, 1989 for more cruise detail). Locations of the sediment cores used in this study are shown in Fig. 1.3-7. Sediments in the Arabian Sea were collected using a box corer, as well as a gravity piston corer (Appendix 1), which on recovery was subsampled using polycarbonate liners of 3" diameter (Appendix 2, Watson, 1989). As the box core would normally retain an intact water/sediment interface, the sediment had hardly been disturbed. Brief core descriptions are given in Table 1-2 for cores 1733, 1734(a), 1735, 1736 and 1739 (Hermelin and Shimmiel, 1990). These cores were selected for this study, mainly because they were the only group of cores from the Gulf of Oman, the farthest north of the cruise, where less work had been done.

**Table 1-2 Details of the box core samples from Cruise 17 of the R/V Charles Darwin**

<table>
<thead>
<tr>
<th>Core 17</th>
<th>Water depth</th>
<th>Length cm(no.)</th>
<th>Position Lat. (N) Long (E)</th>
<th>Depositional environment</th>
<th>Brief sample description</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>2680</td>
<td>50(2)</td>
<td>22°40'.8 60°09'.0</td>
<td>Lower continental slope</td>
<td>Dark yellow brown, silty mud, common diatoms</td>
</tr>
<tr>
<td>34(a)</td>
<td>1540</td>
<td>40(2)</td>
<td>22°41'.1 59°45'.2</td>
<td>Middle/upper continental slope</td>
<td>Dark yellow brown, medium fine silt, common diatoms</td>
</tr>
<tr>
<td>35</td>
<td>530</td>
<td>75(1)+ 750(P)</td>
<td>22°36'.6 59°37'.4</td>
<td>steeply sloping shelf close to coast</td>
<td>Dark olive brown, silty clay, organic binding of sediment</td>
</tr>
<tr>
<td>36</td>
<td>1620</td>
<td>50(1)</td>
<td>22°39'.5 59°43'.2</td>
<td>Middle continental slope</td>
<td>Dark yellow brown, fine silt, common scallopods</td>
</tr>
<tr>
<td>39</td>
<td>1570</td>
<td>70(2)</td>
<td>22°10'.7 63°08'.9</td>
<td>Topographic high on Murray Ridge</td>
<td>Dark yellow brown, foraminiferal silty clay (oxidising red top, 2-3 cm)</td>
</tr>
</tbody>
</table>

P: piston core
1.4 Literature Review

The Chinese Region

• previous work

The Loess Plateau has been intensively studied, in wake of the successful comparison between the magnetic susceptibility profile in loess and the deep-sea $\delta^{18}O$ profile (e.g. An et al., 1990). Liu Tungsheng and Kukla are the representatives of the multinational scientific team. Several valuable books and various papers about the palaeoclimate on the plateau have been compiled (e.g. Liu et al., 1985, Kukla and An, 1989, Sun and Zhao, 1991, Chen et al., 1997, more references in the following chapters). For the Holocene palaeoenvironment, however, Zhu (1973) had set a milestone for many other researchers to follow. For the Bohai and Huanghai Seas, at least five representative books have been published concerning their geology and geochemistry (IOCAS, 1985, Qin et al., 1989, Liu et al., 1987, Zheng, 1989, Zhao and Yan, 1994), but unfortunately they are not widely known to the outside world, mainly because of language barrier. Since the two seas are on the shallow continental shelf, they had been frequently influenced by sea-level changes and related hazards in geological history, which have drawn considerable attention in China (IGCP 200, 1986, Qin and Zhao, 1991, Liu and Liang, 1995). Glacial palaeoenvironmental reconstruction on the continental shelf has been actively studied in recent years (e.g. Zhao and Liu, 1995, Zhao et al., 1996).

• current situation

Palaeoenvironment reconstruction in the Chinese region has not been carried out in a systematic way so far, though some specific aspects have been studied (CQRA, 1997). The current palaeoenvironment studies in China seem to be divided into two parts, on land and at sea. On land, some local palaeoenvironments, e.g. those on the Loess Plateau and some basins on the North China Plain, are well studied and connections between the Loess Plateau and the Tibetan Plateau and the relationships with the East Asian monsoons have been established, especially during the uplift of the Tibetan Plateau, but the land-sea connection was somehow neglected, which in part reflects the practical difficulties in reconstructing the Holocene history of the
Huanghe River, the main connection between land and sea. As the sedimentation processes in the Bohai and Huanghai Seas in the Holocene were still unclear, the palaeoenvironmental reconstruction for the whole region could not make the best use of continuous sedimentary records and was thus largely limited.

**The Arabian region**

- previous work

Studies of the geology, surface processes and the marine upwelling system off the Arabian coast have thrived largely because of the abundant oil reserve on the peninsula. Many advanced technologies have been applied on this piece of land, e.g. remote sensing and satellite imagery (Fig. 5.3-2, Short *et al.*, 1976). It is found that as the main dust sources in this region, the Arabian deserts, together with those in Iran and North Africa, also serve as the relic of ancient wind field on land, providing valuable data about the wind direction and strength since the last glacial maximum through the shape and alignment of the sand dunes (Winser, 1989, Boggs, 1987). Quite a few scientists, e.g. Prell, Shimmield, Clemens, Sirocko, Sarnthein and Duplessy, among others, have contributed a great deal to the study of the Arabian Sea (see Chap. 5 for references). The Leg 117 of the Ocean Drilling Program running from 23 August 1987 to 18 October 1987 with a primary goal of recovering continuous sedimentary sections from the Arabian Sea, an area of high biological productivity, has provided insight into the paleoceanography and palaeoclimate in the Arabian Sea (Prell and Niitsuma, 1991). The upwelling in the Arabian Sea off Oman associated with the summer monsoon makes the region one of the most fertile areas in the world (Spaulding, 1991) and attracts many workers, whose contributions can be partly found in Summerhayes *et al.* (1992).

- current situation

Although extensive palaeoenvironmental studies have been carried out in the region, many of them involved long records with relatively inadequate resolution. These long records helped to establish the relationship between the orbital parameters and palaeoclimate (Milankovitch cycle), contributing greatly to global palaeoenvironment reconstruction. However, the studies did not point out the detail mechanisms in this
environmental system dominated by monsoons. For the palaeoenvironment since the late Pleistocene, two different opinions are noticed in literature, one is represented by Prell and the other represented by Sirocko (references in Chapter 5). Prell et al. started with the wind-driven upwelling signals, and attributed them to the southwest monsoon prevalent in the Arabian Sea at present, while Sirocko et al. concentrated on sediment sources and emphasised the northwesterlies in geological time. They are both truth-telling, but not comprehensive enough; in fact, the combination of the two can give the best interpretation, i.e. the palaeomonsoons varied in both their strength (wind-speed) and their direction, and hence their influential scopes. Prell and others correctly pointed out the connection between the Indian monsoons and the Tibetan Plateau, but as the southwest monsoon was regarded as the only variable, they failed to go a step further in that right direction. The dominant aeolian processes in this region provide a relatively simple basis for palaeoenvironmental reconstruction, but as the previous work somehow neglected the Gulf of Oman area, the land-sea correlation (terrestrial records) and the anthropogenic influences, and could not make the best use of high resolution records and multi-disciplinary approach, the palaeoenvironment reconstruction in the Arabian region is far from complete.

**Global scenario**

- effort being made

Regional palaeoenvironment studies and teleconnections (e.g. Sirocko et al., 1996) are becoming popular in the last decade in light of the fact that more and more palaeoenvironment data are available, pushing the global palaeoenvironment reconstruction forward (e.g. Bradley, 1989, Wright et al., 1993). Computer simulations (Berger et al., 1989, Kutzbach et al. 1993) have also contributed a lot to the understanding of the palaeoenvironment, though the results are still in their preliminary stage and approximate due to the complexity of the real world, especially the orographic features of the Himalayas described in Shroder (1993). The palaeoenvironment reconstruction across the Eurasia via the Tibetan Plateau is very important in forming a global picture.
1.5 Thesis Structure

- chapters

The whole thesis is composed of five chapters. Chapter 1 gives the introduction of the thesis and the essential information about the study areas and sediment cores from the Chinese and Arabian regions. Chapter 2 will concentrate on principles of five subjects applied in this thesis, and the basic data from the measurements. Chapter 3 will establish chronostratigraphy for the two regions as well as determine the accumulation rates for the top sediments. Chapter 4 will examine the sedimentation processes in both regions, establish the mechanisms active in the recent environmental systems, evaluate the sedimentary records in ware of the influences from turbidites, and locate the palaeoenvironmental indicators. Chapter 5 will explore the temporal variations of the sedimentation processes since the late Pleistocene in the two regions, examine the environmental mechanisms on a time scale, correlate palaeoenvironments of the two regions in ware of the interactions between human civilisation and environment, and reconstruct the palaeoenvironment since the late Pleistocene across the Eurasia via the Tibetan Plateau. The relationship and information flow between the five chapters are illustrated in Fig. 1.5-1.

Fig. 1.5-1 Information flow between the chapters and their relationships
1.5 Thesis Structure

- logic for arrangement of chapters

Chapter 1 would simply initiate the study in a concise framework and provide basic information for the following chapters. Measurements in Chapter 2 will produce a large amount of data and put all the sedimentary records on a depth scale; and then Chapter 3 can put them on a time scale after the establishment of chronostratigraphy for the two regions. To interpret the data concerning palaeoenvironment reconstruction, two steps can be designed. The first step will be completed in Chapter 4, which is to limit the time scale to the recent past, but in the meantime, to concentrate on the wide correlation between the data from each region, and with other reference data and information available in literature. As the time span is close to present, the sedimentation processes and mechanisms discussed in Chapter 4 will be able to be better testified by reference data of high quality, which should add credit to the interpretation and lay a firm ground for further discussion. The second step will apply the sedimentation processes and mechanisms not only in a broader region (trans-continent), but also in a greater time span (from the late Pleistocene to present), which will be done in Chapter 5. Attention has to be paid to those mechanisms which are not obvious at present, but used to be dominant in the geological past.

- sections

As the Chinese region and Arabian region are parallel in this study, though the overall emphasis may be slightly different and specific issues are different (e.g. the river in the Chinese region will be replaced by monsoons in the Arabian region), sections in a chapter are divided in principal into three parts: the Chinese region, the Arabian region and the comparison of the two. In certain region, cores are addressed according to their locations, usually the distance from land, water depth and core length. Therefore in the Chinese region, the Bohai Sea comes the first and then the Huanghai Sea; and the estuarine JX91-3B usually comes the first and then the central JX91-2A in the Bohai Sea and JX91-7m comes before JX91-7G in the Huanghai Sea. In the Arabian Sea, the order is core 1735, 1736, 1734(a), 1733 and 1739. When subjects are applied, the order is determined by their size scales: lithology,
sedimentology, rock magnetism, geochemistry and radiochemistry. These orders are also applied to data presentation throughout the thesis. A line of key words is added before every paragraph in the sub-sections in order to make the following text clearer, which should be of a little help in the multi-dimensional approach adopted in this thesis.

- logic in the thesis

The basic criterion to follow in this study is that conclusions should be drawn from more than one line of mutually supporting evidence. It is found in many cases that so-called evidence or causes need support from their inferences. Although we start from sedimentary records, which can be viewed as preconditions in logic, as a matter of fact, they are results of palaeoenvironmental changes that will appear as conclusions in this study. Except for obvious external forcing, it is not logically correct to pinpoint the original internal forcing in the earth system, as all the processes are actually interacting and interdependent. The firstly addressed processes, therefore, may not be the determining ones to the following processes as every process may be a result and a cause of the others at the same time. What is important here is that all the data match with each other in the integrated interdependent earth system.
Chapter 2. Measurements and Results

2.1 Introduction

This section will focus on the necessity and significance of the measurements and the reason for such an arrangement, aware of the connections between the measurements. This will be discussed in two subsections: measurements to take and measurements carried out on the sediment cores from both the Chinese and Arabian regions.

Measurements to Take

Marine sediments can possibly best preserve the records of palaeoenvironmental changes, not only for their quantity but also for their quality, as compared with lake sediments or igneous rocks (e.g. Kukal, 1971). It is believed that all major environmental changes can be recorded eventually in marine sediments, no matter whether the change is mostly on land or at sea in wake of the wide-spread interaction and interdependence in the earth system. However, it is often found that certain environmental changes can be better recorded in one aspect of the sedimentary records than the others (see Chapter 4 in this thesis). In order to show all the environmental changes in a wide spectrum, high resolution quantitative sedimentary records in as many aspects as possible are needed.
Mathematically, an object can only be fully described with a complete set of independent parameters. A convenient and widely used set of parameters is that of spatial dimension, i.e. the size scale. Sediment can be viewed as a mixture, often laminated though, of grain assemblages of different sizes, which can break down according to the size scale (Fig. 2.1-1). From large to small, these size categories are relating respectively to structure, grain, mineral, element and isotope. The idea is that siliciclastic sediment structure is produced by a particular pattern of grain assemblage and alignment, and grains are normally composed of different minerals, and minerals, usually impure, bear various elements in their lattices, and all elements have isotopes, radioactive and/or non-radioactive. There may be overlaps between these categories, e.g. grain and mineral, but little gap should exist in between, though it is rather weak here at the molecular level. This scale is open at both ends, beyond sediment structure to infinite and down from nuclei to infinitesimal.

Figure 2.1-1 Sketch of the size scale and the corresponding five subjects
• five subjects
Many traditional sciences have been developed under different size scales, e.g. geochemistry concentrates mainly at the elemental level, but does not reveal sediment fabric. In order to study the sediments as a whole, measurements have to be carried out with a multi-disciplinary approach, under different names of subjects. Concerning the above dimensional division, five subjects will be applied, as shown in Table 2-1.

Table 2-1 Five subjects applied to retrieve sedimentary records

<table>
<thead>
<tr>
<th>level</th>
<th>size scale</th>
<th>specific subject</th>
<th>main content</th>
<th>objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>macro</td>
<td>lithology</td>
<td>stratification and bioturbation</td>
<td>structure</td>
</tr>
<tr>
<td>2</td>
<td>physical</td>
<td>sedimentology</td>
<td>particle size analysis</td>
<td>particles/grains</td>
</tr>
<tr>
<td>3</td>
<td>mineralogical</td>
<td>rock magnetism</td>
<td>susceptibility, ARM &amp; (S)IRM</td>
<td>ferromagnetic minerals</td>
</tr>
<tr>
<td>4</td>
<td>chemical</td>
<td>geochemistry</td>
<td>XRF major and trace elements</td>
<td>elements</td>
</tr>
<tr>
<td>5</td>
<td>atomic</td>
<td>radiochemistry</td>
<td>$^{210}$Pb and $^{14}$C</td>
<td>isotopes</td>
</tr>
</tbody>
</table>

• connection
Conventionally, the first two subjects are typically physical ones. Rock magnetism, or more properly called 'environmental magnetism', is an interdiscipline of physics and chemistry. Geochemistry is typical chemistry but radiochemistry seems more like atomic physics in nature, though its application to marine sediment deals with problems at higher scale levels, e.g. bioturbation. A combination of these subjects will allow a closer insight into the sediment at different levels. As significant environmental changes will have their impacts on sedimentary records at different levels, greater response to the changes may be found at a particular level, e.g. glaciation is better responded in some places in level one (physical) as Heinrich event, but impacts little on radiochemistry. And that is why some findings are only firstly made in certain subject, and then recognised in the others, though usually less distinct.

Measurements Carried Out
• Measurements carried out
In this study, as many measurements and descriptions as possible have been carried out. All the measurements carried out on the Chinese and Arabian cores are shown in Table 2-2.
### Table 2-2 Measurements carried out on sediment cores from the two regions

<table>
<thead>
<tr>
<th></th>
<th>JX2A*</th>
<th>JX3B</th>
<th>JX7m</th>
<th>JX7G</th>
<th>1733</th>
<th>1734</th>
<th>1734a</th>
<th>1735</th>
<th>1736</th>
<th>1739</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{210}$Pb</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+&quot;</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>XRF</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>P. S.</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Mag.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>wet, w</td>
<td>wet, w</td>
<td>w</td>
<td>wet, w</td>
<td>w</td>
<td>w</td>
<td>X, wet, w</td>
<td>w</td>
<td>w</td>
<td>wet, w</td>
</tr>
</tbody>
</table>

* JX2A is JX91-2A for short, which applies to other Chinese cores.

where JX2A and JX3B are from the Bohai Sea, JX7m and JX7G from the Huanghai (Yellow) Sea and 17?? from the Arabian Sea.

$^{210}$Pb: + indicates measurements carried out on normal samples (alpha counting); +' indicates higher resolution (0.5 cm interval), and +" is gamma counting.

XRF: XRF major and trace elements.

P. S.: Particle size analysis. ++ means two measurements, one is on bulk sediment and the other is on foraminifera-free samples.

Mag.: Magnetic measurements including magnetic susceptibility, ARM and (S)IRM, and demagnetisation of SIRM in 1734a.

Other: X is X-ray photograph and 'wet' means wet sediment density. All samples are measured for water content, 'w'.

### Discussion

In this study, only siliciclastic part of sediment is focused on, whilst trapped gas and pore water in sediment have not been studied. The solid part of sediment is mainly inorganic matter, though biogenic matter (foraminifera skeletons) and biological effects such as bioturbation are discussed as well. Despite the incomplete list of applied subjects, which is always so, a fairly reasonable coverage of sediment measurements is achieved. In some of the subjects the research has not reached a satisfactory depth; for instance, magnetic measurements are far less adequate for general mineralogical study, as they only deal with ferromagnetic minerals, but in this study it serves nearly as well. Since element data can be used to construct mineralogical composition theoretically, the lack of mineralogical work can be partly compensated. All these measurements will lay a multidisciplinary ground from which conclusions of this study will be drawn.
2.2 Lithology

- significance and content of lithology

Lithology deals with sediment properties relating to structure, colour change and grains size, which cannot be substituted completely by quantitative analytical methods (e.g. particle size analysis). Lithological change is actually a combination of changes of several parameters: sediment macro structure, fabric, particle size distribution, redox condition, pore water (quantity and its chemical composition) and minerals etc. The visual characteristics of sediment prove to be reliable and can hardly be obtained from other analyses in this study, e.g. shell layers, colour bands and sediment disturbance, though they are not much quantified and sometimes subjective. On the dimensional scale, this subject is at the upper macro end, and the techniques include photography and X-ray as well as conventional lithology profile which also benefits from technological development, e.g. standardised colour panel used for Arabian sediment colour description.

**Chinese Cores**

- profiles and basic characteristics

Lithological profiles for JX91-3B, 2A and 7G were taken when the cores were opened on board and shown in Fig. 2.2-1. Generally speaking, the cores are well stratified with clear boundaries, but quite homogeneous within layers, indicating stable depositional environments being often shifted from one to another. JX91-3B contains many homogeneous layers, and the muddy and sandy layers appear alternatively in the upper part of core but no obvious colour change is noticed throughout the core, except those caused by lithological changes (see Chen, 1994 for more detail). JX91-2A is composed of homogenous layers and shows a trend of coarsening downcore, with a distinct colour change at 275 cm from grey to brown. JX91-7G presents no clear-cut strata, though in its lower part below 250 cm lithological and colour changes are seen to be much more frequent. JX91-7m appears quite homogeneous (no original profile available). Except in JX91-2A, sulphides are not obvious, and it is not clear whether the magnetic properties of sediments are altered by possible authigenic magnetic sulphides or diagenetic effects.
Fig. 2.2-1 Lithological profiles for the cores from the Bohai Sea (JX91-3B&2A) and the Huanghai Sea (JX91-7G) (based on Dr. Shimmield's manuscript, 1991)
2.2 Lithology

**Arabian Cores**

- core description and photograph

Detailed lithology profiles are not available for the Arabian cores, though their brief descriptions can be found in Table 1-2. Comparing the core descriptions in Table 1-2, core 1734 is seen to be quite typical in the Arabian cores. X-ray photograph (Appendix A3) and conventional photos were therefore taken on this core (1734a), which depict the core from both outside and inside (Fig. 2.2-2a and b respectively). Unfortunately, no such photos or X-rays can be obtained for the Chinese cores. The two X-ray photographs were taken in two orthogonal angles (90° rotation). In order to reveal details in the lower part of core, longer exposure time was applied to produce clearer positives from the same negatives (lighter images).

- description

The darkness on an X-ray is proportional to the amount of mass in the way of X-ray beam. Therefore the lighter area reflects generally lighter material and/or more porous space. In the Arabian core 1734a, the latter seems more likely, because progressive darkening is found downcore, which is very likely to be a result of compaction. In the photo, diagenesis can be seen clearly at top core as a reddish mark present roughly from 7 to 12 cm. The lower part of core looks rather homogeneous, except at about 22 cm where a brownish band is seen. The additional oxidisation of top 1734a is possibly due to the failure of top sealing, as it seems this remarkable oxidisation happened only individually among the cores kept in the cool room and the inner part of sediment is virtually not affected.

- two features: worm tunnel and swirl

Bioturbation in the core is confirmed by the messy lines mainly in the top 5 cm of core, and especially by a clear barrow tunnel in the sediment, which appears in both X-rays but with different shape owing to different view angles. As the wall of this tunnel is quite smooth and little damaged, it is likely to be a fresh one, indicating the active benthic activities still going on in the deep Arabian Sea. Also
Fig. 2.2-2 Photo and X-rays of core 1734a. (a) photo. N.B. the remarkable oxidisation at the top is only a surficial phenomenon, but not the brownish band at ca. 22 cm. (b) X-rays (Appendix A3). Two orthogonal positions are shown with the lower parts having longer exposure time when developed. Note the worm tunnel at the top and the swirl near the bottom.
2.2 Lithology

noticed in the X-ray is a lighter-coloured wedge at around 30 cm with turbulent inner structure, which apparently is not a normal deposition. It is interesting to note that the thin band of brownish colour at around 22 cm on the photo does not show in the X-ray, indicating a probable redox origin (see Chapter 5).

Comparison and Discussion

• between cores and different photographs
Comparing the three Chinese cores with reference to their locations and distances from land, we can see the lithological changes become less intensive with distance, and the layers with shells (fragments mainly) appear less frequently, reflecting a much variable influence from land and sediment supply. As for the Arabian cores, this kind of difference is not clear. Comparison between X-ray and photo of core 1734a shows that the two images, one for physical structure and the other for redox condition, are dissimilar, although both contain important information.

• between the two regions
Although the lithological profiles of cores from the two regions are not compared directly, several features still can be seen. One is stratification and the other is colour. Arabian sediment is less, if any, stratified than the Chinese sediment, whilst showing well developed diagenesis profile with colour changing from reddish brown to grey and to green-grey in core 1734a, which is apparently absent from the Chinese cores. In JX91-313, for instance, the colour change of the upper part of core is alternating rather than presenting a general trend.
2.3 Sedimentology

- significance and measurement

Sedimentology in this section is mainly of particle size analysis, which is the most quantitative and descriptive technique in sedimentology (ref. to Boggs, 1987). Particle size is a fundamental physical property of sediment, which can directly reflect sedimentation mechanisms and depositional conditions, whether in water (current) or in air (wind); however, this analysis obviously cannot give more information about the chemical composition of the sediment and the palaeoenvironmental changes in this regard. A laser particle size analyser (Coulter 100) is used (ref. to Appendix A4) to measure the particle size distribution over the range of 0.4-1000 μm. Particle size distributions of bulk sediment from the cores are measured, but for core 1739 the bulk sediment was treated with acid to get rid of forams (Appendix A4). During the preparation of samples, inspection of sediment was also conducted, mainly for grains larger than 500 μm, which usually are shell fragments and plant debris in Chinese cores, and large forams and big sands in Arabian cores.

- graphical data presentation

The laser analyser can produce large amounts of data that usually expressed in a histogram over particle diameter ranging roughly from 0 φ to 11φ, representing particles from coarse sand to clay according to the standard size classes of sediment (Friedman and Sanders, 1978). Putting particle size distributions of all samples down the length of core will form a 3D presentation, which will help to inspect visually the trend in the data. In a 3D diagram, the vertical axis is differential volume in percentage, the sum of which equals 100% over the size scale (see below). Another sophisticated graphical presentation is probability plot (section 4.1, Appendix B2), which shows the cumulative curve on log probability scales and is wildly used for environmental analysis (e.g. Visher, 1969, Middleton, 1976). Usually the curve can show two or three straight-line sections, each of them represents a sub-population of particles that were transported by a certain mechanism, suspension, saltation or bedload.
To describe the particle size distributions in mathematical language, four principal groups of statistical parameters are commonly used (see the following chapters), which are average size (M, Md and mode), sorting (So), skewness (Sk) and kurtosis (K_G) (Kukal, 1971, McManus, 1988, Boggs, 1989).

1a) Mean (M). The best measure of average size, the mean is computed from sizes of particles spread through a range of percentile values. Generally speaking, the higher the value, the higher-energy of the depositional conditions.

1b) Median (Md). Half of the grains are coarser and half finer the median diameter, whose size is most readily determined from the 50 % line of the cumulative distribution curve. Although useful for many uni-modal sediments, in poly-modal distributions the median may fall in the tails of two sub-populations of grains, in a size fraction which is scarce.

1c) Mode. On a size frequency distribution plot the highest point on the curve provides the modal value. The modal size, therefore, the commonest grain size in a distribution.

2) Sorting (σ or So). The sorting or dispersion is represented by the breadth of the frequency curve or the shape of the cumulative frequency distribution. The smaller the value is, the better the sorting is, i.e. the sharper the distribution curve is, and hence the smaller variations in depositional conditions.

3) Skewness (α or Sk). In a normal distribution with a bell shaped frequency curve the mean and the median values coincide. Any tendency for a distribution to lean to one side, i.e. to deviate from normality, leads to differences between the median and the mean values. These differences are used to characterise the asymmetry or skewness of the curve. The skewness has a positive or negative value when more fine or more coarse materials are present than in a normal distribution and are called positively or right skewed and negatively or left skewed respectively. The greater the absolute value is, the further the shape of the curve is away from symmetrical, which can be caused by preferential deposition or sediment reworking etc..

4) Kurtosis (β or K_G). The kurtosis is related both to the dispersion and the normality of the distribution. Very flat curves of poorly sorted sediments or those with bi-modal frequency curves are platykurtic, whereas very strongly peaked curves, are leptokurtic. In this study, the negative value indicates platykurtic and the greater the absolute value is, the more platykurtic the curve is; so is the positive value to leptokurtic. If the value is around zero, it can be regarded as mesokurtic, i.e. the shape is close to that of a normal distribution. This parameter is not commonly used in environmental studies yet.

**Chinese Cores**

- JX91-3B

Fig. 2.3-1 shows the 3D particle size distributions of JX91-3B. Very distinct features can be seen in the upper part of core (0-180 cm): two completely different types of sediment are revealed. Three sandy layers with little fine-grained fraction are found interspersed with the muddy layers, just as shown in its lithological profile (Fig. 2.2-1). The top two sandy layers are separated by a very thin muddy layer. The core is seen to be overwhelmed by uni-modal sediment.
Fig. 2.3-1 Particle size distribution of JX91-3B

Fig. 2.3-2 Particle size distribution of JX91-2A
Fig. 2.3-3 Particle size distributions of (a) JX91-7m and (b) JX91-7G
• JX91-2A
Fig. 2.3-2 shows the 3D particle size distributions of JX91-2A. It is clear that the coarser fraction at the bottom of core is diminishing upwards and finishes at around 300 cm, where the fine fraction reaches its maximum. The two fractions are relatively persistent in mode, though the fine fraction tends to be coarser while the coarse fraction finer going upwards in the core. Bimodality is clear in two sections: between 140 cm and 300 cm and in the top layer. The two populations seem to overlap to a considerable extent at the top of core, showing a general trend in the Bohai Sea sediment. At 370 cm, a piece of root-like plant debris is found.

• JX91-7m&7G
Fig. 2.3-3 shows the particle size distributions for JX91-7m (a) and JX91-7G (b). There are two different types of sediment in both cores. One is the dominating coarse sediment and the other is the bi-modal sediment at the top and around 70 cm of JX91-7m and the top of JX91-7G. The coarser fraction is quite persistent throughout the cores.

Arabian Cores
• cores 1735 and 1736
The particle size distribution in core 1735 is relatively variable (Fig. 2.3-4). Abrupt changes are common, and little sediment mixing is evident. Some sediments present vague bimodality. Core 1736 (Fig. 2.3-5) is relatively homogeneous and uni-modal, except near the base. These two cores are not well stratified in terms of particle size.

• core 1734(a)
Fig. 2.3-6 (a) shows the previously subsampled core 1734 and (b) the later subsampled (in smaller interval) sister core 1734a. In both cores, the upper parts appear uni-modal while the lower parts bi-modal. The trend in core 1734 seems clearer than that in core 1734a. The vague bimodality at around 29 cm in core 1734a is found to be correspondent with the wedge shown in its X-ray (Fig. 2.2-2).
Fig. 2.3-4 Particle size distribution of core 1735

Fig. 2.3-5 Particle size distribution of core 1736
Fig. 2.3-6 Particle size distributions of (a) core 1734 and (b) core 1734a
Fig. 2.3-7 Particle size distribution of core 1733

Fig. 2.3-8 Particle size distribution of core 1739
• cores 1733 and 1739

Figs. 2.3-7 and 8 show the 3D particle size distributions of cores 1733 and 1739. Core 1733 looks quite homogenecous throughout, though the top of core is a bit different from the lower part as the proportion of coarse fraction increases. Core 1739 (foram-free) shows dramatic changes in particle size distribution at 20 cm, where bimodality is replaced by unimodality upwards. This pattern is also seen in core 1734(a), but not revealed in their visual descriptions (Table 1-2) and X-rays (Fig. 2.2-2), which actually bears important information about the palaeoenvironmental changes in the Arabian region (chapter 5).

Comparison and Discussion
• within and between regions

In Chinese region, JX91-3B looks quite different from JX91-2A and JX91-7m&7G, which in fact reflects the different intensity of variations of depositional conditions in the three coresites. The much higher peaks (more than 15%) in the sandy layers of JX91-3B indicate a much stronger yet more stable hydrodynamic conditions, which are related to the shallower water and more importantly the nearer position to the sediment supplier, the Huanghe River. The bimodality commonly seen in JX91-2A and JX91-7m&7G indicates that more than one sedimentation processes co-exist in those areas. In the Arabian region, the sediments present smaller variations, except for the modality, where bimodality is noticed in the lower parts of several cores, e.g. 1739 and 1734(a). When comparing the two regions, we can see the Arabian sediments are generally more homogenous and well sorted, as they should be (Roberts, 1989), suggesting the basic characteristics of the fluvial and aeolian deposits. However, all the sediments, no matter whether they are uni-modal, bi-modal or even tri-modal (core 1739), can be traced downcore in terms of mode or population and can be correlated within each region, implying continuous sedimentation in the regions.
2.4 Rock Magnetism

- significance
Rock magnetism here deals mainly with magnetic properties of marine sediments. Iron is one of the most abundant and active elements on earth, and many minerals containing iron are ferromagnetic (Nagata, 1953, Butler, 1992). Since magnetic signals of ferromagnetic minerals are normally a few orders of magnitude stronger than the non-magnetic material (e.g. Nagata, 1953), it is possible to detect a small content of magnetic minerals and its variation in high resolution. Magnetic study in this thesis also serves as a mineralogical tool, as the magnetic minerals coexist widely with other minerals and are seldom differentiated. Since magnetic minerals are quite environment sensitive, the magnetic technique is now widely used in environment study (Thompson and Oldfield, 1986), which is also because this technique is fast, accurate and cost-effective. Many magnetic parameters can be used for this purpose, among which magnetic susceptibility (MS) and its frequency dependence \( (X_{fd}) \), (S)IRM and ARM are the most popular ones. These parameters and their combinations will provide information about the magnetic properties of sediment in three important aspects: the types of magnetic minerals (mainly magnetite, titanomagnetite and haematite), their concentrations and their grain sizes. Appendix A5 outlines the techniques used in the rock magnetic studies.

Magnetic Susceptibility

- definition and significance
Magnetic susceptibility is a measure of the ease with which a material can be magnetised (e.g. Tarling, 1983). Magnetic susceptibility of natural materials mainly depends on their magnetite content (e.g. Currie and Bornhold, 1983), so magnetic susceptibility can be used as a rapid, surrogate measure of magnetite concentration in sediment.

- frequency dependent susceptibility
Magnetic susceptibility depends on the frequency of the applied field. Susceptibilities at different frequencies, usually measured at 1 kHz and 50 kHz, can help identify
samples with grains spanning the superparamagnetic/stable single domain boundary (e.g. Thompson and Oldfield, 1986, Mullins and Tite, 1973). Alternating current susceptibility is divided into 'in-phase' and quadrature ('out-of-phase') components. The overall trend of the two components falls with increasing frequency of measurement. This fall is accounted for by the magnetisation of grains becoming 'blocked in' as the superparamagnetic/stable single domain boundary shifts to smaller volumes with increasing frequency of measurement (Thompson and Oldfield, 1986). Therefore frequency dependent susceptibility can reflect the grain size of magnetic minerals.

**IRM and SIRM**
- definition and significance

The remanent magnetisation acquired by deliberate exposure of a material to a steady field at a given temperature (mostly room temperature) is called an isothermal remanence (IRM) (e.g. Tarling, 1983, Butler, 1992). The amplitude of the remanence depends on the strength of the steady magnetic field applied. The acquisition curve increases slowly in low fields, then more rapidly before saturating. The maximum remanence is called saturation isothermal remanent magnetisation (SIRM). SIRM is mainly a measure of magnetite content, but is also dependant on grain size and can be strongly influenced by other magnetic minerals such as haematite, because different minerals have their own saturation remanence. Furthermore, as pure magnetite saturates at about 100 mT, while haematite does not saturate until fields of over 1-3 T (Tarling, 1983), the acquisition curve of IRM can tell the magnetic mineralogy of the sediments.

**ARM**
- definition and significance

ARM (Anhysteretic Remanent Magnetisation) is generally imparted by subjecting a sample to a strong alternating field which is smoothly decreased to zero in the presence of a small steady field (Tarling, 1983, Butler, 1992). In detail, anhysteretic remanences are more difficult to interpret than isothermal remanences (Dunlop, 1983) as they display somewhat more complicated variations with grain size and they
are reduced more by grain interactions (Jaep, 1971). However, it is sometimes referred to as the ideal remanence, for it is free from hysteresis (Thompson and Oldfield, 1986).

**Magnetic Measurements Carried Out**

- measurements and application of magnetic parameters

Table 2-3 lists the measurements carried out on the Chinese (JX91-3B, JX91-2A and JX91-7G) and Arabian (core 1734a) cores. As a matter of fact, in terms of reliability of identifying magnetic minerals, their concentrations and their grain size distributions, the ratios of these parameters are usually more efficient, e.g. the SIRM/ARM ratio in detecting ultra-fine magnetic minerals (Kneller, 1980). The magnetic data and discussion will be presented in the context in the following chapters (chapter 4 in particular), mainly for recognition of sediment source, characterisation of sedimentation processes and identification of mass-flow deposits. As magnetic minerals in sediment may have various origins, e.g. detrital, biogenic, authigenic and diagenetic, the magnetic signals should be interpreted after the origins of magnetic minerals are examined (see chapter 5), otherwise these magnetic parameters could mislead the palaeoenvironmental interpretation.

<table>
<thead>
<tr>
<th></th>
<th>JX91-3B</th>
<th>JX91-2A</th>
<th>JX91-7G</th>
<th>core 1734a</th>
</tr>
</thead>
<tbody>
<tr>
<td>magnetic susceptibility</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$X_{fd}$ (%)</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>ARM</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>(S)IRM</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
2.5 Geochemistry

- introduction and significance

Geochemistry is a powerful analytical technique used in marine sediment study. As the sediment is measured down to the elemental level quantitatively, many subtle changes in sediment composition can be revealed, which are usually related to palaeoenvironmental changes, either in sediment source or in \textit{in situ} biogeochemical conditions. Geochemical analysis in this study is mainly of XRF major and trace elements (Appendix 6). The 10 major elements measured are Si, Al, Fe, Mg, Ca, Na, K, Ti, Mn and P, and the 21 trace elements are Sc, Ba, V, La, Ce, Nd, Cr, Ni, Cu, Zn, Pb, Th, U, Rb, Sr, Y, Zr, Nb, Mo, I and Br, which are all presented as salt-free data in the thesis (Appendix B1). Other measurements, e.g. water content (porosity) and LOI (Loss On Ignition), have also been included in this section.

- applications

Geochemistry has a wide range of applications (e.g. Rollinson, 1993). It will become more successful especially when it is correlated with other datasets, such as particle size analysis. As it can reveal chemical composition of sediment profoundly, it will be used in this study mainly in core correlation, turbidite recognition and palaeoenvironment characterisation. While the absolute element concentrations are very helpful in revealing the basic chemical characteristics of sediment, the ratios of the elements, usually over Al (rich in clay minerals), will eliminate to certain extent the effects of dilution, e.g. by carbonate in deep-sea sediments, and provide more precise information about the biogeochemical changes. Core correlation using geochemical data is based mainly on the assumption that the geochemical processes are similar in the study area so that environmental change-induced signals can be correlated between the cores. Turbidite (or other mass-flow deposit) recognition is based on different ideas that the element profiles present irrational changes, either too great and abrupt (chemically intercepting events) or against established rules (e.g. diagenesis process represented in Br and I in deep-sea sediment). Palaeoenvironment characterisation will involve the significance of individual elements or ratios or a certain group of elements, and associate them with palaeoenvironmental changes.
• some important elements

Generally speaking, the majority of the elements are detrital, and only a few elements are environment or diagenesis sensitive in most sediments. The former can provide reliable information about the terrestrial sediment sources, while the latter can reflect the biogeochemical conditions and environmental changes. Two elements directly affected by diagenesis are Fe and Mn, which are associated with redox condition and responsible for the colour changes in sediment profile; however, except for the enrichment in the top sediment, the relative variations of Fe and Mn downcore can still reflect the basic features of the original records (ref. to Schlesinger, 1991). Another two elements controlled by diagenesis and used for turbidite recognition in the Arabian cores are Br and I, which should show a constantly decreasing trend downcore, and any disturbance of this curve is almost exclusively due to physical sedimentation processes such as turbidites. Sr and Ca seem to be very important in the China cores because of their relationship with shells (Zhao and Yan, 1994). Many other elements are also very important in the two regions, e.g. P and Ti in the Bohai Sea, and Ba, Cr and Zr in the Arabian Sea (see the following chapters).

• PCA

Geochemical data can be processed and presented in many ways (Rollinson, 1993). As it is often found that many elements present similar pattern which differs from the others, and that this particular pattern is controlled by a particular process (e.g. Shimmield and Mowbray, 1991), it is essential to identify these patterns (group the elements) for palaeoenvironment study. An effective way to do this is using a statistical technique called PCA (the Principal Component Analysis), which can reduce a large number of variables to a few uncorrelated variables (Rollinson, 1993); i.e. it can extract the principal independent variation patterns from the dataset. Three principal components are usually used (normally exceeding 80% of the total variance) and plotted on biplots. To view the grouping of elements at a glance, the author will also prepare a 3D presentation of the PCA results (section 5.1). Moreover, the same idea can be used for core correlation, the closest samples are best correlated in terms of element concentrations (Appendix B3).
2.6 Radiochemistry

- introduction
Radiocchemy is a branch of chemistry based on atomic physics concerning the radioactivity of some radioactive isotopes of elements, whose element number is greater than that of radium. The theory is that the concentration of these radioactive elements in nature has been decreasing constantly since their formation billions of years ago. One of the advantages of this technique is that the half life of a radioactive isotope cannot be affected by any ordinary physical or chemical processes in nature, and thus lays ground for absolute dating methods. In this thesis, two radiometric dating methods are applied, the\(^{210}\text{Pb}\) dating and \(^{14}\text{C}\) dating.

2.6.1 \(^{210}\text{Pb}\)

- general
\(^{210}\text{Pb}\) measurements on the sediments were mainly carried out on an alpha counter (gamma counter for core 1736) using methods developed and contributed by many workers (e.g. Benoit and Hemond, 1988, Fleer and Bacon, 1984 and Flynn, 1986). In fact, \(^{210}\text{Pb}\) is not directly measured in the measurement. What is measured is \(^{210}\text{Po}\), a daughter element of \(^{210}\text{Pb}\). As the half life of \(^{210}\text{Po}\) is fairly short (3.8 days) as compared with 22.3 years of \(^{210}\text{Pb}\), it is actually in equilibrium with \(^{210}\text{Pb}\), i.e. the activity of \(^{210}\text{Po}\) is practically the same as that of the \(^{210}\text{Pb}\) (Ivanovich and Harmon, 1982). As intensity of radioactivity depends on time, all the raw countings are calibrated to the time when the \(^{208}\text{Po}\) spike was made (7/10/94), so that all the data can be comparable. The lab preparation of \(^{210}\text{Pb}\) samples is given in Appendix A7, and the results are shown in Figs. 2.6-1 and 2 for the Chinese and Arabian cores.

- three elements of the \(^{210}\text{Pb}\) activity curve
Three elements of the \(^{210}\text{Pb}\) activity curve are important: the surface (latest) value, the supporting level and the shape of curve in between. The curve shape is usually examined for its consistence with logarithm law and is evaluated for the extent of sediment disturbance, usually bioturbation (e.g. Ivanovich and Harmon, 1982), while
the surface value and supporting level are indicators of scavenging and deposition processes and the properties of the $^{210}$Pb related materials (uranium series).

**Principle of $^{210}$Pb Dating**

- **principle**

$^{210}$Pb exists in the atmosphere, ascribing to its precursor $^{222}$Rn which escapes from the earth's surface. The residence time of $^{210}$Pb in the troposphere is estimated to range from days to a month before it is removed by precipitation and dry fallout. This atmospheric flux of unsupported $^{210}$Pb is presumed to have remained constant at a given locality. Two methods of $^{210}$Pb dating have been proposed, (i) constant initial concentration, or (ii) constant rate of supply, which will yield the same result when sedimentation rate is constant (Ivanovich and Harmon, 1982 and references therein). The application of $^{210}$Pb method covers a wide range of work (Kershaw and Woodhead, 1991, Broeker and Peng, 1982), and the formula for calculation of accumulation rate can be found in Appendix B5.

- **limitation**

$^{210}$Pb profiles are usually quite variable and can be influenced by many factors, including sediment mixing, bioturbation and lithological change. Accumulation rates derived directly from the $^{210}$Pb curves are called apparent accumulation rates because they may be very different from the true accumulation rates, up to a few orders of magnitude. What makes the situation even worse is that sometimes no appropriate apparent accumulation rates can be calculated based on the shape of curve, and other approaches have to be sought for (see chapter 3). In most cases, the biggest problem for $^{210}$Pb dating is bioturbation, which has various patterns depending on the particular living habits of the creatures. It is possible that the $^{210}$Pb profile has been greatly altered, but its physical effect (sediment mixing) is limited. For example, the water circulation (carrying excess $^{210}$Pb) in sediment profile created by certain worms can produce a $^{210}$Pb profile upside down (Kershaw and Woodhead, 1991). Because of these, bioturbation does not simply mean sediment mixing, though some mixing did occur. The interpretation of $^{210}$Pb profile in this regard may conflict with other sedimentary records, e.g. particle size or geochemistry.
2.6 Radiochemistry

Fig. 2.6-1 Pb210 profiles for the Chinese cores, JX91-3B, JX91-2A and JX91-7m

Fig. 2.6-2 Pb210 profiles for the Arabian cores 1735, 1736, 1734a and 1739
The concept of apparent accumulation rate is important, especially in deep-sea sediment such as those from the Arabian Sea, mainly because bioturbation there is rather ubiquitous (e.g. Hermelin, 1992). As we can see from Figs. 2.6-1 and 2, the reversed trend of $^{210}$Pb activity downcore (e.g. at top of JX91-2A and core 1739) is against the presumptions for $^{210}$Pb deposition, and must be a result of bioturbation. As we will see in section 3.1, the apparent accumulation rate for core 1739 is exceptionally high for that coresite, but for core 1735 which shows no distinct bioturbation, the accumulation rate appears very reasonable. Therefore only under 'ideal' circumstances (no disturbance and high sedimentation rate) can the apparent accumulation rate be the true accumulation rate.

2.6.2 $^{14}$C

$^{14}$C dating may not be a perfect dating method, especially for inorganic carbon, however it is regarded as one of the best methods to date Quaternary sediments (e.g. Williams et al., 1993). $^{14}$C dating on organic matter, e.g. peat, is thought to be much more reliable. The $^{14}$C dates for the Arabian and Huanghai sediments are listed in Table 2-4. The first four samples are sediments which should contain about 4 g of carbon each, calculated from CaCO$_3$ content using (Ca-0.28Al)x12/40 (Watson, 1989). The Huanghai sample is a mixture of peat and sediment with the exact carbon content unknown (Appendix A8).

<table>
<thead>
<tr>
<th>Sample</th>
<th>core</th>
<th>depth (cm)</th>
<th>material</th>
<th>$^{14}$C dating</th>
<th>$\delta^{13}$C</th>
<th>Lab*</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU-4594</td>
<td>1734</td>
<td>25-28</td>
<td>bulk sediment</td>
<td>18870 ± 260</td>
<td>-0.4 %o</td>
<td>SURRC</td>
</tr>
<tr>
<td>GU-4595</td>
<td>1734</td>
<td>32-35</td>
<td>bulk sediment</td>
<td>22580 ± 260</td>
<td>-0.5 %o</td>
<td>SURRC</td>
</tr>
<tr>
<td>GU-4596</td>
<td>1736</td>
<td>26-30</td>
<td>bulk sediment</td>
<td>8700 ± 80</td>
<td>-0.7 %o</td>
<td>SURRC</td>
</tr>
<tr>
<td>GU-4597</td>
<td>1739</td>
<td>36-38</td>
<td>bulk sediment</td>
<td>9410 ± 90</td>
<td>-0.6 %o</td>
<td>SURRC</td>
</tr>
<tr>
<td>AA-21243</td>
<td>JX91-7G</td>
<td>320</td>
<td>peat</td>
<td>11845 ± 90</td>
<td>-27.9 %o</td>
<td>Arizona</td>
</tr>
</tbody>
</table>

* SURRC: Scottish Universities Research and Reactor Centre, East Kilbride, Scotland
Arizona: University of Arizona AMS Facility.
2.7 Discussions

- brief summary of the datasets

Datasets from different measurements have been presented in the previous sections, each of them stresses certain aspect of the sediments. Lithology focuses on colour change, accurate boundary depth and sediment structure (bioturbation and turbidite in particular); particle size reveals the physical aspect of the sediment quantitatively; magnetism shows the changes in magnetic minerals, a representative of detritus minerals in sediments; geochemistry gives quite complete information of the sediments' composition and radiochemistry suggests the disequilibrium in uranium series in the top sediments. Each subject also has its own interests, e.g. geochemistry is very useful to reveal the characteristics of the sediments on one hand, which is related to sediment source, and can indicate the particular environment through environment sensitive elements on the other hand, such as depositional and post-depositional processes (diagenesis Fe, Mn-oxidised at the top of core etc.). Moreover, each subject will find its difference in the two regions. Take geochemistry as an example: while the distribution of Br and I downcore is directly related to diagenesis in the deep-sea, the same phenomenon is not seen in the Chinese cores where the concentrations of Br and I are about one order of magnitude lower. Generally speaking, the element concentrations are comparable within each region, however they are not systematically comparable between the two regions, e.g. while many heavy element concentrations in the Bohai Sea are much higher than in the Arabian Sea (Zr, Pb etc.), the concentration of Ni and Sr etc. are much higher in the Arabian Sea. Although the subjects and measurements are independent, similarity and close relationships are found between the datasets quite often.

2.7.1 Comparisons between Datasets from Different Subjects

- selected comparisons

If all the five subjects are compared, there will be 10 combinations. To obtain a rough idea about how these datasets are related, only a few important comparisons will be made here, including those of lithostratigraphy with particle size, particle size
with XRF major and trace elements, and rock magnetism with particle size and element analyses.

**Lithostratigraphy and particle size**
- good agreement

Obviously lithostratigraphy and particle size analysis are in very good agreement in the Chinese cores, though particle size analysis gives more quantitative information on sediment grain size, in particular the modality of particle size distribution. However, this relationship is not well defined in the Arabian core (e.g. 1734a). For instance, the swirl in core 1734a was not reflected in particle size analysis, but can be clearly seen in its X-rays, i.e. lithostratigraphy can provide more information in this case. Speaking in general, the physical properties of the sediments can be well represented by particle size data.

**Particle size and XRF element analyses**
- good agreement in Chinese, but not Arabian cores

Brief comparison of the data from particle size and XRF element analyses shows consistence as well as difference between the two datasets. Many element profiles for the Chinese cores are seen to be controlled by particle size, e.g. JX91-3B. However, in the Arabian cores few elements show similar patterns to that of particle size.

**Particle size, XRF element analyses and rock magnetism**
- good agreement between certain groups

Some magnetic parameters agree very well with particle size and element data, e.g. $X_{fd}$ in JX91-3B, however, these relationships associated with certain magnetic parameter are not valid in every core, e.g. $X_{fd}$ is irrelevant to particle size data in JX91-7G. Magnetic susceptibility can be compared with many various parameters, e.g. lithological changes in JX91-7G and Zr in core 1734a. More often, magnetic parameters are found to form specific patterns for their own, especially in the Arabian core, e.g. ARM in core 1734a, reflecting the complexity concerning the deposition of ferromagnetic minerals.
2.7 Discussions

2.7.2 Scope of Data

- lack of study on gaseous and liquid material
  Although the measurements are quite complete in terms of size scale, work on the
gaseous (if any) material and pore water (two of the three states of matter) has not
been done, though effect of pore water is considered somewhat in the geochemical
analysis.

- lack of study on palaeontology and organic chemistry
  During the study of the bulk sediment, the biogenic and organic part of sediment is
not stressed. However, the particle size feature of forams can be seen in the
comparison of particle size distributions in core 1739 before and after acid treatment
of bulk sediment.

- use of data
  The basic data presented above are very useful in the discussions in following
chapters. Although basic data can be sufficient in revealing the various properties of
the sediments, the combination of data (ratios etc.) and comparison between different
datasets are sometimes much more helpful in depicting the sediments in more detail.
In this study, the basic data can be generally categorised as physical parameters and
chemical parameters. The former mainly includes water content, wet sediment
density, particle size, magnetic susceptibility, $X_{sd}$, ARM and (S)IRM, and the latter
consists of XRF major and trace elements, $^{210}\text{Pb}$ and $^{14}\text{C}$. They should be able to
record physical processes as well as biogeochemical processes concerning the
sediments. Other studies on the cores may also help to make best use of the data, e.g.
the tilt (14°) of JX91-2A found by Chen et al. (1995) should be noted at least for the
sake of true depth of core.
Chapter 3 Accumulation Rate and Chronostratigraphy

- time frame: short and long terms

The wide-range of measurements in Chapter 2 have provided a great deal of valuable data about the sediments. However, they may be largely devalued if not fit into a well established time-frame. In this chapter such a time frame will be set up in two steps to solve the chronological problem. Firstly, accumulation rates for the top sediments will be determined in section 3.1, i.e. the present and recent values, which may be extrapolated down the whole core ideally. Secondly, in section 3.2 the rest of core will be examined to create a time scale over a longer time span, and eventually establish chronostratigraphy for the sediments. Comparison and discussion will be made in section 3.3. This chapter is crucial to palaeoenvironment reconstruction and will lay a cornerstone for the discussions in the following chapters by answering the question of when the sediments were deposited.

- methods

In the Bohai Sea, the accumulation rate will be determined from a combination of three aspects: modelling (sediment dispersion), $^{210}$Pb dating, and historical records (channel switching); and in the Huanghai Sea only the $^{210}$Pb dating and historical records are used. In the Arabian Sea, as bioturbation is commonly intensive, apparent accumulation rates from $^{210}$Pb dating are usually far from the true values and need to be corrected using theoretical model (total excess $^{210}$Pb model); in the meantime, core correlation using mainly geochemical and particle size data will be established in order to constrain the true accumulation rates, taking into account the $^{14}$C dating and other sources (e.g. sediment trap and dust fall).

3.1 Accumulation Rate

- relationship between $^{210}$Pb dating and historical records

Apart from $^{210}$Pb dating, other various data and information can also be used for determining accumulation rate, which can safeguard the resolution and reliability of $^{210}$Pb dating. Historical records, among others, are the most important information
source of chronology. Written human history is relatively short in terms of geological time-scale, but as it can provide accurate dates over the past centuries, sometimes millennia, during which dramatic climatic changes have been seen worldwide, we can not afford to neglect it when studying recent sediments. Two factors are considered in this thesis when utilising historical records: one is that the present day or the most recent information can set boundary conditions for any interpretation of sediment cores, and the other is that geological events in history recorded in the form of event stratifications can help testify the interpretation and chronostratigraphy of sediment deduced from the various measurements.

3.1.1 The Bohai Sea

- accumulation rate determination: modelling and $^{210}$Pb

Most of the sediment in the Bohai Sea comes from the Huanghe River. Due to a weak current system, dispersal of sediment across the sea, except for very fine-grained sediment, is quite limited, therefore the accumulation rate depends largely on the distance between the coresite and the Huanghe River delta, and the direction relative to the rivermouth (e.g. IOCAS, 1985, Pang and Si, 1980, Li et al., 1998a&b). The accumulation rate in the Bohai Sea area can be assessed in two ways, theoretical modelling and $^{210}$Pb measurement. With adequate present-day hydrographical data, it is possible to get a reliable accumulation rate using a reasonable theoretical model for sediment dispersion. In fact, $^{210}$Pb dating should be more or less in line with the modelling results; and of course a combination of the two should be able to provide results with least bias. Historical channel-switching records will give support to the accumulation rate derived from the two.

Sediment dispersion model around the Huanghe River delta

- model parameters

In order to set up a sediment dispersion model properly, basic characteristics of the delta concerning its shape and lateral and longitudinal sediment transport need to be quantified as model parameters. The parameters here are not very accurate, as the model itself is only required to give rough estimates.
• 1. shape of the modern Huanghe River delta
The Huanghe River delta belongs to high constructive deltas that developed in relatively quiet depositional environment. It is true that the delta will grow steadily along the lobe(s), but for the Huanghe delta, several channel switching cycles from east to north completed in its history of about 140 years (Pang and Si, 1979) have resulted in a somewhat circular delta shape. This circular shape has remained, more or less, at the sub-aqueous delta front. The Huanghe River delta at present looks quite like a quarter of a circle at the southwest corner of the Bohai Sea (Fig. I.1-2).

• 2. longitudinal variation
When the river enters the sea, it tends to deposit its load along its channel under momentum. Within a certain period when the river channel is stable, the river sediment is therefore deposited in a predominant direction in the Bohai Sea, though in a wide angle (IOCAS, 1985, Pang and Si, 1980). As will be discussed in chapter 4, estuarine turbidity current may involve in the sediment transportation into the Bohai Sea, so the actual sedimentation process with distance will not be similar to pure diffusion, nor to natural decay mathematically. The suspension concentration near the seafloor is seen to be decreasing from the river mouth (IOCAS, 1985).

• 3. lateral variation
In the long run, i.e. in the order of a few decades when a cycle of channel switching could be completed, it is reasonable to assume that the sediment would be deposited evenly around the delta in terms of direction. In fact, the sub-aqueous sand bars outside the rivermouth extend laterally at a wide angle, more than 90 degrees, into the Bohai Sea (Li and Xue, 1993). The Huanghe sediment covers roughly an area within a radius of about 100 km from the delta, though it may go further towards the Bohai Strait, taking advantage of the tilting relief of the seafloor (IOCAS, 1985).

• first order approximation
As a first order approximation, the accumulation rate can be regarded as linearly decreasing with the distance from the delta. The advantages of this linear relationship are that there will eventually be an end of sedimentation and a limited
The Bohai Sea

original accumulation rate, making the model more realistic than the theoretical $1/x$
function. However, it needs to be stressed that the sediments following this
relationship do not include those deposited immediately at or very near to the river
mouth, but those dispersed to outer water, which account for a quarter of the total
sediment transported to the delta (Li, 1995, Pang and Si, 1979, Milliman, 1983).

Estimation of Accumulation Rate
Around the Huanghe River Delta

![Dispersion model for the Huanghe sediment in the Bohai Sea](image)

Fig. 3.1-1 Dispersion model for the Huanghe sediment in the Bohai Sea

- model establishment and theoretical results

The Huanghe sediment dispersion model in the Bohai Sea is thus established as
described in Appendix C1 and shown in Fig. 3.1-1, in which the Huanghe River
delta has been simplified as a quarter of a circle and the sediment (a quarter of the
total sediment of the Huanghe River carried to the delta area) is deposited around
the delta only within 100 km in the Bohai Sea with a linearly declining accumulation
rate. At 100 km, the sedimentation will be terminated, i.e. accumulation rate equals zero (Fig. 3.1-1). The yearly sediment load to the Bohai Sea from the Huanghe River is 1.2 billion tons, which has an average density of 1.8 g/cm$^3$. According to this model, the constant $k$ is thus determined as $2.05 \times 10^7$ (yr$^{-1}$), and the accumulation rate at the estuarine coresite of JX91-3B, 30 km off the delta, is 1.4 cm/a and 0.6 cm/a for JX91-2A at the Central Basin about 70 km from the delta.

**discussion**

It would be appropriate to say that the accumulation rate at station 3 is at the order of 1-2 cm/a and at station 2 under 1 cm/a, roughly half of that at station 3. It should be noticed that there are variations laterally or longitudinally and even the total sediment input may vary, so the figures above should be regarded as the long term averaged accumulation rates, at most. However, the true accumulation rates would not be too far from these figures.

**$^{210}$Pb dating**

- **JX91-3B (the Huanghe estuary)**

Fig. 2.6-1 (a) shows the $^{210}$Pb activity curve for JX91-3B, which presents a quite linear decline in the top 40 cm, but varies greatly in the lower part with a big fall in activity intensity at 40 cm. A supporting level needs to be determined before the accumulation rate is calculated, which is based on the excess $^{210}$Pb. The supporting level for the muddy layer in JX91-3B is not clearly shown in the $^{210}$Pb profile. As this muddy layer is similar to that in the upper JX91-2A (cf. Figs. 2.3-1&2), where the supporting level can be confirmed (Fig. 2.6-1 (b)), the supporting level in the muddy layer of JX91-3B is therefore taken as 1.00 dpm/g, the average of activities at 55 cm and 65 cm in JX91-2A. As a reflection of lithological influence on the $^{210}$Pb activity, the supporting level of silty mud between 20 and 30 cm in JX91-3B is taken as 1.20 dpm/g, the average of those at 45 and 60 cm in JX91-2A. As for the sandy layer lacking clay minerals, the supporting level is difficult to determine. The best estimate, 0.815 dpm/g, comes from JX91-7m at 29 cm (Fig. 2.6-1 (c)); however, we will use 0.8 dpm/g for sand here.
Influencing factors: lithology, physical and biogenic disturbances

It has been noted that the $^{210}\text{Pb}$ content in the Huanghe estuarine sediment is strongly associated with lithology (Ye et al., 1991), which is also obvious in JX91-3B (Fig. 2.6-1(a)). To obtain more reliable results, $^{210}\text{Pb}$ data from one lithological layer should be used, though normalisation on particle size is possible for different facies (Ye et al., 1992). Apart from this, physical post-depositional disturbance like that caused by storm in the shallow Bohai Sea may also play a significant part, which will outweigh the bioturbation, as benthic activities are rare in the Huanghe estuary (e.g. IOCAS, 1985). In the estuarine core JX91-3B, the homogeneous muddy top is 35 cm thick, and of typical Huanghe River sediment (Fig. 2.2-1). A reasonably constant accumulation rate should be expected for this muddy layer. However, the $^{210}\text{Pb}$ profile does not show a classic exponential decrease, due to the sediment mixing, which is believed to be of storm origin mainly. Moreover, it is seen that at the sharp boundary between the muddy and sandy layers, no trace of bioturbation can be found. The low level of bioturbation can be compared to a similar situation at the Changjiang River mouth and its vicinity, where, also with high accumulation rate, the density of total benthic productivity and diversity are much lower, over two orders of magnitude, than outward area to the sea (Liu, et al., 1992). If the physical mixing by storm occurred frequently enough, say a few times a year, the mixing will certainly affect the precision of accumulation rate calculated from $^{210}\text{Pb}$ profile. In this case, only data below the mixing zone can be used for determination of accumulation rate (ref. to Appendix C2).

Apparent accumulation rate

The apparent accumulation rate for the top JX91-3B (10-30 cm) is thus determined as 1.13 cm/a (Fig. 3.1-2 (a)) (ref. to Appendix B5 for formula). The apparent accumulation rate in the sandy layer (45-75 cm), crossing a muddy slab though, turns out to be 2.65 cm/a. Exceptional points at 35, 40 and 65 cm are avoided because some special processes might have involved, e.g. redistribution of $^{210}\text{Pb}$ and interception of sedimentation.
3.1.1 The Bohai Sea

- JX91-2A (the central Bohai Sea)

The $^{210}\text{Pb}$ activity curve of JX91-2A, Fig. 2.6-1 (b), demonstrates the expected trend downcore generally, however, disturbance is still seen at the top of core marked by a narrow trough. Although the curve zigzags below 25 cm, the magnitude of fluctuation is fairly small and it is likely that an equilibrium has been reached.

- bioturbation

The lithological change in JX91-2A is less dramatic than in JX91-3B, particularly at the top, so the lithological factor can be actually neglected. However, as the water gets less turbid in the Central Basin (IOCAS, 1985), benthic biological activities are considerably intensified (chapter 1), making bioturbation relatively more important than in the estuary.

- apparent accumulation rate

Fig. 2.6-1(b) shows an unusual trough at about 1.5 cm in the $^{210}\text{Pb}$ profile for JX91-2A, which is a common bioturbation pattern (cf. core 1739) and obviously different
from the top JX91-3B (0-10 cm) where the activities are heavily averaged by intense physical mixing. According to Appendix B4, 1 ppm uranium should result in 0.74 dpm/g $^{210}$Pb activity; thus the supporting level from about 3 ppm uranium in JX91-2A should be 2.2 dpm/g, far too high to accept. This is because the uranium series has not reached its equilibrium yet and it will probably never do if $^{222}$Rn loss always occurs (Ivanovich and Harmon, 1982). The apparent supporting level for $^{210}$Pb in JX91-2A is quite clear, though there are still small fluctuations (Fig. 2.6-1(b)). An acceptable supporting level for the muddy Huanghe sediment should be around 1.0 dpm/g, which is also used in JX91-3B. Excluding the bioturbated top 5 cm, the accumulation rate for the top JX91-2A (5-35 cm) is 0.34 cm/a or 0.13 cm/a for 5-10 cm (Fig. 3.1-2(b)). It is worth noting that, as seen in other circumstances, e.g. in the Arabian cores, bioturbated sediment can hardly give accurate accumulation rate (see section 3.1.3) and even the best estimate is much greater than the real and practical accumulation rate.

- another source: channel switching

Accumulation rate at the top of JX91-2A may be assessed through Huanghe River channel switching too (see section 3.2). The top layer, ca. 0-5 cm, might have a connection to the last channel switching of the Huanghe River in 1855, as suggested in the foram analysis (Chapter 5). The accumulation rate can therefore be determined as 0.037 cm/a or 37 cm/ka, similar to the overall accumulation rate of 50 cm/ka for the Central Basin (IOCAS, 1985). What makes it difficult to give a reliable rate is that the top of core could have been eroded during mooring of the Mackereth corer. Considering this, the recent accumulation rate of JX91-2A could be much higher than 37 cm/ka, and 50 cm/ka would appear conservative. Historical records of channel switching on the Huanghe River delta are seen to be very helpful in determining the accumulation rate in JX91-3B in the following section 3.2.

Discussion

- error analysis

From the above calculation, it can be estimated that errors caused by the model itself and its parameters are around 30% for a moderate rate, i.e. about 0.4 cm/a. The
The general accumulation rate in recent time would be acceptable if ranging from 1.0 to 1.6 cm/a for JX91-3B and 0.1 - 0.7 cm/a for JX91-2A. The sediment mixing may also cause sometimes considerable error to the $^{210}$Pb results, apart from that of $^{210}$Pb measurements themselves. Another error for $^{210}$Pb assessment may come from the tilt of the core as suggested by Chen et al. (1996), which tends to raise the value of accumulation rate.

- comparison

The two methods, theoretical modelling and $^{210}$Pb dating, stress on different aspects of sedimentation rate. The former gives long-term effect of up to a few thousands years, and is more generalised, while the latter stresses short term effect on a 100 year time scale, and is more specific. However, the two different approaches have yielded results in good agreement. At the estuary, model rate is 1.4 cm/a and $^{210}$Pb rates are 1.13 cm/a for mud and 2.65 cm/a for sand, and in the Central Basin model rate is 0.6 cm/a, while $^{210}$Pb rate is 0.13 - 0.34 cm/a. These figures are generally consistent with the results given by other researchers (e.g. Li and Yuan, 1990, Li and Xue, 1993), who found that the accumulation rate in the central Bohai Sea ranges from 0.068 cm/a to 1.39 cm/a and averages 15 cm/a at the delta front.
3.1.2 The Huanghai Sea

$^{210}$Pb dating

- JX91-7m
  A very ideal $^{210}$Pb curve is shown in Fig. 2.6-1 (c) for JX91-7m. Small variations are present in the lower part below 15 cm, though a fairly good supporting $^{210}$Pb level is obvious. JX91-7m is recovered with an intact water/sediment interface, whilst JX91-7G is suspected to have its top missing as described in the lithological profile (Fig. 2.2-1). Therefore $^{210}$Pb dating should only be carried out on JX91-7m for the Huanghai Sea.

- apparent accumulation rate
  Taking logarithm of the total activity of Fig. 2.6-1 (c), the first 6 points (1-11 cm) appear to be on a straight line, yielding an accumulation rate of 0.163 cm/a. It is obvious that it will be higher if section of 13-15 cm is taken into account. There is a clear supporting level of $^{210}$Pb activity in Fig 2.6-1 (c), about 0.90 dpm/g for the muddy top (0-25 cm), and slightly less, about 0.8 dpm/g, for the underlying silt (27-37 cm). Again theoretical uranium supporting level is exaggerated for the core. If the excess $^{210}$Pb is determined by 0.9 dpm/g, the accumulation rate will be 0.122 cm/a for the top 5 cm and 0.081 cm/a for the top 13 cm (Fig. 3.1-2 (c)).

- discussion
  Seen from the shape of $^{210}$Pb activity curve, there seems to be little bioturbation to the sediment, nor physical mixing, especially in the top 15 cm. Moreover, while the lithological change takes place at 20 cm, the excess $^{210}$Pb has nearly depleted at about 15 cm, so the $^{210}$Pb activity profile could not have been affected by lithology as encountered in the estuarine core JX91-3B. On the other hand, the supporting level and the points selected for the calculation are still somewhat arbitrary, which can affect the result. A ubiquitous 0.9 dpm/g has been used for the supporting level rather than a uranium-adjusted value, due to the disagreement between the theoretical and practical figures. The accumulation rate may still vary at the top JX91-7m,
however, it can be concluded as $0.12 \pm 0.04$ cm/a, which should reflect the average accumulation rate in the central South Huanghai Sea.

**Evidence from historical records**

- Huanghe channel switching from the Huanghai to the Bohai Sea

This accumulation rate in the order of 0.1 cm/a in central south Huanghai Sea is consistent with the previous dating in the same sedimentation province, where the typical accumulation rate turns out to be 0.17 cm/a (Qin, *et al.*, 1989). Although this region is classified as low-deposition area, the deposition is fast enough to make correlation with historical records on a time scale of decade. The Huanghe channel switching between the Bohai Sea and the Huanghai Sea is well known over the past millennium. The most significant one in the recent history is the channel switching in 1855, when the river switched from the Huanghai Sea to the Bohai Sea. Although the coresite of JX91-7m and 7G is some 300 km away from land, influence of the Huanghe River can still be felt (Chapter 1). Similar to the situation in the Bohai Sea, where sediment gets coarser when the river imposes direct impact on the depositional environment at the coresite (e.g. JX91-3B), and otherwise finer, lithology of the Huanghai sediment at the coresite of JX91-7m and 7G can also reflect the river impact. Actually various studies outside the old Huanghe rivermouth have shown that the sub-aqueous delta of the Huanghe river extends over 100 km into the Huanghai Sea (Qin, *et al.*, 1989), making direct transportation of river sediment to the coresite possible.

- comparison and confirmation of accumulation rate

The channel switching in 1855, if recorded in sediment, should cause a distinct lithological change from coarser to finer sediment. This change is found in both particle size (Fig. 2.3-3) and geochemical (Fig. 2.5-3) data at about 20 cm. Take a modest accumulation rate of 0.14 cm/a, this boundary will be 143 years BP, fairly close to the expected 137 years BP (1855 -1991). The historical records of Huanghe channel switching can thus reasonably agree with the accumulation rate and readjust it to around 0.14 cm/a at the central South Huanghai Sea.
3.1.3 The Arabian Sea

- core locations

Locations of the Arabian cores relative to land are shown in Fig. 1.2-2. A sketch transect profile of the nearshore cores, 1735, 1736, 1734(a) and 1733 is shown in Fig. 3.1-3. N.B. A-A’ is a different line from A’-A” with an angle of about 45° up north, but the distance from land are correct. Core 1735 is closest to land, followed by cores 1736, 1734a, 1733 and 1739. The water depths of these cores do not increase proportionally to the distance from land, owing to local topographic features, e.g. core 1736 has a greater water depth than the nearby core 1734a by 80 m. As far as aeolian transportation of dust concerns, distance from land appears more important than water depth, therefore it is expected the accumulation rates of these cores will take the order of, from high to low, 1735, 1736, 1734a, 1733 and 1739.

Figure 3.1-3 Sketch transect profile of the Arabian Sea cores near Oman.

$^{210}$Pb dating

- data format

Four of the five cores from the Arabian Sea, viz. cores 1735, 1736, 1734a and 1739, are dated using $^{210}$Pb method. Core 1736 has been dated using a gamma counter.
3.1.3 The Arabian Sea

whilst the others an alpha counter. In order to make the data comparable, the gamma counter data are converted to alpha counter data format, using formula B7-1 given in Appendix B7. Based on these data, apparent accumulation rates for the Arabian cores can be calculated.

- core 1735

An almost ideal $^{210}$Pb curve is shown in Fig. 2.6-2(a) for core 1735. No obvious disturbance, usually caused by bioturbation, can be detected down to 22 cm. The supporting level can be determined directly from the curve as about 1.33 dpm/g. In core 1735, the $^{210}$Pb activity decreases almost exponentially down the core (Fig. 2.6-2(a)). If calculated over the ideal section 4-12 cm using a supporting level of 1.33 dpm/g, the apparent accumulation rate will turn out to be 0.075 cm/a or 75 cm/ka (Fig. 3.1-4(a)).

![Graph](image-url)

**Fig. 3.1-4 Ln$(\text{xPb-}^{210})$ and apparent accumulation rates for the Arabian cores**
Apparent accumulation rates are seldom correct in deep-sea sediment (see below), however, in core 1735, the $^{210}\text{Pb}$ activity curve appears to be nearly ideal, indicating the absence of severe bioturbation. In fact, benthic biogenic activities are mainly controlled by nutrient supply (Groombridge, 1992). As shown in the satellite imagery (Fig. 4.3-3), the surface productivity in this part of Gulf of Oman is rather low and it can be expected the planktonic fallout, vital for the benthic biota, will not be high. Moreover, the aeolian sand deposits are hardly nutrient rich. Therefore bioturbation in core 1735, if any, may not be able to affect the $^{210}\text{Pb}$ dating significantly, and the apparent accumulation rate of 75 cm/ka should be close to the true value. As a matter of fact, even if a constant bioturbation or disturbance of other forms is present, as suggested at the top 4 cm of the core, a true accumulation rate can still be worked out (Appendix C2.1). This core is located on a steeply sloping shelf close to coast (Table 1-2, Fig. 3.1-3), and may be prone to receive deposits from the upper part of slope in the long term. However, over the section 4-12 cm, particle size analysis shows little change in sediment mode, indicating a quite stable depositional environment. Core 1735 is quite ideal in every aspect for $^{210}\text{Pb}$ dating and the result should be reliable.

Core 1736 is measured using a gamma counter. Gamma counter and alpha counter should give identical results, if properly calibrated between the two (Appendix A7). The gamma counter uses two types of pellets, 10 g and 15 g ones, so the first step of data processing is to convert the 15 g-pellet data (fewer) to 10 g-pellet data format (Appendix B6); and then to convert the gamma counting data to alpha counting data format (Appendix B7). Fig. 2.6-2 (b) shows the $^{210}\text{Pb}$ activity curve for core 1736. The curve is quite ideal, though the important top of core (3 cm) is missing. The shape of $^{210}\text{Pb}$ activity curve remains almost the same after the second conversion. The supporting level for the upper part of core is determined from 17 cm downward as 2.85 dpm/g. Accordingly, the apparent accumulation rate is calculated as 0.13 cm/a from 3 to 15 cm, which is irrational, and 0.06 cm/a from 15 to 25 cm (Fig. 3.1-4 (b)).
The apparent accumulation rate of core 1736 should be smaller than that of core 1735, but it may not necessarily be so. This is because core 1736 is in the middle continental slope at a greater water depth than cores 1735 and 1734, and hence capable of receiving lateral material advected from the continental slope, though turbidite and alike may not be present in the upper part of core as seen from particle size and geochemical data. The almost ideally shaped $^{210}$Pb curve has excluded the possibility of dramatic sedimentational change, however the several missing points in the top three centimetres make it hard to say whether the curve is a result of constant thin-layer bioturbation or a natural outcome; so the apparent accumulation rate of 130 cm/ka cannot be taken as granted. Judging from the high apparent accumulation rate, especially the segmented logarithm curve (Fig. 3.1-4(b)), it is thought that the curve may reflect a constant bioturbation whose exact pattern and intensity are unknown.

**core 1734a**

Fig. 2.6-2 (c) presents the $^{210}$Pb profile for core 1734a. The decrease of $^{210}$Pb activity is quite linear, and the equilibrated part is certainly below 15 cm. The supporting level can not be surely determined. $^{210}$Pb activity profile of core 1734a differs from those of cores 1735 and 1736 by presenting a rather linear decrease down core. The supporting level of the core is unclear, though it seems to be getting flat around 16 cm. Using the estimated supporting level of 3.75 dpm/g, the apparent accumulation rate is determined as 0.26 cm/a over 0-7.5 cm and 0.10 cm/a over 7.5-15.5 cm (Fig. 3.1-4(c)), which are not quite there. Another measurement on core 1734 gives a different profile, which looks similar to that of core 1739, and a minimum apparent accumulation rate is determined as 0.038 cm/a.

**discussion**

Again the apparent accumulation rate is far higher than expected. A possible cause of the high rate is that the more efficient organic scavengers in core 1734a can bring down more $^{210}$Pb, more than double that in core 1735 (Table 3-1), and make the detectable excess $^{210}$Pb stay longer to prolong the bioturbation effect. Fig. 5.3-4 shows a rather large gradient of surface productivity in this area, and it is likely the
organic matter content has a big shift over a short distance from core 1736 to core 1734a (Fig. 3.1-3). Core 1734a locates on a topographic high on the middle/upper continental slope. No evidence shows any turbidites or other mass-flow deposits in the top 20 cm of core, and the homogeneous sediment suggests a quite stable depositional environment. Bioturbation may be more intensive in this core which can be viewed in the x-ray (e.g. Fig. 2.2-2), however it does not seem to be a thorough mixing of sediment, as suggested by element profiles, e.g. La. The apparent accumulation rate, though comparable with that of core 1736, is difficult to modify through a proper model so far due to the lack of data, particularly those of organic matter content and its effectiveness as compared with inorganic particulates. The bioturbation in the core, also reflected in the shape of $^{210}$Pb profile, makes the true accumulation rate difficult to derive. It seems that even the smaller apparent accumulation rate of 0.10 cm/a is about an order of magnitude higher than the true accumulation rate (see also section 3.2).

- core 1739

$^{210}$Pb activity curve for core 1739 is shown in Fig. 2.6-2 (d), which is featured by a deep trough at around 2 cm. Although the core is very likely to be bioturbated, the rest of core has presented a linear trend of decrease. The specimens for $^{210}$Pb dating are actually from an archive core from the same box core of 1739. Seen from the $^{210}$Pb profile, the top of core is obviously disturbed. Apparent accumulation rate can only be worked out on a relatively undisturbed section from 3.5 to 9 cm. Problem arises in determining the supporting level, which seems to be around 4.0 dpm/g. Accordingly, the apparent accumulation rate is calculated to be 0.072 cm/a on that section and 0.058 cm/a on 3.5-7 cm (Fig. 3.1-4(d)). In order to have an idea of the minimum accumulation rate at this site, the same calculation is applied on section 1-2 cm, and it turns out to be 0.011 cm/a.

- discussion

As the core sits on the Murray Ridge, there should not be any direct sediment input other than aeolian dust, and no physical disturbance seems likely. Bioturbation, on the other hand, may have played a key role in determining the shape of $^{210}$Pb activity
curve. Speaking in general, continuous bioturbation can result in a higher accumulation rate, so even the 0.011 cm/a rate can be exaggerated.

**Total excess $^{210}$Pb estimate**

- **background**

It is difficult to evaluate the validity of the accumulation rates derived only from the shape of $^{210}$Pb activity profile (section 2.6), because it can be easily altered by various factors/processes, bioturbation in particular. Owing to the great diversity of biogenic activities, it is hard to determine how these activities disturbed the downcore profile and how they varied with time. Deep bioturbation model (over 10 cm deep) is usually doubtful, not only because the frequency and strength of the bioturbation are often in question, but also because it usually lacks supporting evidence for sediment mixing from other data, e.g. geochemical data, which should present smoothed and compatible element profiles. Here I would like to propose a different approach, total excess $^{210}$Pb method (Appendix C2.2), which may resolve this problem.

- **theory**

The fundamental idea is that the total excess $^{210}$Pb, with a half life of 22.3 years (Ivanovich and Harmon, 1982), will remain the same in the whole profile if $^{210}$Pb is supplied constantly with time, because the $^{210}$Pb 'reservoir' in sediment would practically reach an equilibrium within a century or so. However, the total excess $^{210}$Pb may vary from place to place, depending mainly on the $^{210}$Pb source and the scavengers. Suppose the efficiency of scavengers is the same, and $^{210}$Pb distributes universally in seawater as it is in most part of the ocean (Broecker and Peng, 1982), the total excess $^{210}$Pb in sediment will be only dependant on water depth and the quantity of particulates as $^{210}$Pb scavengers (ref. to Appendix C2.2). The later is directly associated with accumulation rate.

- **result: modification to core 1736**

It is reasonable to assume the total excess $^{210}$Pb is mainly determined by the depth of water column within a small area where topographic features are distinct. Considering the short distance (ca. 10 km) between cores 1735 and 1736, the total
excess $^{210}\text{Pb}$ model is applied, instead of the thorough mixing model (Appendix C2.1). If bioturbation did involve in the redistribution of $^{210}\text{Pb}$, the shape of curve in the missing top of core 1736 would not be steeper than in the underlying sediment, as shown in core 1735 and JX91-7m etc., and a maximum total excess $^{210}\text{Pb}$ can therefore be estimated by extrapolating the curve to the surface of sediment and summing up all the excess $^{210}\text{Pb}$. Assuming the accumulation rate of core 1735, 0.075 cm/a, is close to the real value, the rate of core 1736 can therefore be modified using formula C2-7 in Appendix C2.2 from 0.11 cm/a to 0.016 cm/a, about 21.3% of that of core 1735 (Table 3-1).

- result: connection between cores 1734a and 1739

As topographic features of the coresites 1734a and 1739 and their positions in the present upwelling system are similar (Fig. 4.3-3), though core 1734a seems a bit closer to the upwelling centre, it is possible to relate the apparent accumulation rates of the two cores under the total excess $^{210}\text{Pb}$ assessment. Suppose the accumulation rate of core 1734a is 100 cm/ka (100%), the rate for core 1739 will be 20 cm/ka (20%), as the total excess $^{210}\text{Pb}$ in core 1734a is 5 times more than in core 1739 (Table 3-1). Since the organic matter content in the water column at core site of 1734a may be higher (e.g. Fig. 4.3-3), the actual ratio of accumulation rate between the two cores may be slightly less than 5.

### Table 3-1 Total excess $^{210}\text{Pb}$ in the Arabian cores and accumulation rates

<table>
<thead>
<tr>
<th>Core</th>
<th>w. depth (m)</th>
<th>sup. level (dpm/g)</th>
<th>total excess $^{210}\text{Pb}$ (dpm/cm/g)</th>
<th>accumulation rate (cm/a) [calculated]</th>
<th>data quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>1735</td>
<td>530</td>
<td>1.33</td>
<td>115.8</td>
<td>0.075 [0.075]</td>
<td>a</td>
</tr>
<tr>
<td>1736</td>
<td>1620</td>
<td>2.85</td>
<td>73.3</td>
<td>0.016 [0.13, 0.06]</td>
<td>b</td>
</tr>
<tr>
<td>1734a</td>
<td>1540</td>
<td>3.75</td>
<td>256.0</td>
<td>0.057 [0.26, 0.10] (100%)</td>
<td>c (b)</td>
</tr>
<tr>
<td>1739</td>
<td>1570</td>
<td>4.00</td>
<td>51.0</td>
<td>0.011 [0.058] (20%)</td>
<td>c (b)</td>
</tr>
<tr>
<td>1734</td>
<td>1540</td>
<td>1.66</td>
<td>124.7</td>
<td>0.028 [0.038]</td>
<td>c</td>
</tr>
</tbody>
</table>

### Sediment trap and dustfall

- consistent nearshore, not in outer area

There is no historical records available concerning the accumulation rate in the Gulf of Oman, however, there still is a means of verifying the accumulation rates obtained through $^{210}\text{Pb}$ dating and subsequent model modification. The dust source of the
Arabian silts is mainly on the Arabian Peninsula (Sirocko and Lange, 1991, Sirocko et al., 1991) and the transporting dust storm has already been confirmed by satellite data (Chen, 1986). Ittekkot et al. (1992), Curry et al. (1992) and Nair et al. (1989) have provided some useful data from sediment traps deployed in the Arabian Sea. In western Arabian Sea, the total particle flux is 33.9 g m\(^{-2}\) yr\(^{-1}\) (Nair, et al. 1989), which is roughly equivalent to 3.3 cm/ka, as the wet density of top sediment of 1734a is near 1 g/cm\(^3\). Sirocko et al. (1991) also studied the sedimentation in the Arabian Sea and gave a sedimentation rate of 15 - 20 cm/ka for the southwest Gulf of Oman, which is quite consistent with that for core 1736, and about 5 - 10 cm/ka for the central area of the Gulf of Oman.

**Discussion**

- core 1735 as reference, incomplete inter-connections

The accumulation rates for the Arabian cores are so far determined at different credit levels. The most reliable accumulation rate is seen in core 1735 (75 cm/ka), which is reasonable and can serve as a reference for all the others. Measurement and modelling have ensured a quality connection between accumulation rates of cores 1734a and 1739 as a ratio of about 5:1, though the absolute value needs to be decided, which should be definitely lower than the above values (Table 3-1). The other connections made through the total excess \(^{210}\)Pb model may not be very reliable, especially the connection between cores 1736 and 1734a, which looks irrational because the accumulation rate for core 1734a should be smaller due to a greater distance from land and its position on a topographic high. Core 1734 is not further explored here mainly owing to the poor quality of data. Generally speaking, direct \(^{210}\)Pb dating is not quite suitable for deepwater sediment where accumulation rate is at the order of 10 cm/ka or less.

- hope: core correlation

In order to obtain reliable accumulation rates for the Arabian Sea, other relevant data concerning individual cores as well as core correlation should be looked into, in addition to the sediment trap data and dust fall observations, which will be done in section 3.2.
3.1.4 Discussions

- influences to the results

The reliability of the accumulation rate depends mainly on three factors, i.e. constant $^{210}$Pb deposition, preservation of radioactivity record and calculation. Constant $^{210}$Pb deposition is often satisfied, especially within a short time span, ca. 100 years, but it may vary from place to place, as it is noted that the surface value of $^{210}$Pb activity is much higher in the Arabian cores than in the Chinese cores, though the supporting level is much lower. Formulae for calculation have been established and the error is mainly caused by the raw data, though theoretical correction models are still badly needed for various situations. The major problem for $^{210}$Pb dating is preservation of original records, i.e. disturbance of sediment, either physical or biological. It is quite difficult to define a universal pattern of bioturbation, though physical disturbance in terms of sediment mixing is easier to model. Lithological change may also affect $^{210}$Pb activity in some cores, e.g. JX91-3B, but generally speaking the $^{210}$Pb profile is quite independent of lithology. As for $^{14}$C dating, the old or dead carbon from land may be the major factor making the $^{14}$C age inaccurate (older) in the Arabian cores.

- compaction effect and tilt of core

The accumulation rate expressed in the unit of cm/a as in this study can be affected by compaction effect. However, as $^{210}$Pb dating only involves the upper part of cores, where compaction is negligible, the $^{210}$Pb dating results are reliable in this regard. Moreover, for young sediment, e.g. JX91-3B, it seems that porosity does not show a downcore trend due to sediment compaction, therefore only in low accumulation rate area the compaction effect can be distinct. The tilt of core can also affect the accumulation rate by exaggeration, which may be applicable to the Chinese cores.

- two mixing patterns and their effects

Concerning sediment mixing, the accumulation rate derived from curve shape of $^{210}$Pb activity profile has problems related not only to bioturbation, but also to different sediment source. Both processes involve fresh sediment being mixed with depleted material; however, in the former the mixing happens in situ within the sediment column, while in the latter the sediments are mixed when they are
3.1.4 Discussions

deposited. Although generally speaking, the final $^{210}$Pb profile is more likely a result of the two processes combined, the latter may be more meaningful in the Arabian Sea than in the China Seas because of steeper slope and looser structure in the aeolian deposits. The appearance of final product of these two mixing patterns may look the same, but their possible corrections would be different. When only part of the sediment acted as scavengers whilst the rest came from lateral deposition of pre-deposited sediment (no excess $^{210}$Pb), the total excess $^{210}$Pb would be the same in the sediment profile as that without the lateral input. If the sediment is not disturbed, the shape of $^{210}$Pb activity profile will give correct in situ overall accumulation rate, but not the aeolian dust accumulation rate, which is smaller and can be possibly determined by total excess $^{210}$Pb. This is one of the circumstances where the two methods can be virtually different. It is interesting to note the inverse impact from organic matter scavenger which brings in more $^{210}$Pb but occupies less space, or even disappears through decomposition later on. All these contribute to the complexity of $^{210}$Pb dating.

• bioturbation intensity

It may be true that bioturbation, expressed in biogenic activity per unit time, in the Bohai Sea is more intensive than in the Arabian Sea, however, if mass bioturbation, i.e. biogenic reworking per unit weight of sediment, is considered, the bioturbation by weight in the Arabian Sea will surely surpass that in the China Seas. So the bioturbation intensity is actually associated with accumulation rate in some sense and appears more important in the Arabian cores. The main aspects of accumulation rate determination procedure are summarised in Table 3-2.

<table>
<thead>
<tr>
<th>Table 3-2 Accumulation rate determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>sediment disturbance</td>
</tr>
<tr>
<td>physical</td>
</tr>
<tr>
<td>calculation scenario</td>
</tr>
<tr>
<td>model support</td>
</tr>
<tr>
<td>examination and confirmation</td>
</tr>
</tbody>
</table>

* see Section 3.2
3.2 Chronostratigraphy

- different dating methods combined

Generally speaking, no single chronological method can provide absolutely accurate dates, it is therefore necessary to introduce other techniques to safeguard the accuracy of the dating (Williams, 1993). More and more researchers now realise that a combination of dating tools with different methods offers the best solution (Berglund, 1991). In this section, different dating methods will be applied wherever suitable, ranging from historical documents, core correlation, \(^{14}\text{C}\) to \(^{210}\text{Pb}\) dating (see sections 2.6 and 3.1). Chronostratigraphy in the Bohai Sea will be discussed in 3.2.1 and 3.2.2 for the Huanghe River estuary and the Central Basin respectively, and that in the Huanghai Sea in 3.2.3 and that in the Arabian Sea in 3.2.4.

3.2.1 The Bohai Sea: the Huanghe River Estuary

- application of historical records...

Chronological resolution is often limited to the annual level, unless where varves or similar laminations are present. However, for recent sediments, say less than 5,000 years old, it is possible to use historical records to get better age resolution. Actually, historical dating provides the most accurate age among all the dating methods (Williams, 1993), which is associated with historical documents relating to human activities and the environment. The key step is to locate precise chronostratigraphical markers in sediments first, as practised on tephra layers by Knox (1993), and then correlate these stratigraphical events with those recorded in historical documents, and finally confirm the timing of the events using numerical dating and/or other sources.

- channel switching as potential chronostratigraphical maker

China is an old country with long written history. The Huanghe River is the largest river in north China and its history is well documented in the last two thousand years, which enables us to make high resolution correlation between the river’s history and its sediment. As the Huanghe River is the most turbid river in the world and has made the Bohai Sea one of the most rapidly deposited area, its major changes, such
as channel switchings, can definitely serve to provide stratigraphical events over a certain area. The sediment core, JX91-3B, taken from the Huanghe River estuary has provided us almost the unique opportunity to examine and establish a highly-desired correlation between historical records and sediment stratigraphy.

**Identification of the three events**

- **description of three event stratifications: sandy layers**

  The sediment of JX91-3B is characterised by interspersed coarse and fine-grained layers, especially in the upper part of core (200 cm upwards). The lithology profile of JX91-3B shows two types of sediment: one is fine-grained muddy sediment and the other is coarser sandy sediment. Each sediment is quite homogeneous inside, but displays fairly sharp lithological changes at the boundaries. Downcore particle size analysis has confirmed that the sediments are quite homogeneous within the sedimentary layers but have shifted mode and other parameters at the lithological boundaries (Fig. 3.2-1). Particle size analysis revealed the differences between the two kinds of sediments quantitatively. The medians of the muddy and sandy sediments are about 15 \( \mu m \) and 65 \( \mu m \) respectively, indicating the sandy sediment is more than four times coarser than the muddy one. The muddy layers are fairly consistent, whilst the sandy layers show variability between them. Despite the small difference, the main features of the three sandy layers are the same, so it is reasonable to regard them as three event stratifications resulting from one common mechanism.

- **definition of the three sandy layers**

  The present sediment at the core site is fine-grained, as shown at the top of core, which is typical of the Huanghe River deposits and can be widely found in the Bohai Sea now and in the past. An outstanding feature in this core is that the three sandy layers have appeared as three depositional events, within the muddy matrix. From past to present, i.e. from lower to upper level in the core, the three events can be called first, second and third events respectively. The spatial pattern of the three stratifications is interesting to note: the second and the third stratifications are only separated by a very thin muddy slab, and quite separate from the first one.
3.2.1 The Bohai Sea: the Huanghe River Estuary

*What are these events?*

- some possibilities

The dates of these events can be roughly estimated using the accumulation rates determined in section 3.1, and the actual dates are believed not far away from these estimates. During the last century or so, the history of the Bohai Sea, the Huanghe River and its delta is fairly clear, so that some more controversial long term events, such as sea-level change, will not be included in the event list anyway. The most possible mechanism which can cause the event stratifications are the delta progradation and retreat, storm and channel switching.

- progradation and retreat of delta? No.

Since the turbid Huanghe River empties its massive load into the Bohai Sea, an area of quiet depositional condition, the Huanghe River delta easily falls in the category of highly constructive deltas (Reading, 1986). There will be no large scale retreat of delta at all. As the progradation of the delta has predominated the history of the delta

![Fig. 3.2-1 Statistics of particle size analysis for JX91-3B](image-url)
development in the past century, it is not likely that progradation-retreat cycles can be found, especially at a distance of ca. 30 km from the delta. Actually, the particle size analysis failed to show such cycles. This eliminates the possibility that the muddy-sandy layers of the sediment are caused by the progradation-retreat cycles.

- Storm sediment? No.
As often found in shallow waters, the storm stirred sediment is another possibility. It is true that in the Bohai Sea storm penetration depth can exceed the water depth and stir up sediment at seafloor (IOCAS, 1985), but the JX91-3B clearly lacks the features of storm stirred sediment. Firstly, storm sediment has typical sequences (Boggs, 1987), involving mixing of different size grains, a result of fast deposition. However, in JX91-3B, no trace of such mixing is found, i.e. no coarsening downward but distinctive boundaries above and below the sand horizons. Particle size analysis has concluded that no storm mixing occurred in the sediment for two simple reasons: the homogeneity inside the sediment and the uni-modal particle size distribution. Moreover, if it were storm-induced, since the storm is unlikely to produce a fluid flow strong enough to transport the coarse sediment from where it originally was, we still have the unanswered questions as to how and where the coarse sediment was formed in the first place. Furthermore, no sandy layers, or even obvious coarsening of sediment, are found in the past few decades at this coresite, though winter storm occurs every year with similar strength in the Bohai Sea.

- further sedimentological requirement and suggestion
As the top of JX91-3B is well-preserved, it is certain that in the last 35 years or so Huanghe sediment at the coresite is all fine-grained. As the annual water discharge and sediment load of the Huanghe River varies significantly from year to year (ref. to Chapter 5), the sandy layers can not be produced by the different yearly sediment supply from the Huanghe River, and cannot be formed under the present and recent weak hydrodynamic conditions. Normally coarser sediment is formed under stronger hydrodynamic conditions, especially when the original sediment supply remains relatively constant, so the sandy layers in JX91-3B must have been formed when the hydrodynamic conditions are much stronger than at present and in the recent past.
3.2.1 The Bohai Sea: the Huanghe River Estuary

In the semi-isolated Bohai Sea, the depositional environment is rather quiet, and the Huanghe River plays a key role in determining the hydraulic conditions around the Huanghe River delta (e.g. Pang and Si, 1980). The Huanghe River deposits its sediment so rapidly on the delta that the riverbed can be raised above the surrounding area very quickly, which will inevitably result in a channel switching. Once this occurs, it will shift the hydraulic conditions around the delta abruptly and hence impose enormous impact on the estuarine sediment, especially near the river mouth (ref. to Chapter 4 for more sedimentological detail). With a clearly documented history about the Bohai Sea and the Huanghe River in the last 150 years, the Huanghe River channel switching on the delta therefore becomes the only possible sedimentological mechanism which can explain the event stratifications in JX91-3B.

When did these events happen?

- chart of channel switching history: three corresponding periods

The channel switchings on the modern Huanghe River delta have been recorded precisely in historical documents. Pang and Si (1979), among others, have compiled the channel switching history on the Huanghe River delta since 1855 as shown in Figure 3.2-2. Examining Fig. 3.2-2, we can see there are only three periods when the Huanghe river mouth was close to the coresite, viz. channel switchings No. 3, No. 7 and No. 8. It is interesting to note that the last two periods are successive and they occurred quite some time after the first one. This temporal pattern agrees very well with the spatial pattern of the three event stratifications in JX91-3B, suggesting strongly the correlation between the two.

- consistence in time

The accumulation rates in JX91-3B (section 3.1) can be taken as 1.1 cm/a for the muddy top and 2.65 cm/a for the sandy layer. As the core was taken using the pneumatic Mackereth type corer (Mackereth, 1958), the presence of the sediment top (37 cm) should be guaranteed. Therefore, the whole muddy top is about 34 years old, i.e. the last event is estimated to terminate around 1957 AD, which is very close to the actual termination time of channel switching No.8 in 1953. Moreover the third
3.2.1 The Bohai Sea: the Huanghe River Estuary

event is estimated to last 12 years (2.65 cm/a), which looks close to the No.8 actual lasting time of 19 years (1934-1953) but is actually more reasonable considering the interception of the Huanghe River during 1938-1947 (e.g. Pang and Si, 1979). Considering the 30% error involved in estimating accumulation rate, the small differences are practically within the error margin.

Fig. 3.2-2 Channel switching of the Huanghe River on its delta in the Bohai Sea since 1855 AD (redrawn from Pang and Si, 1979).

- correlation between channel switchings and event stratifications

All of the above have virtually confirmed that the event stratifications are closely associated with the Huanghe channel switchings and that the third event stratification (the upper sandy layer) was created during the channel switching No. 8. This association suggests strongly the other event stratifications are formed in a similar way, i.e. channel switchings No. 7 and No. 3 are correspondent to the second and the first event stratifications respectively. As a matter of fact, if we extrapolate the mud...
accumulation rate, which is relatively more reliable, the interval between the events 1 and 2 is about 33 years, reasonably close to the actual 25 years (1904-1929).

### Table 3-3 Primary event chronostratigraphy of JX91-3B

<table>
<thead>
<tr>
<th>Switching</th>
<th>Year (AD)</th>
<th>Age (yrs)</th>
<th>Duration (yrs)</th>
<th>Depth (cm)</th>
<th>Thickness (cm)</th>
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<tbody>
<tr>
<td>3</td>
<td>May 1897</td>
<td>94</td>
<td>7</td>
<td>190</td>
<td>45</td>
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<td>4</td>
<td>2 June 1904</td>
<td>87</td>
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<td>7</td>
<td>August 1929</td>
<td>62</td>
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<td>110</td>
<td>40</td>
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<td>8</td>
<td>August 1934</td>
<td>57</td>
<td>19*</td>
<td>70</td>
<td>33</td>
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<tr>
<td>9</td>
<td>July 1953</td>
<td>38</td>
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<td>present</td>
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* The Huanghe River stopped flowing into the Bohai Sea during 1938 - 1947, making the actual total usage of course for 9 years and 2 months (Pang and Si, 1979).

- establishment of chronostratigraphy

Once the correlation is established between the event stratification and the channel switching, the chronostratigraphy of JX91-3B can therefore be determined at a high resolution of one year. The major correlations between the channel switching and the stratigraphy are listed in Table 3-3, which is far from complete though.

### Discussion

- significance of the correlation

After the accumulation rates from $^{210}$Pb dating are calculated, sediment dispersion model is applied and historical records of channel switching are examined, it is confirmed that the channel switchings on the Huanghe River delta are directly correlated to the event stratifications (three sandy layers) in JX91-3B. It is suggested that the sandy layers represent the periods when the river mouth discharged towards the core site, while the fine-grained sediment indicates periods of typical low-energy deposition in the Bohai Sea. Actually, the sub-changes in particle size profile are also found to be well correlated with other channel switchings far away from the coresite. Based on these correlations the chronostratigraphy of the recent estuarine sediment is thus established to a high resolution of about one year.

- other support and complexity

As a matter of fact, the above conclusion is also supported by sedimentology (see Sect. 4.1) and magnetic measurements (declination, inclination and anisotropy of
magnetic susceptibility) on the core which gave meaningful directions of palaeo-current around the delta (Chen, 1994). Moreover, the rationality of its inference, the relationship between accumulation rate and distance (see below), can form another line of evidence. Concerning the application of the chronostratigraphy, however, it should be pointed out that although the boundaries of event stratifications are dated accurately, it does not necessarily mean the sedimentation within the two boundaries is constant. For example, the sediment may be eroded when the upper layer, more likely the sandy layer, was laid down, and there may be interruption in sedimentation, such as the 10-year-long breach of the Huanghe River in 1938, which is recorded as the thin 'mud black partings' at 60 cm.

- accumulation rates readjusted

During the establishment of chronostratigraphy for JX91-3B, various sources of evidence are explored, any one of which may not be very supportive, but once the chronology is finally confirmed, its feedback can be used to reassess the individual evidence. The accumulation rates, for instance, can be readjusted according to the established chronostratigraphy (Table 3-3). The accumulation rate for the top layer (mud) of JX91-3B will have an average of 1.0 cm/a, and for the upper sandy layer 1.7 cm/a, the middle sandy layer 8.0 cm/a and the lower sandy 6.4 cm/a. The rather low accumulation rate in the upper sandy layer is partly due to the interception of the Huanghe River during 1938 - 1947 when the Huanghe levee was breached. Take this into account, the accumulation rate would be 3.7 cm/a, still lower than those in the other sandy layers, which is understandable considering the greater distance between the rivermouth and the coresite during much of the time (Fig. 3.2-2). In fact, these accumulation rates for sandy layers directly reflect the distance from the rivermouth and show a proportional relationship (ref. to Fig. 3.2-2). The general accumulation rate for sandy layers around the delta would be better taken as the average of the three, which is 6.0 cm/a. Even these readjusted accumulation rates are not exact and may vary from place to place owing to different in situ depositional environment and particular events such as redistribution and erosion.
3.2.2 The Bohai Sea: the Central Basin

- summary of the established chronostratigraphy

The chronostratigraphy of this core has been established by Chen (1994) based on information from five categories, viz. lithology, sedimentology, geochemistry, palaeomagnetism and palaeontology. Relative dating of the sediment used data from sea-level change curves (Fairbridge, 1961, Han et al., 1987), channel switching records (Ren et al., 1985), recent geomagnetic dipole moment curve (McElhinny, 1983) and previous dating results (e.g. Li, 1990). The whole procedure of chronostratigraphy establishment and major evidence can be summarised as below:

1. Lithological, sedimentological and palaeontological studies have shown no interception of sedimentation in the core, indicating an age of no older than 9,000 years, because it is widely agreed the seawater entered the Bohai Sea only around 8,500 years BP (14C date of widespread peat).

2. The lower part of core is quite sandy and gets finer upward, showing typical transgression sequences, so the lower part was formed from 6,000 to 8,500 years BP, as around 6,000 years BP the transgression reached its maximum, which is supported by other data.

3. Yellowish sediment occurred when foram assemblage changed significantly (Table 3-4), indicating the input of the Huanghe River at around 4,200 years BP as seen from the channel switching records.

4. The geomagnetic dipole moment curve, which has been well dated, generally agrees with the palaeointensity indicator in this core and thus pinpoint some dates.

- particle size

Fig. 3.2-3 shows four of the most commonly used parameters of JX91-2A, Mean (M), Median (Md), mode and sorting (So), and the less used skewness. The obvious difference between the lower and the upper parts of core (divided at about 300 cm) is that the lower part is much coarser and relatively poorly sorted, and presents a smooth trend of decline. In the upper part, two segments are obvious: the lower one (140 - 300 cm) features in bimodality and the upper one is finer.
3.2.2 The Bohai Sea: the Central Basin

- **Huanghe's role to forams**
  Apart from the great shift of foram assemblage at 275 cm, other changes are also believed to be reflecting environmental changes. The environment in the Bohai Sea is largely influenced by the Huanghe River, because the fresh Huanghe riverwater can determine the salinity of the Bohai seawater and the Huanghe River is the major nutrient supplier to the Bohai Sea, both of which are vital to forams.

- **Forams' reaction to channel switching: a close relationship**
  Diversity of forams is generally determined by salinity and nutrient supply in continental shelf (Groombridge, 1992). It is observed in the Bohai Sea when the environment is diversified yet stable, the foram diversity increases, and *vice versa* (personal communication with Li Tiegang, 1996). When the Huanghe River entered the Bohai Sea, it would create different environments and biological zones in the Bohai Sea and drive the foram diversity up, therefore according to the forams assemblage change, a relationship can be established between the channel switching
history of the Huanghe River since the mid-Holocene (ref. to Fig. 1.1-2) and the stratigraphy of JX91-2A. Seen from the foram assemblage, high biodiversity is a distinct feature between 140 cm and 275 cm, indicating the presence of the Huanghe River in the Bohai Sea. It is interesting to note that the long lasting *Ammonia sp.* disappeared near the top, suggesting the vanishing of the typical shallow water environment without the Huanghe River as shown in the lower part of core (275 downward). This should be regarded as a clear signal of the genuine input of the Huanghe River, hence the boundary should be set at 1855 AC.

### Table 3-4 Biostratigraphy of JX91-2A
*(after Prof. Cang Shuxi's manuscript, 1992)*

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D: Depth (cm), F: Fragments of shell, P: Plant etc., *: Fe, Mn Oxide, ?: Candonielia (fresh water) A: Ammonia annectes E: Elphidium advenum T: Textularia foliacea Q: Quinqueloculina seminula B: Buceella frigida C: Cerithion incertum S: Sinocythereidea leiotovata L: Leguminocythereis hodgii M: Maneyeia japonica
3.2.2 The Bohai Sea: the Central Basin

- chronostratigraphy

In the lithologic profile, the appearance of the yellow brown mud indicates the presence of the Huanghe River in the Bohai Sea, coincident with the foram record, which shows the only fresh water foram in the whole core. The brownish colour upward from 275 cm indicates the influence from the typical Huanghe River sediment, mainly loess from the Loess Plateau. Based on all the data above, the dates of the stratum boundaries can be determined as in Table 3-5 below, and the accumulation rate is about 0.16 cm/a.

**Table 3-5 Chronostratigraphy of JX91-2A**

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<thead>
<tr>
<th>depth</th>
<th>lithological feature</th>
<th>date</th>
<th>years BP</th>
<th>channel switching</th>
</tr>
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<td>~0</td>
<td>eroded(?) surface</td>
<td>1991 AD</td>
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<tr>
<td>10</td>
<td>top dark layer</td>
<td>1855 AD</td>
<td>136</td>
<td>into Bohai</td>
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<tr>
<td>45</td>
<td>grey brown fine-grained mud</td>
<td>1484 AD</td>
<td>507</td>
<td>out Bohai</td>
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<td>140</td>
<td>as above with occasional monosulphides at upper part</td>
<td>1128 AD</td>
<td>863</td>
<td>partly into Bohai</td>
</tr>
<tr>
<td>220</td>
<td></td>
<td>10 BC</td>
<td>2001</td>
<td>into Bohai</td>
</tr>
<tr>
<td>240</td>
<td>grey brown fine-grained mud with occasional black specs</td>
<td>602 BC</td>
<td>2593</td>
<td>partly into Bohai</td>
</tr>
<tr>
<td>275</td>
<td>soft yellow brown mud</td>
<td>2278 BC</td>
<td>4269</td>
<td>into Bohai</td>
</tr>
<tr>
<td>395</td>
<td>grey silt graded into grey mud</td>
<td>8500</td>
<td></td>
<td>out Bohai</td>
</tr>
</tbody>
</table>

NB. the sampling interval is 5 cm and the depths could have an error of about 5 cm.
3.2.3 The Huanghai Sea

- procedure

Chronostratigraphy will be established based on particle size and geochemical data and other information, particularly the Huanghe channel switching, for JX91-7m and 7G. Core correlation between the two cores is vital and will be made before absolute dating ($^{14}$C) is incorporated in the establishment.

Core correlation

- pre-condition: no local change

JX91-7m and 7G were recovered in a relatively low accumulation rate area in the central South Huanghai Sea, where mud prevails at present (Qin et al., 1989). As the major sources of sediment are far from the coresite, similar sediment spreads over a large area and appears quite stratified. Therefore, although the two cores were not taken at the exact same coresite, they should be nearly identical at the top.

- core correlation: missing top in JX91-7G

As shown in Figs. 3.2-4 (a) and 2.3-3 (a), JX91-7m presents two types of sediment: one is featured with smaller particle size and poor sorting due to bimodality at the top of core and around 70 cm, and the other is uni-modal and coarser. The latter is seen comprising of the main part of JX91-7G (Figs. 3.2-4 (b) and 2.3-3 (b)). Although the lower part of JX91-7G (below 240 cm) does not show any special pattern, except at the very bottom where the parameters vary greatly, alternating between those of the two types of sediment, JX91-7m and JX91-7G cannot be correlated depth for depth. This is because the Mackereth mini-corer had recovered an intact water/sediment interface while the gravity corer had probably missed the sediment top. If the muddy tops of the two cores are supposed from a same layer, it will be hard to explain why the particle size mode in JX91-7m is much lower than that in JX91-7G, and why a ca. 10 cm thick muddy layer around 70 cm in JX91-7m does not appear in JX91-7G and so on. Therefore the muddy top in JX91-7G cannot be correlated to the top of JX91-7m, instead, it is quite reasonable to correlate to the muddy layer around 70 cm in JX91-7m.
Fig. 3.2-4 Statistics of particle size analysis for (a) JX91-7m and (b) JX91-7G
• geochemical evidence

From the geochemical analysis, we can also see that it is impossible for the muddy layer at the top JX91-7G to correspond to the muddy top of JX91-7m, either from magnitudes of element concentration or from the relationship with other horizons (Figs. 3.2-5 and 6). It is noted that the 50 cm long sandy part in JX91-7m does not appear in JX91-7G, which cannot be missed by sampling (10 cm interval for JX91-7G). So the mud top in JX91-7G should be correlated to the middle muddy layer in JX91-7m. This is confirmed by geochemical analysis and supported by all the parameters from the particle size analysis. Further analysis (PCA, see Appendix B3) of the geochemical data reveals the top part of JX91-7G can be indeed correlated directly to the layer around 70 cm in JX91-7m (Fig. 3.2-7).

• confirmation of missing

The missing of ca. 70 cm thick sediment top was unexpected. In fact, it occurred not only during coring, when the 20 cm thick surficial muddy layer would be missed easily by the heavy gravity corer, but also during recovering, when the sand could be washed away on the way up. Actually it is still remembered that during the cruise when JX91-7G was laid on the deck to be extruded, sand was seen flowing out with seawater from the coring tube. It is very likely that the 10 cm thick muddy layer in JX91-7G had acted as a piston, preventing further loss of sediment below it.

• construction of a new combined core, JX91-7mG

Examined carefully on the particle size and geochemical profiles, the very top of JX91-7G is determined to correlate to 72 cm in JX91-7m. To establish a continuous chronostratigraphy, it is quite necessary to combine the two cores, JX91-7m and JX91-7G, into one core, JX91-7mG. In order to keep up the high resolution in JX91-7m, JX91-7mG will be composed of the whole dataset from JX91-7m and data from 40 cm (inclusive) down the length of JX91-7G, i.e. the depth of JX91-7mG, D(7mG), can be calculated from depth of JX91-7G, D(7G), using the formula below,

\[ D(7mG) = D(7G) + 72 \quad (D(7G) \geq 40 \text{ cm}). \]

The total depth of JX91-7mG will extend to 392 cm.
Fig. 3.2-5 (a) XRF major elements for JX91-7m
Fig. 3.2-5 (b) XRF trace elements for JX91-7m
Fig. 3.2-6 (a) XRF major elements for IX91-7G
Fig. 3.2-6 (b) XRF trace elements for JX91-7G
Fig. 3.2-7 PCA results of geochemical data from JX91-7m & 7G for core correlation. Note the top of JX91-7G (G0) is best correlated with JX91-7m at 71 cm (m71)
3.2.3 The Huanghai Sea

**\(^{14}\)C dating of peat**

- description of the terrestrial peat

A thin layer of peat is found at the very bottom of JX91-7mG, though not mentioned in the lithology profile, which seems to be widespread in the central Huanghai Sea with a water depth of over 50 m (Qin et al., 1989). The peat is dark brown and darkens at the boundary with the overlying sediment. It consists mainly of plant debris, giving rise to the 'coarse' fraction in its particle size distribution (Fig. 2.3-3). This peat sample was sent to the University of Arizona for \(^{14}\)C AMS dating (Sample No. AA-21243). The result shows little inorganic carbon in the peat sample, though it had mixed up with some normal sediment when preparing. The \(\delta^{13}\)C is too light, only -27.9‰, for a marine signal and would suggest a significant terrestrial input (\(^{14}\)C dating report). So the peat was probably formed in fresh water swamp environment.

- \(^{14}\)C date

The \(^{14}\)C date for the peat is determined as 11,845 ± 90 years BP, just at the beginning of the Holocene. As organic carbon normally gives the best \(^{14}\)C date, this date is regarded as a very reliable one. It is consistent with other \(^{14}\)C dates based on forams (Zhao et al., 1996) and Huanghai peat, though an older age about 33,000 years BP was sometimes given to similar peats (Qin et al. 1989).

![Fig. 3.2-8 Relative sea-level change in the Huanghai Sea since 30 ka BP (redrawn from Qin et al., 1989).](image)

- support from sea-level change

The 11,845 years BP is also reasonable in terms of sea-level change. It is known that the sea-level had dropped to about 120 m below present during the last glacial period (Park et al., 1994) (Fig. 3.2-8), when the whole seafloor of the Huanghai Sea was...
exposed. The sea-level at 12,000 \(^{14}\text{C}\) years BP is around 80 m below present (Qin et al., 1989), while the peat now is about 75 m below present sea-level, close to the palaeo-sea-level. The peat was then buried in the rapid Holocene transgression in the Huanghai Sea. As the \(^{14}\text{C}\) ages are quoted in conventional years BP (before 1950 AD), we would rather say the peat is 11,900 \(^{14}\text{C}\) years BP (before 1991) for convenience, or roughly 14,000 conventional years BP (Bard et al., 1990).

Establishment of chronostratigraphy for JX91-7mG

- two basic data
In the combined core JX91-7mG, the accumulation rate at the top muddy layer has been determined as around 0.13 cm/a (Section 3.1), and the bottom of core has been dated as 11,900 years BP. Since the sea-level has not lowered again below that at 11.9 ka BP, the sedimentation in the core should be without interception, though accumulation rate would be different from time to time. As suggested previously, this variation is mainly owing to the change in depositional environment at the coresite caused by sea-level change and Huanghe channel switching.

- sea-level change: 8,500 years BP
As shown in the particle size and geochemical profiles, from 372 cm in JX91-7mG the sediment becomes comparable to that of today and recent past. Moreover, down from 372 cm, the sediment gets coarser drastically, presenting a typical transgression sequences. This implies the relative sea-level by then had probably approached the height of today, and the time could be around 8,500 years BP according to Fig. 3.2-3.

- sea-level and peat forming
Sea-level should also be considered when comparing peats in the Bohai Sea and the Huanghai Sea. The fresh water peat was formed during low and relatively stable sea-level period with sufficient fresh water supply. Peats found in the Bohai Sea are widely dated to be within 8,000-11,000 yr BP (Qin et al., 1989). No peat has been found before that, though the sea-level was also low enough and palaeotemperature was similar. For the Bohai and Huanghai areas, the Huanghe River is possibly the major supplier of freshwater. It may be therefore inferred that the Huanghe River
entered the exposed Bohai Sea during 8,500-11,000 yr BP and entered the Huanghai Sea before that to foster a kind of peat-forming wetland around 12,000 yr BP.

- **Huanghe channel switching in 1855 at 27 cm**
  According to the accumulation rate derived from the top 15 cm of JX91-7mG, the boundary at 27 cm may indicate the channel switching in 1855 AD (section 3.1). As such channel switching occurred before, the recognised channel switching in 1855 will also be helpful in identifying earlier channel switchings.

- **establishment of chronostratigraphy for JX91-7mG**
  The chronostratigraphy of JX91-7mG is outlined in Table 3-6, mainly using three sedimentological criteria: i) present bimodality represents river entrance to the Bohai Sea, ii) coarse unimodality represents river entrance to the Huanghai Sea, and iii) terrestrial peat was developed at wetland near the Huanghe River mouth.

### Table 3-6 Chronostratigraphy of JX91-7mG

<table>
<thead>
<tr>
<th>depth (cm)</th>
<th>age (yrs BP)</th>
<th>description</th>
<th>data quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>water/sediment interface</td>
<td>a</td>
</tr>
<tr>
<td>27</td>
<td>136</td>
<td>Huanghe channel switching in 1855 AD</td>
<td>a</td>
</tr>
<tr>
<td>292</td>
<td>863</td>
<td>Huanghe channel switching in 1128 AD</td>
<td>a</td>
</tr>
<tr>
<td>352</td>
<td>4,270</td>
<td>earliest record into Bohai Sea, 2278 BC</td>
<td>b</td>
</tr>
<tr>
<td>372</td>
<td>8,500</td>
<td>River entrance to the Huanghai Sea</td>
<td>c</td>
</tr>
<tr>
<td>380</td>
<td>11,000</td>
<td>River through the Bohai Sea area</td>
<td>c</td>
</tr>
<tr>
<td>392</td>
<td>11,900</td>
<td>(^{14} \text{C} ) dating on peat, River to Huanghai Sea</td>
<td>a</td>
</tr>
</tbody>
</table>

**Discussion**

- **further support**
  Further analyses in the following chapters will show more evidence supporting the chronostratigraphy established above and good agreement between the chronostratigraphy and other datasets. It is important that the chronostratigraphy for the Bohai Sea and the Huanghai Sea will match with each other.

- **accumulation rate readjusted**
  The average accumulation rate for the muddy top of JX91-7mG (27 cm) can be readjusted to 0.2 cm/a according to Table 3-6, even higher than that in the central Bohai Sea, though the accumulation rate near the bottom of core is much lower.
3.2.4 The Arabian Sea

- three different approaches

Chronostratigraphy for the Arabian cores will be established on a multi-disciplinary basis, including $^{14}$C dates, accumulation rates ($^{210}$Pb) and core correlation. Core correlation is important here since both of the numerical dating results can be biased more or less by unquantified factors; moreover, it will accommodate a wider range of data and information, and make the chronostratigraphy more credible.

Core correlation

- two concerns

Core correlation is not always straightforward, particularly for not-so-clearly laminated sediment like those in the Arabian Sea. Attention has to be paid to two aspects of it in the Arabian Sea. One is that, concerning the establishment of chronostratigraphy, stratigraphic markers in different cores could have different ages and therefore may not be isochrons, though the mechanism behind the markers is really the same; the other one is that various local impacts may play a considerable part in affecting sedimentation of the cores even in a quite small (nearshore) area, which should be identified and calculated individually.

- difficulties and the possible way to do it

Core correlation concerning chronostratigraphy should not be made unless it is ensured the stratigraphic markers are indications of a synchronous event. This seems to be a rather distinctive problem among the cores from the Arabian Sea, partly because the sedimentation in the Arabian Sea is influenced largely by the changing monsoonal winds and the consequent upwelling system. Stratigraphic markers can be found in particle size and geochemical data, neither of which, however, can be perfect markers in light of the complexity of the whole system. A better core correlation therefore should be based on both the regional sedimentological and geochemical markers. Another important factor to consider is the involvement of different sedimentation processes, which may vary from place to place, e.g. the mass flow deposits (chapter 4) in the near shore cores 1736 and 1734a.
A. Cores 1735 and 1736

- particle size parameters as markers

Cores 1735 and 1736 have rather different water depths on the same steep continental slope off Oman, however, despite the fact that core 1736 may be more likely affected by mass flow deposits (turbidites), they are in similar depositional environment. Suppose wind strength was uniform in this small area, particle size, as a good wind strength indicator, should present synchronous change in the sediment profile. The obvious features in particle size data in core 1735 (Fig. 3.2-9) are a sharp decrease in Md and mode at the top of core and a notch in the underlying monotonous sediment at 33 cm. The same can be found in core 1736 too, yet only in the top 10 cm (Fig. 3.2-10). As core 1735 reaches its end after a peak of Md at 39 cm, which can possibly correlate to a similar peak at 9 cm in core 1736, the whole core may be thus correlated to the top 10 cm of core 1736.

- geochemistry

The geochemical profiles of core 1736 (Fig. 3.2-11) show extremely high variations in some elements over a small interval, e.g. 30% over 4 cm for Ca and 23% over 2 cm for Cu at several depths. These great shifts cannot have been made by even the most rapid natural environmental and climatic changes, considering the typical accumulation rate of ca. 20 cm/ka in this area (Sirocko and Samthein, 1989), therefore these signals cannot be true indicators of environmental changes, but reflections of unusual sedimentational processes, mass-flow deposits (see also chapter 4). It will therefore not be appropriate to correlate core 1735 with the lower half of core 1736 (27 cm downward). Geochemical data support broadly the correlations between the two cores outlined by the particle size data, or at least do not contradict with it. So the ratio between the depths of the two cores can be determined as,

core 1735 : core 1736 = 45:10 = 1: 0.222
Fig. 3.2-9 Statistics of particle size analysis for core 1735

Fig. 3.2-10 Statistics of particle size analysis for core 1736
Fig. 3.2-11 (a) XRF major elements for core 1735
Fig. 3.2-11 (b) XRF trace elements for core 1735
Fig. 3.2-12 (a) XRF major elements for core 1736
Fig. 3.2-12 (b) XRF trace elements for core 1736
B. Cores 1736 and 1734a
- bimodality and scope for correlation

In the sedimentological point of view, core 1736 is definitely younger than core 1734(a) (cores 1734 and/or 1734a), because the bimodality found at about 20 cm in both cores 1734 and 1734(a) is never well developed in core 1736, though a second mode is quite clear in the coarser end of the fine-grained fraction at the bottom of core (Fig. 3.2-13 and Fig. 2.3-6). The clear emergence of the second mode occurs at 23 cm in core 1734 and 24 cm in core 1734a. As core 1734 is subsampled at an interval of 2 cm and only 1 cm for core 1734a, the occurrence of the second mode may actually be at the same depth. Therefore the whole core 1736 can only be possibly correlated with the upper part of core 1734(a) (23 cm upward). Nevertheless, not all parts of core 1736 are comparable with core 1734(a). As discussed previously (see also chapter 4), only the upper half of core 1736, which is turbidites-free, can be correlated with the uni-modal section of core 1734a (23 cm upwards).

Fig. 3.2-13 Statistics of particle size analysis for core 1734a
correlation detail and the difference in datasets

Seen from the particle size parameters, median (Md) and mode, correlation can be made between 17 cm in core 1736 and 10 cm in core 1734a, a significant lowering of Md from the top; or even possibly 23 cm to 13 cm, a rising of Md below a trough. Geochemical correlation based on element profiles agrees with the 17 cm to 10 cm link and suggests other corresponding points at 19 cm in core 1736 and 11 cm in core 1734a, i.e. −18 cm in core 1736 to −10.5 cm in core 1734a (Fig. 3.2-14). However, many geochemical data do not agree with the correlation at the lower depth as suggested by particle size data. The reason is probably that particle size data reflect sedimentational processes almost exclusively, which is good for core correlation in this small area, whereas elements, particularly biogeochemical elements, can also be influenced by other processes, usually over a larger area such as coastal upwelling. This difference could have caused the above phenomenon, especially when the controlling factors were not acting synchronously in the compared cores.

misleading of some geochemical indicators

It is interesting to note some element profiles in core 1736 (e.g. Ba, Cu and Sr in the top 23 cm) mimic those in core 1734a, which implies that the same biogeochemical situation occurred again in core 1736 after a certain period. An overall correlation is possible only when the two cores are in one sedimentational and biogeochemical regime, i.e. the same upwelling and monsoonal regime covering these particular sites in the Gulf of Oman (see also chapter 5); and that is why only in the upper 18 cm in core 1736, a better correlation with core 1734 can be obtained (chapter 5). When using geochemical data to correlate, care must be taken to ensure that the elements are controlled by processes acting synchronously on the compared cores.

depth ratio

As the sedimentary correlation of core 1736 with core 1734a is 23 : 13 = 1 : 0.565, and the joint (sedimentary and geochemical) correlation ratio is 18 : 10.5 = 1 : 0.583, the overall depth ratio between the two cores can be taken as the average of the two: core 1736 : core 1734a (= 18 : 10.5 = 23 : 13) = 1 : 0.574
Fig. 3.2-14 (a) XRF major elements for core 1734a
Fig. 3.2-14 (b) XRF trace elements for core 1734a
C. Cores 1734a and 1733

- similar environment, direct correlation

Again aeolian processes will play a key role in the core correlation here because winds can move more freely than ocean current and the geochemical signals associated with oceanographic (upwelling) changes may be less consistent in this area due to the large variation. From present day satellite imagery (Fig. 5.3-4, p.251), it is clear that these two cores are in a similar sedimentational and biogeochemical environment (relative to the upwelling centre). Coastal effect may be less important in this area, making the correlation between the two cores straightforward. The spikes commonly found in elements at 17 cm in core 1734a can be directly correlated with those at 11 cm in core 1733 (Fig. 3.2-16), which is supported by particle size data (Fig. 3.2-15). Therefore the core correlation ratio between the two is:

\[
\text{core 1734a : core 1733 = 17 : 11 = 1:0.647}
\]
3.2.4 The Arabian Sea

Fig. 3.2-16 (a) XRF major elements for core 1733
Fig. 3.2-16 (b) XRF trace elements for core 1733
D. Cores 1733 and 1739

- difficulty and possibility

It is difficult to correlate these two cores, mainly because of the long distance between them and their different topographic locations. However, coastal influence is almost negligible in both areas, and the scope of comparability should be largely broadened.

- correlation detail

A shift in sedimentation is seen in core 1739 around 20 cm (Fig. 3.2-17), which is not observed in core 1733. If core 1733 had experienced the change in core 1739, it would have shown the change somehow, though the exact pattern of change is not highly expected. Therefore the core 1733 can only be related to the upper part of core 1739 (uni-modal section). The most likely correlation between the two cores is 35 cm in core 1733 to 19 cm in core 1739. Another possibility is 11 cm (core 1733) to 6 cm (core 1739), rather than the somewhat apparent 8 cm (compare Zr and Y etc.) (Fig. 3.2-18). The core correlation ratio can therefore be determined as, core 1733 : core 1739 (= 19 : 11 = 11 : 6) = 1 : 0.562

Fig. 3.2-17 Statistics of particle size analysis for core 1739
Fig. 3.2-18 (a) XRF major elements for core 1739
Fig. 3.2-18 (b) XRF trace elements for core 1739
3.2.4 The Arabian Sea

As the same peak in core 1733 is used to correlate with cores 1734a and 1739, the counterparts can be correlated equally well, if not better, i.e. the greatest spike at 17 cm in core 1734a to a general spike at 6 cm in core 1739. Core 1736 can also be correlated to core 1733 through the spikes or troughs at 15 cm in core 1736 and 5 cm in core 1733, making the ratio 1: 0.333, close to 1: 0.364 derived from the above core correlation. The cross correlation here have strengthened the core correlation established above for the Arabian Sea cores.

- discussion and summary

It has been noted that there are no stratigraphic markers that can be used to correlate all the cores throughout the Arabian Sea, however, local stratigraphic markers are still available to enable sound core correlation. The ratios in Table 3-7 give the rough idea of how these cores can be correlated; nevertheless, they may not be accurate at certain particular other than the correlating points or throughout the core, because the accumulation rates between the correlated points may not be constants, let alone the inevitable errors occurred in the determination of the correlated points or the errors caused by large sampling intervals.

<table>
<thead>
<tr>
<th>Core</th>
<th>1735</th>
<th>1736</th>
<th>1734a</th>
<th>1733</th>
<th>1739</th>
</tr>
</thead>
<tbody>
<tr>
<td>1735 (1: 1</td>
<td>1</td>
<td>0.222</td>
<td>0.127</td>
<td>0.082</td>
<td>0.046</td>
</tr>
<tr>
<td>1736 (1: 4.50</td>
<td>1</td>
<td>0.574</td>
<td>0.354</td>
<td>0.200</td>
<td></td>
</tr>
<tr>
<td>1734a (1: 7.87</td>
<td>1.74</td>
<td>1</td>
<td>0.647</td>
<td>0.364</td>
<td></td>
</tr>
<tr>
<td>1733 (1: 12.2</td>
<td>2.82</td>
<td>1.55</td>
<td>1</td>
<td>0.562</td>
<td></td>
</tr>
<tr>
<td>1739 (1: 21.7</td>
<td>5.00</td>
<td>2.75</td>
<td>1.78</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

\(^{14}\text{C} \text{ dating}\)

- \(^{14}\text{C} \text{ dating results}\)

\(^{14}\text{C} \text{ dating is the most sophisticated dating method at present, which gives the most accurate ages in most cases (Williams et al., 1993).}^{14}\text{C} \text{ measurements are carried out in the Scottish Universities Laboratory in East Kilbride, Scotland using the liquid}

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3.2.4 The Arabian Sea

scintillation counting method. The results of $^{14}$C dating on the Arabian cores are listed in Table 3-8.

Table 3-8 Radiocarbon dating results on the Arabian cores

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Core</th>
<th>Depth (cm)</th>
<th>$^{14}$C age</th>
<th>$\delta^{13}$C</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU-4594</td>
<td>1734a</td>
<td>25-28</td>
<td>18870±260</td>
<td>-0.4‰</td>
</tr>
<tr>
<td>GU-4595</td>
<td>1734a</td>
<td>32-35</td>
<td>22580±260</td>
<td>-0.5‰</td>
</tr>
<tr>
<td>GU-4596</td>
<td>1736</td>
<td>24-28</td>
<td>8700±80</td>
<td>-0.7‰</td>
</tr>
<tr>
<td>GU-4597</td>
<td>1739</td>
<td>36-38</td>
<td>9410±90</td>
<td>-0.6‰</td>
</tr>
</tbody>
</table>

N.B. 1. The above $^{14}$C ages are quoted in conventional years BP (before 1950 AD). The errors are expressed at the one sigma level of confidence.

2. The calibrated age ranges are determined from the University of Washington, Quaternary Isotope Laboratory, Radiocarbon Dating Program, 1987. The 20 year atmospheric calibration curve is used throughout and the calendar age ranges, obtained from the intercepts (Method A), are expressed derived from around the UK coastline, an apparent age (reservoir effect) of 405±40 years (Harkness, 1983) is subtracted from the conventional $^{14}$C age prior to calibration using the 20 year atmospheric curve.

- $^{14}$C ages too old for core 1736 and 1734a

The $^{14}$C ages of core 1734a and core 1736 seems to be far too old, according to the accumulation rates and core correlation. This may be due to the dead carbon in the sediments of terrigenous origin (see chapter 4). The coarse fraction of sediment may be responsible for the major part of dead carbon, as it is noticed that the higher proportion the coarse fraction is, the older $^{14}$C age it gives. Older $^{14}$C ages are quite understandable for the nearshore cores, considering that the major part of sediments, mainly aeolian input, is from the Arabian deserts (Sirocko and Sarnthein, 1989).

![Figure 3.2-19 Regional $^{14}$C ages of cores 1734a and 1736. The depth axis is for core 1734a, and the depth of core 1736 is converted according to the accumulation rate in section 3.1.](image-url)
3.2.4 The Arabian Sea

• consistency?

It is very interesting to note that the $^{14}$C ages within the area for cores 1736 and 1734a might be consistent with each other, as seen from Fig. 3.2-19 plotted on depth of core 1734a with the depth of core 1736 converted using the depth ratio set out above. Although this does not necessarily mean the $^{14}$C ages are correct for the two cores, it does indicate in the small area, the distribution of $^{14}$C may be comparable within and between cores, and the core correlation set out in Table 3-6 for the two cores is reasonable. This may also be viewed as evidence for a constant decrease of dead carbon due to less coarse terrigenous input.

• biogenic carbon, reliable $^{14}$C age

Core 1739 may have the correct $^{14}$C age, because the majority of carbon in the sample is from calcium carbonate in the form of foraminiferal skeletons. This is seen when the sample from 37 cm in core 1739 (the same for $^{14}$C dating) was treated with acetic acid. The sediment changed from pale to brownish colour with a huge reduction in volume. It was found that about 55% (in volume) of the bulk sediment was dissolved away, which is roughly equivalent to about 20% of Ca in the sample by weight. This leaves about 3% of total Ca for terrigenous Ca, mostly bound in other minerals other than calcium carbonate. The percentage of forams revealed in particle size analysis is also in agreement with LOI in XRF analysis. If half of the sediment in weight is forams, the LOI will be $(1/2) \times 44\% = 22\%$ as a result of emission of gaseous CO$_2$; in comparison, the measured LOI is about 26%, leaving a marginal 4% for other unstable minerals. In fact, Sirocko and Sarnthein (1989) estimated the lithogenic carbonates in the bulk fraction at the coresite of 1739 was only about 3% (Dolomite ca. 2% and detritic CaCO$_3$ ca. 1%). That is to say most of the carbon can reach equilibrium with the seawater and produce correct $^{14}$C age, whilst the dead carbon will have little effect. If the dead carbon is considered, the actual $^{14}$C age will be slightly younger for this core.

• calendar year: 11,000 yr BP for core 1739

The $^{14}$C sample in core 1739 is dated as 9410±90, $\delta^{13}$C =-0.6 %. Calculated from Bard's curve (Bard et al., 1990), the $^{14}$C age can be converted to calendar year as
3.2.4 The Arabian Sea

11100 ± 400 years BP. It is noticed the conversion curve has a plateau around 9000 $^{14}$C years and the actual $^{14}$C age would be slightly less than 9400 $^{14}$C years, it seems appropriate to put the true age of 37 cm in core 1739 at 11,000 years BP. This age agrees with the maximum solar insulation anomaly in the northern hemisphere at approximately 11,000 years BP (Berger, 1979).

**Chronostratigraphy**

- two reliable end data and one reliable chain

Chronostratigraphy of the Arabian cores is now achievable with two much more reliable dating results, the accumulation rate in core 1735 and the $^{14}$C age in core 1739, and one much trustworthy core correlation. The accumulation rate is greatest in core 1735 and smallest in core 1739, making the structure of the chronostratigraphy for the Arabian cores look like a chain of well correlated cores constrained by $^{210}$Pb dating in core 1735 on one end and $^{14}$C dating in core 1739 on the other.

- verification: successful

However, it still needs to be verified whether the two ends can meet with each other through the chain correlation. This can be viewed as the final testimony of the whole chronology for the Arabian cores. The accumulation rate in core 1735 is 75 cm/ka; through the core correlation (Table 3-6) it will become 3.45 cm/ka in core 1739. If the correlation between cores 1735 and 1736 is modified as 1 : 0.213 as the greatest possible ratio suggested by total excess $^{210}$Pb modal, the accumulation rate at core 1739 would be 3.35 cm/ka. On the other hand, calculated from the $^{14}$C dating, the general accumulation rate in core 1739 will be 37 (cm)/11,000 (calendar years) = 3.36 cm/ka. They are practically identical, suggesting strongly the validity of the chronostratigraphy, even though the numbers may not be as precise as they look, considering an estimated overall error accumulated up to ±10%.

- establishment

The Arabian cores are quite homogeneous, and are difficult to locate stratigraphic boundaries. In this regard, the chronostratigraphy is not very much more than
chronology. So for many of the cores, an overall accumulation rate will be informative enough in practice. Summarising the data from 1) $^{210}$Pb dating and the total excess $^{210}$Pb modelling, 2) $^{14}$C dating and 3) core correlation analyses, the final core correlation and accumulation rates for the Arabian cores are determined (Table 3-9).

<table>
<thead>
<tr>
<th></th>
<th>1735</th>
<th>1736</th>
<th>1734a</th>
<th>1733</th>
<th>1739</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR (cm/ka)</td>
<td>75.0</td>
<td>16.0</td>
<td>9.23</td>
<td>6.00</td>
<td>3.35</td>
</tr>
</tbody>
</table>

- some interesting dates

It is worth noting that the dramatic particle size change at about 19 cm in core 1739 can be dated as 5670 years BP, and a similar but smoother change at 24 cm in core 1734a is 2600 years BP. The mass-flow deposits below 27 cm in core 1736 is about 1700 years BP. All these will be explained in a framework outlined in chapter 5.

Discussion

- further support

In tropical Atlantic, where sediment is transported by the Africa monsoon, accumulation rates are found ranging from 2.3 to 7.3 cm/ka (Ruddiman, 1997), giving an idea of the magnitude of the accumulation rate of aeolian dust at sea. The chronology here above has shown good agreement when compared with previous dating results. In core MD77-203 from the proximal region of the coastal upwelling off Arabia, an accumulation rate of about 20 cm/ka is noticed and the adjacent core RC9-161, about 100 km southwest to MD77-203, yields a rate of 10 cm/ka (Prell, 1984). As both of the cores are outside the Wahiba Sands, the accumulation rate in core 1733, which is about 6 cm/ka, is reasonable as compared with them. Other data from $^{18}$O stratigraphy also support the ca. 4 cm/ka accumulation rate at core 1739 (Shimmield, 1992).

- further explanation for correlation between cores 1735 and 1736

For the core correlation, the most difficult one is that between core 1735 and core 1736, where a relative big gap is not sampled in the rapidly changing environment.
Another signal comes from the total excess $^{210}$Pb method, which gives a ratio of 1:0.208, comparable to that from core correlation 1:0.325. The comparison of particle size data gives two additional matching points: one at 33 cm and the other at 39 cm in core 1735, corresponding to points at 7 cm and 9 cm in core 1736 respectively. These yield an average ratio of about 1:0.22. The differences between these data are understandable, as they either result from sampling resolution or are induced by natural differences in the cores, such as varying accumulation rate, different response to the same events, different extent of sediment reworking and so on.

- offset on $^{14}$C age in core 1739? No.

It is well known that shells and carbonates are troublesome for exchanging carbon, and it is often difficult to know what is dated. Brown et al. (1989) noted that $^{14}$C age on big forams may be offset as compared with bulk sediment which they measure on, but when the bulk sediment consists about half of big forams, only a relative small offset incurred (Thomson et al., 1995), therefore this effect will not have a great impact on the $^{14}$C age in core 1739.

- $^{210}$Pb and $^{14}$C

For the cores close to shore, where accumulation rate is normally high but relatively less bioturbation, the $^{210}$Pb dating seems more reliable. On the other hand, in the mid-ocean on the Murray Ridge, where relic carbon plays a minor role in the whole sediment and bioturbation prevails, $^{14}$C dating may give a better result.
3.3 Discussion and Summary

- section arrangement

In this section, all the previously determined accumulation rates and chronostratigraphy for the Chinese cores (3.3.1) and the Arabian cores (3.3.2) will be compiled and summarised, and comparison between the two will be made in 3.3.3. In comparison with accumulation rate, chronostratigraphy seems more comprehensive, as accumulation rate, which focuses on the present or recent sedimentation, can be well reflected in a sound chronostratigraphy.

3.3.1 Chronostratigraphy for the China Seas

- refined chronostratigraphy

Although primary chronostratigraphy for the Chinese cores has already been decided, since the recognition of event stratigraphical markers can be improved as multidisciplinary studies go on, the chronostratigraphy is bound to be refined. Channel switching is mainly a physical process, possessing other impacts as well though, therefore further sedimentological analysis, including palaeomagnetic study in the following chapters and Chen (1994) will lead to a better resolution of the chronostratigraphy for the Chinese cores, JX91-3B in particular. Table 3-10 outlines the chronostratigraphy for the Chinese cores with some results from studies in Chapters 4 and 5 and Chen (1994), which is still not quite complete.

- Huanghe River in low sea-level period

Actually, whether the Huanghe River went into the Bohai Sea and Huanghai Sea before 8,500 yr BP is not meaningful, because the sea-level was so low at that time that the Huanghe rivermouth would always be in the now Huanghai Sea even if the river ran through the now Bohai Sea.

- ages of the bases of core

The bases of the cores in Table 3-10 have been put at certain points of time, which may not be accurate. However, there are reasons for doing this, because corers are
usually stopped at lithological boundaries with the underlying sediment harder to penetrate, as seen in the base bits in cores JX91-3B and JX91-7mG. In the Huanghe-influenced Bohai Sea and Huanghai Sea, this often means channel switching or rapid change of depositional environment, which normally have a certain date. With these closing points, the age-depth curves can be illustrated as in Figure 3.3-1. The time axis is in logarithm to accommodate the large time span in the cores.

Table 3-10 Chronostratigraphy of the Bohai and Huanghai cores

<table>
<thead>
<tr>
<th>age (yrs BP)</th>
<th>3B depth</th>
<th>2A depth</th>
<th>7mG depth</th>
<th>Huanghe River</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>~0</td>
<td>~0</td>
<td>0</td>
<td>Bohai (delta)</td>
</tr>
<tr>
<td>38</td>
<td>37</td>
<td></td>
<td>C/S No. 9</td>
<td></td>
</tr>
<tr>
<td>57</td>
<td>70</td>
<td></td>
<td>C/S No. 8</td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>110</td>
<td></td>
<td>C/S No. 7</td>
<td></td>
</tr>
<tr>
<td>87</td>
<td>145</td>
<td></td>
<td>C/S No. 4</td>
<td></td>
</tr>
<tr>
<td>94</td>
<td>190</td>
<td></td>
<td>C/S No. 3</td>
<td></td>
</tr>
<tr>
<td>136</td>
<td>205</td>
<td>10</td>
<td>27</td>
<td>Bohai</td>
</tr>
<tr>
<td>507</td>
<td>260</td>
<td>45</td>
<td></td>
<td>Huanghai</td>
</tr>
<tr>
<td>863</td>
<td>140</td>
<td></td>
<td>292</td>
<td>Huanghai + Bohai</td>
</tr>
<tr>
<td>2000</td>
<td>290</td>
<td>215</td>
<td></td>
<td>Bohai</td>
</tr>
<tr>
<td>2600</td>
<td>325</td>
<td>240</td>
<td></td>
<td>Huanghai + Bohai</td>
</tr>
<tr>
<td>4,270</td>
<td>275</td>
<td>352</td>
<td></td>
<td>Bohai</td>
</tr>
<tr>
<td>8,500</td>
<td>395</td>
<td>372</td>
<td></td>
<td>Huanghai</td>
</tr>
<tr>
<td>11,000</td>
<td></td>
<td>380</td>
<td></td>
<td>Bohai</td>
</tr>
<tr>
<td>11,900</td>
<td></td>
<td>392</td>
<td></td>
<td>Huanghai</td>
</tr>
</tbody>
</table>

* C/S: Channel Switching on the Huanghe River delta in the Bohai Sea

Fig. 3.3-1 Age-depth curves for the Chinese cores

- accumulation rate

The accumulation rates in the China region are firstly determined by $^{210}\text{Pb}$ dating based on the shape of $^{210}\text{Pb}$ activity curve with considerations about various
disturbance to the sediment; and then tuned with historical records, mainly Huanghe River channel switching between the Huanghai Sea and the Bohai Sea as well as on the Huanghe Delta in the Bohai Sea in the last 140 years. The channel switching records are used in conjunction mainly with its impact directly on sediment and on ambient depositional environment (e.g. foram assemblage change due to dilution of fresh riverwater in the Bohai Sea). The accumulation rates for the top sediments in the China Seas are thus determined as below in Table 3-11. It should be noted that there were still controversies over the $^{210}$Pb dating and so on, but once the correlation between channel switching and stratigraphic makers was firmly established, the related accumulation rates can be regarded as reasonably accurate.

### Table 3-11. Final recent accumulation rates in the China Seas

<table>
<thead>
<tr>
<th>Area</th>
<th>Bohai Sea</th>
<th>Huanghai Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Huanghe estuary basin</td>
<td>trough</td>
</tr>
<tr>
<td>AR (cm/a)</td>
<td>1.0 (mud); 6.0 (sand)</td>
<td>0.16 (mud) 0.2 (mud); 0.4 (sand)</td>
</tr>
</tbody>
</table>

#### 3.3.2 Chronostratigraphy for the Arabian Sea

- chronostratigraphy compiled and its error range

The chronostratigraphy outlined in Table 3-12 is basically a result of core correlation.

### Table 3-12 Chronostratigraphy of the Arabian cores

<table>
<thead>
<tr>
<th>age</th>
<th>1735 (cm)</th>
<th>1736 (cm)</th>
<th>1734a (cm)</th>
<th>1733 (cm)</th>
<th>1739 (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0 (top)</td>
<td>0 (top)</td>
<td>0 (top)</td>
<td>0 (top)</td>
<td>0 (top)</td>
</tr>
<tr>
<td>600</td>
<td>45 (base)</td>
<td>10</td>
<td>13</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>1420</td>
<td>123</td>
<td>13</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1690</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1820</td>
<td></td>
<td>17</td>
<td>11</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>2600</td>
<td></td>
<td>24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3230</td>
<td></td>
<td>19</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3310</td>
<td>53 (base)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3580</td>
<td></td>
<td>33 (base)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5670</td>
<td></td>
<td></td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5830</td>
<td></td>
<td></td>
<td>35 (base)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11,000</td>
<td></td>
<td></td>
<td>37 ($^{14}$C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14,000</td>
<td></td>
<td></td>
<td>47 (base)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ratio</td>
<td>1</td>
<td>0.213</td>
<td>0.123</td>
<td>0.080</td>
<td>0.045</td>
</tr>
</tbody>
</table>

N.B. The stippled areas indicate the primary depths used in core correlation.
Although the chronology is sound, an error of ±5% is expected for each correlation, which can accumulate through the chain, so when the other end of the chain is reached, the error could be up to ±20%. However, the cross correlation will decrease the error range, such as that between core 1734a and core 1739 to about ±10%. Figure 3.3-2 shows the age-depth curves for the Arabian cores based on the chronostratigraphy. The recent accumulation rates in the Arabian Sea are listed in Table 3-9.

![Fig. 3.3-2 Age-depth curves for the Arabian cores](image)

3.3.3 Comparison and summary

**Comparison**

- determination procedure

The determination procedure for the chronostratigraphy of the Chinese cores and Arabian cores is different, which is to a high extent due to the different sediment types in the two regions produced by different sedimentation processes (chapter 4). It is noted that in the China Seas, historical records of the Huanghe channel switching are heavily utilised, whilst in the Arabian Sea numerical dating plays an important part. Table 3-13 outlines the main steps involved in establishing the chronostratigraphy.

- stratification; fluvial and aeolian deposition

The lack of strata in the Arabian cores indicates that the depositional environmental change in the Arabian Sea is either very little or rather gradual, if the sediment source...
remains the same. As for the sediment source, there are two possibilities; one is that the dust sources around the Arabian Sea have similar physical characteristics, and the other is that even there are distinct features individually, their mixing proportion in the sediment did not change very much since the late Pleistocene. In either way, it is quite different from the Bohai and Huanghai sediment, where the major sediment source is the Huanghe River, which has distinct characteristics. The much stratified Bohai and Huanghai sediment is a direct result of variable fluvial processes, which apparently lack in the Arabian Sea. The much different accumulation rates in these two regions, at least an order of magnitude generally, reflect the difference between sediments dominated by fluvial and aeolian processes. These have obviously affected the determination procedures of accumulation rates and chronostratigraphy, making the Arabian cores particularly difficult to date owing to the lack of stratigraphic markers within.

### Table 3-13 Major procedure of chronostratigraphy determination

<table>
<thead>
<tr>
<th>Sea location</th>
<th>Bohai</th>
<th>Huanghai</th>
<th>Arabian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea location</td>
<td>estuary</td>
<td>basin</td>
<td>trough</td>
</tr>
<tr>
<td>accumulation rate</td>
<td>model, $^{210}$Pb</td>
<td>model, $^{210}$Pb</td>
<td>$^{210}$Pb</td>
</tr>
<tr>
<td>correlation</td>
<td>c/s &amp; sands</td>
<td>various</td>
<td>sea-level curve, $^{14}$C</td>
</tr>
<tr>
<td>establishment</td>
<td>c/s on delta</td>
<td>c/s between seas</td>
<td>c/s between seas</td>
</tr>
<tr>
<td>main point</td>
<td>c/s &amp; sands</td>
<td>forams</td>
<td>c/s, JX91-7mG</td>
</tr>
</tbody>
</table>

* c/s: channel switching

### Summary

- Reliability: from the best of the data available

In this chapter, accumulation rates have been determined and chrono-stratigraphy has been established from the best of the data available for the Bohai Sea, the Huanghai Sea and the Arabian Sea, through the steps outlined in Table 3-13 with a multidisciplinary approach based mainly on $^{210}$Pb and $^{14}$C dating, core correlation and historical records.
Chapter 4. Sedimentation Processes in the Bohai Sea, the Huanghai Sea and the Arabian Sea

• section arrangement
Generally speaking, the major sediment transport force in the Bohai and Huanghai Seas is river, while it is wind in the Arabian Sea. These two different processes will inevitably impose their fingerprints on the sedimentation in the two regions. The primary goal of this chapter is to identify, characterise and compare these two sedimentation processes. This will be done in four sections, i.e. section 4.1 for the Huanghe estuary, section 4.2 for the Bohai and Huanghai Seas, section 4.3 for the Arabian Sea and section 4.4 for comparing the sedimentation in the two areas.

• methods
For the Huanghe estuary, facts from three aspects are combined to address the sedimentation processes (in particular the estuarine turbidity current), which are sedimentary records (mainly particle size data and palaeomagnetism) and their interpretations (probability plot etc.), observation and previous studies on turbidites. In the central Bohai Sea and the south Huanghai Sea, sedimentation processes will be discussed based on the results from section 4.1 and the Huanghe channel switching, especially when there was strong current but no direct Huanghe influence. Distal turbidity current and mass-flow are the two major processes to consider. For the Arabian Sea, both particle size and geochemistry data, together with mathematical modelling and rock magnetic data, will be used to characterise the aeolian processes and mass flow deposits (turbidites). In particular, geochemistry will play a major part in identifying turbidites (mass-flow deposits) in Arabian sediments, different from sedimentological analysis in the China Seas.

4.1 Sedimentation at the Huanghe River Estuary

• a special area and special fluvial process
The Huanghe estuary is noted for its importance in connecting the land and the sea, where the dramatic river-sea interaction can be seen. Details of the sedimentation
processes involved in early fluvial deposition at sea will be revealed here, which will also benefit sedimentological studies on a wider range in the Bohai and Huanghai Seas. In this section, a special sedimentological phenomenon at the Huanghe estuary, the estuarine turbidity current (see also Chen, 1994), will be focused on.

4.1.1 Introduction, Observation and Definition

Introduction
- Huanghe River and riverwater
The Huanghe River is famous not for its water discharge (about \(4.8 \times 10^{10} \text{ m}^3/\text{yr}\)), but for its sediment load of \(1.2 \times 10^9 \text{ tons/yr}\) to the Bohai Sea, which is mainly loess from the Loess Plateau at the middle reaches of the river, making the riverwater the densest in the world. Suppose the suspension content of the Huanghe riverwater at the river mouth is 50 g/l and the average density of the solid particulate is 2.7 g/cm³, the density of such a slurry water mixture will be greater than 1.03 g/cm³, heavier than the normal seawater. Actually the riverwater can be even heavier if the chemical constituents in the riverwater are counted in. In fact, the 50 g/l suspension content can be easily exceeded nowadays at the rivermouth in any direction (IOCAS, 1985).

- river-sea interaction: hyperpycnal plume
At the rivermouth, what actually happens is that the riverwater suddenly loses much of its momentum when it encounters the seawater and begins to deposit its suspended load and chemical constituents through physical and chemical precipitation. In the meanwhile, the 'cleaner' and lighter riverwater spreads out to form a hypopycnal plume (Wright, 1988, Li et al., 1998a, 1998b), which mixes up with the seawater eventually and dilutes it. The undergoing hyperpycnal plume, however, is therefore made even heavier by this process, and contributes a great deal to the extremely high suspension content near the rivermouth (see Fig. 4.1-1).

- nature of the Bohai seawater
On the other hand, the Bohai seawater is made possibly the lightest in the world. The density of seawater depends mainly on salt content, a little on temperature. Because
of the large amount of freshwater input from the Huanghe River, the seawater is thus heavily diluted. The salt content of the Bohai seawater varies with seasons and locations, nevertheless the yearly average salt content outside the river mouth can hardly exceed 28% (IOCAS, 1985). When the standard seawater with salt content of 35% and density of 1.025 g/cm$^3$ is diluted to 28% of salt content, the density will decrease to 1.02 g/cm$^3$, equivalent to that of riverwater with 30 g/l suspension content. Other factors, like the water temperature and particulates in seawater, are actually too insignificant to influence the difference between the riverwater and seawater. In fact, the temperature of riverwater is very similar to that in the Bohai Sea and the particulate content is rather low (IOCAS, 1985).

**Conclusion**

Therefore, the turbid Huanghe riverwater at the rivermouth is actually heavier than the diluted Bohai seawater. Under this condition, a gravity flow or density flow should be able to form, just as suggested by many other researchers (e.g. IOCAS, 1985, Wright, *et al.*, 1986, Hsu, 1989).

**Observation**

- underflow found during cruise JX91

During the cruise JX91, a very strong underflow was observed when a Mackereth type mini-corer was tried coring from opposite to the rivermouth ca. 30 km away at a water depth of 11 m (station 4). The surface water seemed reasonably still when the corer, which is about 15 kg heavy and less than 1.5 m high, was lowered down. When it should have touched the seafloor, judging from the length of rope released, the rope holding the corer began to angle. More rope was given only to increase the tilt angle till it reached about 45 degrees toward the ship. It seemed the corer had never rested on the seafloor. Puzzled by this, we tried a second time, making sure it was not the drift of the moored ship, but the same happened again. The mini-corer was then tried on the other side of the ship. This time, we did give ourselves a hard time preventing the corer from running away. The longer and heavier Mackereth type corer failed twice as well. This underflow is actually the hyperpicnal plume found by Wright (1988) and Li *et al.* (1998b).
4.1.1 Introduction, Observation and Definition

- characteristic of the underflow

It seems that only about 3 m above the seafloor could the corer pull the rope vertical, suggesting a rough thickness of the underflow of 3 m. At the preceding station 3 with a shallower water depth (10 m) but a greater distance from the present rivermouth, the underflow did not seem to be so troublesome. The strong underflow is only found around the Huanghe rivermouth, and is very likely to be the postulated gravity flow.

- suspended sediment profile

Even if the strong underflow is confirmed, we are not completely sure whether it is a gravity flow or others, without knowing anything about its distribution. Fortunately a previous marine survey carried out by the IOCAS in the Bohai Sea had revealed the profile of suspended sediment (Fig. 4.1-1), which actually depicts the sediment dispersion pattern in the Bohai Sea.

![Fig. 4.1-1 Profile of suspended sediment content from the rivermouth to Penglai (after IOCAS, 1985).](image)

- characteristic of the profile

This profile shows the suspended sediment content from the rivermouth to Penglai (IOCAS, 1985). In other profiles starting from the rivermouth, the pattern of sediment dispersion remains almost the same, except for the values of the suspension content varying with the angle from the axis of river channel, with its maximum achieved along the axis. The most distinctive feature of the profile is a tongue-like sheet of high suspension load near the seafloor, extending tens of kilometres on the flat seafloor to the Central Basin. The suspension content of this underflow is more
than 20 - 30 g/l, which is close to or over the threshold required for a gravity flow in the Bohai Sea. In fact, an even denser sheet of turbid water mixture was found within 1 m above the seafloor (IOCAS, 1985).

**Conclusion**
The profile has actually depicted the turbid underflow from the Huanghe rivermouth in the Bohai Sea. As this underflow is apparently gravity-driven, it is believed to be a gravity flow. It is noted that the gravity flow extends over 60 km (estimated from Fig. 4.1-1) into the Bohai Sea on a very flat seafloor only with the energy from about 10 m fall and the initial river momentum, which would be almost impossible for other gravity flows except turbidity currents.

**Definition**
- **sediment gravity flows**

Four principal types of sediment gravity flows, viz. turbidity current, fluidized sediment flow, grain flow and debris flow are defined by Middleton and Hampton (1976) as below.

1. Turbidity currents are gravity flows in which sediment is supported by the upward component of fluid turbulence. The presence of this sediment in the flow causes its density to increase above that of the ambient water, resulting in downslope flow. Flow can occur quite rapidly, even on very low slopes.

2. Fluidized and liquefied flows are concentrated dispersions of grains in which the sediment is supported either by upward flow of pore water escaping from between the grains as they settle downward by gravity, or by pore water that is forced upward by injection from below. Liquefaction can occur by sudden shocking of the sediment mass, greatly reducing friction between the grains. These flows can move rapidly down relatively gentle slope (3-10 degrees).

3. Grain flows are dispersions of cohesionless sediment in which the sediment is supported by dispersive pressure owing to direct grain-to-grain collisions or close approaches. Flow can occur rapidly under both subaerial and subaqueous conditions, especially on steep slopes that approach the angle of repose for the sediment.

4. Debris flows and mudflows are slurrylike flows in which large grains, ranging from up to boulder size, are supported in a matrix of fine sediment and interstitial water that has enough strength to prevent larger particles from settling out, but not enough strength to prevent flow. Debris flows can occur on gentle or steep slopes in subaerial or subaqueous environments.
4.1.1 Introduction, Observation and Definition

• estuarine turbidity current

It is obvious that the gravity flow found in the Huanghe estuary is more like the turbidity current than like the others, though the mudflow is close to that too. As a matter of fact one type of process may grade into another under some conditions, just like submarine mudflows may change into turbidity currents downslope with additional mixing and dilution by water (Boggs, 1987). Another consideration about the nature of the underflow is from the viewpoint of density current. Density currents are currents that are generated by gravity acting on differences in density between adjacent bodies of fluids. A turbidity current is a special type of density current that flows downhill along the bottom of an ocean or lake because of density contrasts with the ambient water caused by sediment suspended in water owing to turbulence (Boggs, 1987). So the underflow described above can be properly named estuarine turbidity current.

• other names and further support

There are other descriptions concerning this current, e.g. hyperpycnal plume or gravity-driven underflow (Wright, et al. 1988), but according to the classification of Middleton and Hampton (1976), it is actually a turbidity current. In fact, this kind of 'turbidity current' has been observed under natural conditions in lakes where muddy riverwater enters the lakes, flowing along the sloping lake bottom (e.g. Lambert, 1988), The reason for its 'absence' on a continental shelf is only that the density contrast between muddy riverwater and ocean water is less than that between muddy riverwater and freshwater (Boggs, 1987, Hsu, 1989). In the ideal Bohai Sea the density-contrast is no longer a problem, so a special turbidity current can be formed. As this turbidity current is different from the ordinary ones (see section 4.1.3), even the freshwater turbidity current, it should be therefore called estuarine turbidity current.
4.1.2 Estuarine Turbidites

Classic turbidites

- important feature and shell layers in JX91-3B

Classic turbidites can be recognised by their unique sequences, such like the Bouma sequence, but most turbidites found in nature look quite different (e.g. Hsu, 1989). However, one of the important features of classic turbidites, the poor sorting, should be always there, which means the mixing of particles of different sizes and very often of different materials. Looking back at Fig. 2.2-1, we can find two highly mixed layers in JX91-3B, i.e. the two major shell layers located at the bottoms of event stratifications 1 and 2 (chapter 3).

A. Significance of shell fragments

- no shells and the like at the coresite

It has been noted that there are no living shells at the coresite at present, even no shell fragments in the top layer. As a matter of fact no shell can survive in the highly turbid environment and on such a 'running' bed, owing to the insufficient sunlight, unstable habitat and, more importantly, the lack of food (only sparse diatoms were found by Prof. Cang in palaeontology study on the core). Moreover, the top 30 cm is devoid of any trace of bioturbation as seen through the transparent tube of 8 cm diameter used in coring JX91-3m. Therefore the shells and fragments must be exotic.

- turbidity current transportation

At 100 cm and 185 cm of JX91-3B the layers are described as 'graded' and 'gravely' with shells respectively. When the 'gravels' are cleaned, some of them turn out to be intact shells, which must have been transported there from the intertidal zone where these shells thrive (e.g. Xue, et al., 1993). One shell found was surprisingly big, about 1 cm in length and 0.5 cm in diameter. Such a mammoth shell, together with others, cannot be moved by fluid flows over such a long distance except by a turbidity current. Therefore the shell layers, with a high degree of mixing and very poor sorting, are actually classic turbidites at the Huanghe estuary.
B. Classic turbidites and channel switching

- initial flushing of riverwater on the tidal flat at the beginning of a channel switching

It is interesting to note the positions of the two classic turbidites. It is actually no coincidence that the two shell layers are found beneath the two sandy layers. We know in chapter 3 that the event 1 is associated with channel switching 3, and event 2 with channel switching 7. So the classic turbidites must have formed at the beginning of the two major channel switchings. It can be imagined that one day the big river switched its channel during a big flood to a once-quiet tidal flat. The furious turbid riverwater must have been very erosive and would have destroyed the ecosystem on the flat at the first blow. The first wave of the turbidity current would carry away load of sediment from the tidal flat with shells and their fragments and deposited them far away from the new rivermouth very rapidly. After that, no more shells would be found in the sandy deposits, which is mainly because the shells had been almost completely washed away from the new channel, though the turbidity current itself may become less competent too. This also explains why there are no shells under event 3, when the new rivermouth was either too far away from the coresite or too close to that of the last channel switching 7 (Fig. 3.2-1). After all, the classic turbidites with shells and fragments had been formed under exceptionally strong turbidity current at the beginning of certain channel switchings at the Huanghe estuary. This relationship between the ‘classic’ turbidity current and ‘shell’ layer can also be noticed in earlier estuarine sediment (section 5.1) and in the Huanghai Sea sediment (5.2).

**Particle size**

- internal signature of turbidites: particle size distribution

In the classic turbidites, the shells serve as good turbidite indicators, but just as we see, channel switching 8 failed to produce a classic turbidite, which does not necessarily mean there was no turbidity current and the sediment was not turbiditic. Actually a deposit is turbidite not because it looks like turbidites, but because it is deposited under those special conditions. These special sedimentational processes must have imposed their impact on the sedimentary texture, which can be revealed by quantitative particle size analysis.
A. Mean

- hydraulic significance

The mean is the best measure of average size among mean (M), median (Md) and mode. Generally speaking, the greater the mean, the coarser the sediment and the stronger the hydrodynamic conditions. As the Huanghe sediment is normally finer than 0.02 mm, the coarser sediment can indicate stronger current. The two points below will show how the mean can be used to confirm an estuarine turbidity current.

- continuity between classic turbidites and sands

Firstly, as compared with the 'classical' turbidites (sieving off the shells and big fragments), the sandy sediment does not show a big shift in mean values (Fig. 2.3-5), suggesting the turbidity current had not diminished and that the overall strength of the turbidity current persisted.

- coarse sands comparable to those on land

Secondly, on the Huanghe River delta near the rivermouth the sediment is found mainly composed of 'coarse silt' or more accurately, 32.8% sand, 59.6% silt and 7.6% clay from the active lobe (Xue et al., 1993). Although there are different definitions for 'coarse silt', it would be finer than 63 μm, the common boundary for silt and sand. However, ca. 30 km away in JX91-3B the mean values for the three sandy layers are 60, 70 and 65 μm from events 1 to 3 (Fig. 2.3-5), and the sand proportions are 45%, 65% and 60% respectively (ref. to Figs. 2.3-2 and 4.1-2). This indicates the sands are at least as coarse as those at the rivermouth on land, and have been transported there by a very strong flow, comparable to the Huanghe riverwater on land. This kind of current can only be the estuarine turbidity current as described previously. It is likely that the turbidity current has carried to the coresite the coarsest sediment available from the Huanghe River.

B. Probability plot

- a powerful tool for sedimentological analysis

Particle size distribution contains much more information than the mean value can provide. A conventional and efficient way to interpret the particle size data is to
present the cumulative-volume distributions of the particle sizes on probability plots, which is described by many researchers (Friedman and Sanders, 1978, Middleton and Southard, 1984, McManus, 1988). Visher (1969) had fully discussed the relationship between the particle size distributions and depositional processes using such probability plots (or log-probability plots).

• probability plot for JX91-3B: two groups and two sections

Fig. 4.1-2 shows the probability plot of 65 samples from JX91-3B (Appendix B2). The plot is characterised by two main groups of scatter points; the upper group is generally coarser and identified as sandy samples, while the lower group is for the finer muddy ones. It is obvious that each group can be fitted with two straight-line sections; the section at the finer end represents the suspension population and the one at the coarser end saltation population, but no surface creep population is present (Visher, 1969, Middleton and Southard, 1984).

![Fig. 4.1-2 Probability plot of particle size distribution for JX91-3B](image-url)
4.1.2 Estuarine Turbidites

- analysis: turbidites

The curve shape of the sandy samples agrees with those of some submarine turbidites, though the fluvial sands also show that shape (Visher, 1969). For the fluvial sands their positions are determined within the channel, usually at the base. Considering the coresite of JX91-3B is 10 m below sea-level, the 'fluvial channel sands' can be properly interpreted as the deposits of a strong underflow, the estuarine turbidity current here. It is interesting to note that with a 70% suspension population the muddy sediment does not show the characteristics of the modern fluvial system, in which suspension population can only comprise a maximum of 20%, instead it looks more like turbidites (Visher, 1969). The particle size analysis not only confirms the sandy estuarine turbidites but also suggests a turbidite origin for the muddy sediment (4.1.3).

Magnetic technique

- sedimentary fabric

Another important aspect of sedimentary texture, apart from particle size and particle shape, is fabric of sediment. Sedimentary fabric study of JX91-3B had been carried out by Chen (1994) using magnetic technique rather than conventional optical method which is rather difficult to apply. The basic idea of the magnetic fabric is that ferromagnetic grains are deposited and reworked, if any, in the same way as the non-magnetic ones; hence the overall orientation and packing can be determined magnetically, e.g. by susceptibility anisotropy (see also Chen, et al., 1996). The problem in the application of this method is that ferromagnetic grains may tend to align along the geomagnetic field, especially in a quiet depositional environment, and hence may not represent accurately the overall fabric. However, this problem can be neglected if the hydrodynamic condition is strong enough, e.g. in a turbidity current. In fact the ferromagnetic grains will be largely controlled by such a current, and the declination and inclination of NRM (Natural Remanent Magnetisation), which show the overall alignment of the magnetic grains, can practically indicate the hydraulic conditions by showing their deviation from the theoretical alignment formed under quiet depositional environment.
4.1.2 Estuarine Turbidites

Figure 4.1-3 Palaeomagnetic measurements on declination and inclination of NRM in JX91-3B (Chen, 1994). High values in ‘litho’ indicate sandy sediments, otherwise muddy sediments.

- sands: deposits of turbidity current

The declinations and inclinations of NRM in JX91-3B (Fig. 4.1-3) have reflected the impact of strong hydraulic conditions associated with the three channel switchings, taken the lower part (down from 190 cm) as a rough reference. The turbidity current apparently diverted the magnetic vectors, and made the inclinations in events 1 and 3 shallower but steeper in event 2 (see also Chen, 1994). The magnetic fabrics of the three sandy layers derived from magnetic anisotropy technique (Tarling and Hrouda, 1993) confirm that they are deposits from the turbidity current associated with the three channel switchings, 3, 7 and 8 (see also Chen, 1994), where the susceptibility ellipsoids show relative changes according to the orientation of the river mouth.

- conclusion

After all, the three sandy layers in JX91-3B are confirmed to be deposits of an estuarine turbidity current, i.e. estuarine turbidites, and the classic turbidites with shells and fragments were only formed at the beginning of certain channel switchings by initial flushing of riverwater on the previously very productive tidal flat. This conclusion is supported by various measurements and analyses, including lithostratigraphy, particle size distribution and palaeomagnetism.

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4.1.3 Characteristics of Estuarine Turbidites

- homogeneity and contrasting sediments

These estuarine turbidites in JX91-3B are quite different from the common turbidites mainly found in deep water owing to the special conditions at the Huanghe estuary. Two striking characteristics of the turbidites are their homogeneity and the contrast between the two types of sediment in comparison with deepwater turbidites.

**Homogeneity**

- sedimentological significance and stable sediment supply

In terms of sedimentology, homogeneity in sediment reflects fairly constant, but not necessarily quiet, depositional environment and a stable sediment supply. In the Bohai Sea, a stable sediment supply seems to be the key factor controlling the homogeneity. In fact, the *in situ* depositional environment is also associated with the sediment supply to the coresite. The year-on-year Huanghe sediment input to the Bohai Sea is unstable (e.g. IOCAS, 1985, and ref. to Fig. 5.1-1). However, it seems more important that whenever some sediment is deposited, the depositional environment will be the same. In reality, a reservoir of soft and liquefied sediment at the rivermouth has practically sustained the estuarine turbidity current and stabilised it to a certain extent. As shown in the investigation, this kind of sediment can be easily plunged through with a 4 m scale, and there is actually no water/sediment surface (IOCAS, 1985). Moreover, the wave or storm-stirred suspended sediment also contributes to the 450 g/l suspension near the mouth, making a more constant sediment supply all year round. The stable supply of similar sediment to the coresite is thus behind the appearance of homogeneity.

**Two types of estuarine turbidites**

- an estuarine turbidity current system

At least the upper part of JX91-3B can be viewed as stacked homogeneous deposits from different channel switchings. Although the sediment deposited at the coresite may be different owing to the relative positions to the mouth in different periods, the estuarine turbidity current itself was actually the same, although flowing in different
formation of two types of turbidites in one system

There are two principal types of turbidity currents (Lowe, 1982): low density flows, containing less than 20-30 percent grains, and high-density flows, containing greater concentrations. Normally the high-density flows are found proximal to the source and within the current channel, and the low-density flows out-of-channel and distal. Considering the lateral rather than longitudinal positions of JX91-3B in different channel switching periods, the sandy layers should be regarded as deposits of the high-density flows and the muddy layers of the low-density flows. In high-density flows, support of coarse particles is provided by turbulence aided by hindered settling resulting from high particle concentrations and the buoyant lift provided by the interstitial mixture of water and fine sediment (Boggs, 1987). When the turbulence and buoyant lift fail to support the coarsest particles in the flow, they settle out, but not together with the finer ones, which are later deposited out-of-channel or in distal area. The two types of sediment in JX91-3B are actually deposits from one estuarine turbidity current system as channel-fill (sand) and unchannelled (mud) turbidites.

Comparison with deepwater turbidites

Deepwater turbidites are the commonest turbidites found in nature (Normark et al., 1993), and those in lakes (e.g. Lambert and Giovanoli, 1988) are quite similar to them except on a smaller scale. However, the estuarine turbidites and the whole system in the Bohai Sea are quite unique, and it will be interesting to make a comparison between them.

A. Channel

As already noted, the turbidity current appears strongest along the direction of the main river channel and decreases away from that direction (IOCAS, 1985), which implies the dependence of current intensity on direction. Wright et al. (1988) found
the hyperpycnal plume (high-density turbidity current) was actually quite wide-spread, which is also suggested in JX91-3B as the sandy sediment formed at various big angles to the mouth, tens of kilometres in the Bohai Sea.

- sediment supply and the shapes of direct sediment source and channel

This wide-angle channel is basically imposed by the over-adequate Huanghe sediment supply, and a helpful convex rivermouth. On the contrary, the suspended sediment produced by sediment failure in deepwater system is usually inadequate and needs a concave shape, e.g. submarine canyon, to concentrate the sediment to form a turbidity current (Normark et al., 1993). So the channel in deepwater system is normally well developed and looks more linear than that in this estuary.

B. Erosion and deposition

- current intensity

Although the estuarine turbidity current gains the original energy from sliding down a slope near the sediment source, like that in deep water, plus the initial momentum from the river, the current intensity is not comparable to the deepwater one. This is mainly because the height from the rivermouth to the seafloor (<20 m in the Bohai Sea) is much less than that in the deepwater system, and the convex shape of the delta disperses the current energy. So no significant features like those on the deepwater fans was carved by the estuarine turbidity current (IOCAS, 1985, Normark et al., 1993).

- dominant deposition at estuary

As a matter of fact, due to the relatively low energy of the estuarine turbidity current and the adequate sediment supply, deposition prevails in the whole JX91-3B and erosion can be hardly found, except at the beginning of certain channel switchings (ref. to 4.1.2). Even then massive erosion can only occur at those areas where the relief of seafloor is above the hydraulic stable curve for the new current in the seaward direction. As compared with the proximal erosion and distal deposition of the deepwater system, the erosion in estuarine system is more channel-switching dependant and deposition dominates most of the time and all over the whole system.
C. Sorting

• better and consistent sorting for estuarine turbidites

Sorting of sediment is regarded as one of the important differences between the deposits of sediment gravity flows and the those deposited by normal fluid flows (Boggs, 1987). The poor sorting of common turbidites is due to rapid deposition and lack of reworking of the sediment (Boggs, 1987). On the contrary, in the stable estuarine turbidity current, only particles of certain size can be finally deposited, making good and consistent sorting. As stronger current can rework sediment more thoroughly, the sandy layer with higher mean or median values should have better sorting, and that is what can be seen in Fig. 3.2-1.

D. Sequences

• no Bouma sequences in estuarine turbidites

There is no actual turbidite 'sequences' at all in JX91-3B, except the shell layers. By contrast, the famous Bouma sequences, more often a part of it, are frequently found in the deepwater turbidites, which are actually sedimentary record of the intensity decline of the turbidity current supported by suspended sediment originally produced by a catastrophic event through sediment failure in a short time. It can be postulated that if the sediment supply were consistent, even the deepwater turbidites could not present the typical sequences, but homogenous beds instead. So the sequences are actually not the criterion to judge whether a deposit is turbidite or not.

Conclusion

• unique turbidites

As discussed above, it is the stable turbidity current system and adequate sediment supply from the Huanghe River to the relatively quiet Bohai Sea that have produced all the characteristics of the estuarine turbidites, with the help of the Huanghe channel switching. Homogeneity within the strata, two types of estuarine turbidites and sharp boundaries between them are their major characteristics. Comparison with the deepwater (freshwater) turbidites suggests the Huanghe estuarine turbidites are quite unique and different from deepwater ones in many ways.
4.1.4 Discussion and Conclusion

- assumption and doubt on early turbidites
A simple assumption had been made before an estuarine turbidite system around the Huanghe delta could be constructed, i.e. the Huanghe River has been running in a similar way for so long that the sedimentary records of different periods at one site in the system should be able to depict the synchronous pattern of the system to be derived from different sites. Of course, if the Huanghe River was not like today, e.g. not turbid enough in the early history (lower part of JX91-3B), the so-called estuarine turbidite system would not exist, and hence no turbidites. The estuarine turbidites can only form when all the conditions for a turbidity current were satisfied.

- three key factors for the estuarine turbidite system
The three key factors making the estuarine turbidity system possible are
1) fine-grained clay-rich suspended sediment (loess) which makes the riverwater sediment-saturated and forms a high density water-sediment mixture at the Huanghe rivermouth;
2) adequate sediment supply from the Huanghe River which helps to maintain a rather stable turbidity current;
3) a relatively low energy depositional environment in the Bohai Sea which assures the dominance of the turbidity current and allows the semi-isolated seawater to be diluted by the fresh riverwater.

- estuarine turbidite characteristics
The extraordinary characteristics of the Huanghe estuarine turbidites are the homogeneity of sediments deposited by rather stable turbidity currents and the abrupt lithological changes at the boundaries relating to the Huanghe channel-switchings. At the beginning of certain channel-switchings, classic graded turbidites could be formed. In the estuarine turbidites, the sandy layers are deposited mainly as saltation load and represent the channelled sediments, while the muddy layers are mainly suspended sediments and unchannelled.
a new type of turbidite and its significance

Comparison with the deepwater (freshwater) turbidite system shows the particular sediment dispersive pattern in the Bohai Sea. Typical features of deepwater turbidites, such as erosion (submarine canyon) and Bouma sequences are absent in the Huanghe estuarine turbidites due to the sufficient sediment supply and relatively low energy of the turbidity current. This estuarine turbidites of the recent Huanghe River are so unique that they should be regarded as a new type of turbidite, in addition to the deepwater turbidites and lake (freshwater) turbidites. The study of this turbidites would help broaden our understanding of turbidity currents and their deposits, provide a means of analysing and interpreting similar deposits in other estuaries around the world, and provide a possible example of the special sedimentational processes found only in ancient sediments (Visher, 1969).
4.2 Sedimentation in the Bohai Sea and the Huanghai Sea

- Huanghe influence
In both the Bohai Sea and the Huanghai Sea, the input of the Huanghe River is vital to the depositional and ecological environment. The variation of sedimentation in the two seas, more accurately the coresites of JX91-2A and JX91-7mG, is mainly caused by channel switchings of the Huanghe River in history. The other local rivers around this region are either much less influential to the coresites or so stable that no substantial channel switching occurred. The Huanghe impacts are two fold: the changes of hydrodynamic conditions and nature of seawater owing to the great amount of fresh riverwater supply on one hand, and its sediment supply and redistribution on the other. These two aspects are closely related in the two seas, though not always directly, especially when oceanic current is involved in the distribution of sediment in the Huanghai Sea. In this section, sedimentation of the Bohai Sea (4.2.1) and the Huanghai Sea (4.2.2) will be studied and compared (4.2.3).

4.2.1 Sedimentation in the Bohai Sea

- channel switching records
The channel switching of the Huanghe River between the Bohai Sea and the Huanghai Sea was apparently less frequent than those on the delta (Chapter 3). Only a few big channel switchings had taken place since about 5000 years ago (Ren et al., 1985, Fig. 1.1-2). Other researchers (e.g. Tan, 1953) have described more single switchings, but given similar dates. It is interesting to know what sedimentological effects these channel switchings have on the sedimentation in the Bohai Sea.

Hydrodynamics
- strength of the Huanghe injection: yearly change
Profile of the suspension (Fig. 4.1-1) shows a likely distal turbidity current to the coresite of JX91-2A. From the observation during coring, there seemed a bottom current in the central Bohai Sea though this might not be so strong as in the estuarine area. There is no doubt, however, that the injection of the Huanghe River has altered
4.2.1 Sedimentation in the Bohai Sea

and strengthened the current system in the Bohai Sea, not only in surficial current field but also in the bottom current field. Actually in summer time when the Huanghe runoff reaches its maximum in a year the current system in the central and southern part of the Bohai Sea becomes quite different from that in winter time, apparently diverted by the Huanghe injection (IOCAS, 1985). The low salinity water mass from the rivermouth can extend over 100 km into the Bohai central basin (IOCAS, 1985).

- specific positions of rivermouth

The hydrodynamic condition at JX91-2A is also influenced by the specific position of the rivermouth. It is possible that if the river entered the Bohai Sea, but not towards the coresite, the hydrodynamic condition there would not be greatly affected. However, this entrance could definitely influence the depositional environment chemically and hence biogenically, rather than physically. Foraminifera, among others, in the Bohai Sea were very sensitive to this change caused by the fresh Huanghe riverwater input (Table 3-4).

Sediment transport

- high season and direct transport

Since the river input is varying with season, as is the sediment supply, in the viewpoint of sedimentology, the sedimentary records are actually the records of mainly periods of high sediment supply rather than time-averaged records, i.e. the long period of low sediment supply will leave relatively minor impact in the sediment. Therefore the sedimentary records in JX91-2A were taken mostly under high hydraulic conditions in relatively short summer time when the Huanghe River entered the Bohai Sea. Direct transport of coarse sediment to the Central Basin during high season is quite possible by distal estuarine turbidity current, though the area is less influenced by this as compared with the Huanghe estuary.

Characteristics

- stratification and particle size: weak hydrodynamic condition, less influenced by the river

The characteristics of the JX91-2A, as compared with JX91-3B, are found in two aspects, stratification of sediment and variation in its particle size distribution. It is
noted that lithology of JX91-2A is not so clear-cut as in JX91-3B, though stratification is still obvious. As the Huanghe River is the greatest variance to the depositional environment, the stratification should also be directly associated with hydrodynamic changes, i.e. Huanghe channel switching in the Bohai Sea. Probability plots of the two Bohai cores revealed a difference in hydrodynamic conditions in the two cores (Fig. 4.1-2). In JX91-3B, the coarse fraction and fine-grained fraction are quite different, while in JX91-2A, the difference is rather small. Speaking in general, the hydrodynamic condition in coresite of JX91-2A is weaker than that in the subaqueous channel (coarse sediment), but stronger than that of the off-channel area (fine-grained sediment) in JX91-3B. The Huanghe hydrodynamic impact should be based on the magnitude of difference made by channel switching on the depositional environment. So the two aspects which define the characteristics of JX91-2A, relative to JX91-3B, are generally weak hydrodynamic condition with less influence from channel switching of the Huanghe River but more influence from normal marine condition.

Discussion

- geochemical contribution?

It is possible in principle that the sedimentation in the Bohai Sea can also be characterised geochemically. However, as nearly all the sediments since the last transgression, both genuine deposits and reworked and/or redistributed sediment, are from the Huanghe River, it would be difficult to distinguish geochemically whether the stratigraphy in the Central Basin is a result of channel switching, though it is clearer with palaeontology (Table 3-4).
4.2.2 Sedimentation in the Huanghai Sea

- significance of the river to the Huanghai Sea
The Huanghai Sea used to be called the Yellow Sea in English, a direct translation from Chinese. However, the Huanghai Sea today is not quite 'yellow', and the name was given correctly about 1100 years ago (Song Dynasty) when the Huanghe River (Yellow River) entered the sea (Qin et al., 1989). By that time the river had become so turbid, almost as it is today, that it apparently impacted on the depositional environment in the Huanghai Sea. The impact of the entrance of the river to the Huanghai Sea was quite significant. Firstly, it changed the sediment supply; secondly it changed the local hydrodynamic condition, thirdly it altered the current system, and lastly it modified the seawater composition, though not as much as in the Bohai Sea.

Current system
- circular current system and mud deposition
As shown in Fig. 4.2-1, JX91-7mG locates in the centre of the south Huanghai Sea in the Huanghai Trough. The current system in that area brings in and then traps the Huanghe sediment from the Bohai Sea and sediment from the coastal area to the coresite, forming a vast area of mud deposition (Qin et al., 1989).

- the Changjiang River
The mighty Changjiang River (Yangtze River) is rather close to the coresite of JX91-7mG geographically, however, as the strong along-shore current flowing down from the north Huanghai Sea effectively prevents it from approaching the coresite, with the help of effect of Coriolis force, the Changjiang River can only influence the current system in the far south Huanghai Sea, away from the coresite (e.g. Zhao and Yan, 1994, Qin, et al., 1989).

Sediment sources
- old Huanghe delta and the Bohai Sea
Zhao and Yan (1994) found the sediment input to the coresite of JX91-7mG was mainly from the old Huanghe River mouth, which is supported by investigation of
the Huanghai sediment (Qin et al., 1989). Actually, these sediments are from the old Huanghe sub-aqueous delta, which extended to the south Huanghai Sea up to 200 km (Qin et al., 1989). Sediment from this source is rather coarse, in the range of 4 - 7 $\phi$. At present, apart from the local redistributed sediment input from upslope, the fine-grained Huanghe suspended sediment from the Bohai Sea is the other main sediment source for JX91-7mG, and the Changjiang River cannot transport its sediment up north due to the along-shore current (Qin et al., 1989).

Fig. 4.2-1 Current system in the Huanghai Sea and sediment transport
(redrawn from Zhao and Yan, 1994)

**Present sedimentation**
- two processes relating to two sediment sources at different times

The top of JX91-7mG presents a bi-modal particle size distribution pattern, implying two different sedimentational processes. These two processes should be associated
with two sediment sources, because if there are two processes acting on one sediment source, say the old Huanghe delta in the Huanghai Sea, the source could not provide the finer-grained population exclusively to the weaker process to deposit; on the contrary, the stronger one would have deprived the source of what can be available to the weaker one. Moreover, as suggested by the two types of uni-modal sediment in the Bohai Sea (JX91-3B), two processes would be impossible to deposit at the same time, since the deposits of the weaker process would be lost due to reworking by the stronger one, i.e. the weaker process could not deposit at all when the stronger one was in action. Therefore the practical solution is two sedimentational processes carrying sediments from two sources and deposit at different times.

- old Huanghe subaqueous delta, redistribution, coarse fraction, winter

Fig. 4.2-2 shows the suspension profiles in two sections from the old Huanghe subaqueous delta across the Huanghai Sea in winter and in summer. It is obvious that the suspension concentration near the seafloor is much higher in winter than that in summer, which was regarded as a result of severe winter storm (Qin et al., 1989). This suspension is the stir-up of the old deltaic sediment and redistributed to the coresite of JX91-7mG as the main sediment source. It is interesting to note that the suspension profile shows some characteristics of a mass flow. Actually an obviously turbid bottom current is found running down slope from the old Huanghe delta to the Huanghai Trough. It is therefore not surprising to find coarse sediment (around 63 μm) at coresite of JX91-7mG, about 300 km from land.

- Huanghe sediment from the Bohai Sea: suspension, fine-grained fraction, summer time

Fig. 4.2-2 also shows that in summer when the Huanghe River discharge reaches its maximum in the Bohai Sea, two branches of turbid water can be seen flowing out from the Bohai Sea into the Huanghai Sea (Qin et al., 1989); one of which passes by the coresite of JX91-7mG and the other along the shore. As the suspension is originated from the Huanghe River in the Bohai Sea, it is very fine-grained. This fine-grained fraction gets trapped in the circular current system in the northern part of the south Huanghai Sea before it gets deposited.
4.2.2 Sedimentation in the Huanghai Sea

Fig. 4.2-2 Suspension concentration in the Huanghai Sea in winter and summer (redrawn from Qin et al., 1989). Transect lines are shown in Fig. 4.2-1.

- **discussion:** deposition at different times, homogeneity and bimodality
In the modern Huanghai Sea, the bi-modal sediment has no problem depositing at the coresite of JX91-7mG, maybe at different times with the coarse fraction deposited mainly in winter and the fine-grained fraction in summer. However, the seasonal depositional pattern may not show any visible lamination, particularly when sediment mixing is considered, making JX91-7mG still quite homogeneous.

- **geochemical support:** fine-grained sediment is from the Huanghe River
The Huanghe origin of the fine-grained sediment is also strongly supported by geochemical data. Comparing the elements and their ratios in the Bohai sediments on different particle size categories, Zhao and Yan (1994) found the fine-grained fraction has unique geochemical signature. For example, the average Cu in the mud near the Huanghe delta in the Bohai Sea is 35 ppm, while in the mud of the Huanghai Sea is 27 ppm and 16 ppm in fine sand, therefore the high Cu (30-35 ppm in Fig. 2.5-3b, p.62 and up to 40 ppm in Fig. 2.5-4b, p.64) in the mud of JX91-7mG must be
from the Bohai Sea. Ti/Al and Zr/Al in Fig. 4.2-5 (p.168) also indicate the geochemical relationship between the muds of the Bohai Sea and the Huanghai Sea.

**Recent past sedimentation**

- different from present

Channel switching of the Huanghe River has no doubt been a determinant to the depositional environment in the Huanghai Sea (above and Chapter 3). However, the present sedimentation is quite different from that in the recent past. With the present sedimentation processes in mind, we can possibly infer the recent sedimentation in the Huanghai Sea, caused solely by the Huanghe channel switching.

- no fine-grained fraction in sediment

Obviously, the fine-grained sediment supply from the Bohai Sea would no longer be available when the Huanghe River flowed into the Huanghai Sea. Owing to the reason mentioned above, the fine-grained fraction could not be deposited together with the coarse fraction, which is determined by the *in situ* hydrodynamic condition. This is what we see in JX91-7mG beneath the top layer (Chapter 3).

- estuarine turbidity current? possibly no.

The hydrodynamic condition in the Huanghai Sea would be different from that of today. Similar to the estuarine turbidity current in the Bohai Sea, some kind of mass flow might be possible on the sub-aqueous Huanghe delta. It can be expected, taking the Mississippi delta as an example, that the freshwater plume will extend outward to a wide area, which is prone to be carried away by along-shore surface current (e.g. Hsu, 1989). Near the seafloor, a bottom mass-flow could be developed to transport the Huanghe sediment downslope. The turbid water layer seen in Fig. 4.2-2 would be a permanent feature on the sub-aqueous delta and in the outer area, representing a stronger hydrodynamic condition all year round. Nevertheless, in the Huanghai Sea, the seawater could not be significantly diluted by the fresh Huanghe riverwater, the depositional environment was much more disruptive, leading to loss of fine-grained sediment; an estuarine turbidity current similar to that in the Bohai Sea would be difficult to form in the Huanghai Sea (ref. to section 4.1).
Magnetic mineralogy of JX91-7G is revealed in Fig. 4.2-3 by its IRM curves. It appears that the magnetic minerals are not pure magnetites, and possibly mixed with haematite and/or greigite or other iron sulphides (IOCAS, 1985, Thompson and Oldfield, 1986). Other magnetic parameters, viz. magnetic susceptibility, $X_{fd}$, SIRM and ARM (Fig. 4.2-4) have given more details about its magnetic mineralogy, concentration and grain size, and their downcore variations. These data are processed and presented in Fig. 4.2-5 to show how the concentration of magnetic minerals can be estimated from magnetic susceptibility and SIRM (Thompson and Oldfield, 1986).

As SIRM per unit mass of single-domain magnetite is 10 times higher than that of multi-domain magnetite (and 50 times for haematite), while susceptibility is similar (Thompson and Oldfield, 1986), the group of points (60-210 cm) differs from the others mainly because of their finer grain-sized magnetites. The ratio of SIRM/ARM can also be used for detecting grains slightly larger than superparamagnetic on account of their low SIRM/ARM ratios (Gillingham and Stacey, 1971, Kneller, 1980). The SIRM/ARM ratios on 60-210 cm in Fig. 4.2-4 is around 60 while the others around 350, indicating more fine-grained magnetic minerals over 60-210 cm, which is normally an indicator of soil, and hence direct Huanghe input.
4.2.2 Sedimentation in the Huanghai Sea

Fig. 4.2-4 Magnetic properties for JX91-7G, susceptibility, Xfd, SIRM and ARM

Fig. 4.2-5 Specific susceptibility ($m^3/kg$) vs. SIRM ($Am^2/kg$) in JX91-7G. The straight line is for reference to magnetic properties (Thompson and Oldfield, 1986)

**Discussion**

- stable sedimentation processes of high energy, and upper size limit

It is worth noting that the coarse fraction throughout JX91-7mG did not demonstrate much difference in particle size mode values as expected from the hydrodynamic shift. This is possibly because the coarse fraction always originates from the Huanghe
River and the direct impact from Huanghe riverwater momentum is negligible at coresite of JX91-7mG, which is understandable considering the long distance (300 km) from the rivermouth and the waterdepth of 70 m. It is interesting that even in the estuarine turbidites in the Bohai Sea, the coarse sediment is not apparently coarser than that in the Huanghai Sea. It may be true that the coarse fraction of the Huanghai sediment is only determined by the loess and the transporting ability of the Huanghe River, so that even very strong sedimentation processes afterwards can do very little to increase the upper limit of the particle size.

- catastrophic factor: contribution from earthquakes

Although the bottom suspension in the Huanghai is suggested to be caused by winter storms, it may also be triggered by catastrophic earthquakes in the Huanghai Sea area, which are not uncommon (Qin et al., 1989). Earthquake triggered sediment failure in the coastal area might be more important in the past when the present subaqueous delta was not developed and the sediment source was rather far away from the coresite, say at the beginning of the Holocene.
4.2.3 Comparison between the Bohai Sea and the Huanghai Sea

- greater impact in the Bohai Sea than in the Huanghai Sea

Due to the geographical locations of the Bohai Sea and much of the Huanghai Sea, the Huanghe River appears as the major factor affecting the depositional environment in the two seas, and has different impacts on them. As the Bohai Sea is shallower, smaller and more isolated from the open sea than the Huanghai Sea, the impact from the Huanghe River is much greater in the Bohai Sea than that in the Huanghai Sea.

Influential factors

- channel switching

The effect of channel switching of the Huanghe River is mainly reflected in the sharp boundaries of different facies in the three cores, though the sharpness may vary. The chronostratigraphy enables us to trace the Huanghe sediment in different areas and makes it possible to remove the influence of channel switching and construct an integral and continuous sedimentary record for the Huanghe River. However, such an operation would require high attention because of the errors to be caused near the boundaries, in light of reworking and redistribution of sediment.

- distance from the rivermouth

The distance between coresite and rivermouth determines the intensity of the Huanghe influence. Probability plots of the particle size distribution of the cores (Fig. 4.2-6 cf. Fig. 4.1-2) show an increased depositional stability with distance from the rivermouth as indicated by the decreased scattering of the data points. However, the average hydrodynamic condition at the three coresites do not show much difference in the probability plots by the truncating points, though sorting of the coarse fraction suggests higher hydrodynamic condition at sites closer to the rivermouth. This indicates other forms of mass-flow than estuarine turbidity current may transport the coarse sediment far onto the continental shelf. In fact, element ratios have demonstrated the trend of declining hydrodynamic condition more clearly in Fig. 4.2-7, where typical heavy mineral indicators Ti/Al and Zr/Al are highest in JX91-3B, followed by JX91-2A and JX91-7mG, in the similar sandy layers.
Fig. 4.2-6 Probability plots of particle size distribution for JX91-7m and 7G
4.2.3 Comparison between the Bohai Sea and the Huanghai Sea

Fig. 4.2-7 Geochemical ratios of some elements in the Chinese cores
4.2.3 Comparison between the Bohai Sea and the Huanghai Sea

• geographical locations

The obvious difference between the Bohai Sea and the Huanghai Sea is their openness and the current system, which make the Bohai Sea a better place to preserve the Huanghe sediment. However, when the Huanghe River entered the Bohai Sea, the fine-grained fraction will be relatively less deposited there, relative to the original sediment supplied, much of which is carried out of the Bohai Sea and deposited in the Huanghai Sea. This physical fractionation allows the Huanghai Sea to receive relatively more fine-grained sediment in this period. When the river entered the Huanghai Sea, JX91-7mG could ironically receive less fine-grained sediment, owing to the stronger hydrodynamic condition and along-shore current. That is why the top JX91-7mG is bi-modal while the underlying coarser layer is uni-modal. Actually, none of the 'Huanghe sediment', in both the Bohai Sea and the Huanghai Sea, can keep the exact original fine-to-coarse proportion of the Huanghe River sediment.

• mechanism of transportation of coarse sediment

The old sub-aqueous Huanghe delta in the Huanghai Sea is wider-spread than the modern one in the Bohai Sea. Though submerged at a greater water depth in general, the extensive sub-aqueous delta makes JX91-7mG roughly the same distance from the sub-aqueous delta front as JX91-2A in the Bohai Sea. Even having considered this, it is still hard to imagine the high efficiency of transporting coarse sediment by the mass-flow in the Huanghai Sea. Actually, this may benefit from the stable fluvial process sustained by the Huanghe River, which is more capable of transporting riverine sediment from estuary to outer sea than it was thought.

1) Less energy will be spent on the establishment of the 3D current system so that more energy will be used for sediment transportation.

2) The previous deposits would have built up an equilibrium curve according to the hydrodynamic condition, which can make the sediment move on a nearly iso-potential surface and hence increase the efficiency.

3) As the seafloor slope is generally steeper than that of the riverbed, the coarse fraction, carried on mainly by saltation in riverwater, would be able to gain additional energy when sliding down the delta front, helping develop mass-flow out of the estuary.
The slope in the Huanghai Sea is greater than that in the Bohai Sea (Chapter 1), therefore the mass-flow would possibly be nearly equally effective as the estuarine turbidity current in the Bohai Sea in transporting coarse sediment over a great distance.

**Similarity and difference**

- **similarities**
  Sedimentation processes reflected in the three cores from the Bohai and Huanghai Seas are different, however, the similarity between them is still the major part of their relationship. The basic characteristic of the sedimentation in this region is that almost all of the sediments, both in the Bohai Sea and the Huanghai Sea, are from the Huanghe River. Sediment from other rivers around the two seas is often either too localised, e.g. the Liaohe River in northeast Bohai Sea, or deposited elsewhere other than the coresites of JX91-3B, 2A and 7mG, e.g. the Changjiang River in south Huanghai Sea. Fluvial processes are seen throughout this region.

- **differences**
  Sedimentation differences in the three cores are actually more closely related to the distance from the coresite to the rivermouth rather than their particular depositional environments. The distance here is so important and considering that the differences can be similarly explained under a postulated circumstance, i.e. the three cores had been taken along a transect running from the river mouth to an open marginal sea, ignoring completely the effect of Huanghe channel switching. JX91-3B would represent the initial stage of deposition of Huanghe sediment, where both sedimentational and geochemical processes are intensive; JX91-2A would show the transition zone from estuarine to normal marine condition, where direct river influence is still detectable, but much weaker; and JX91-7mG would indicate normal marine condition, where hydraulic influence directly from the river diminishes and oceanic current plays an important role in distributing sediment, fine-grained sediment in particular, though the mass flow would still be present near the seafloor. The differences can be summarised in Table 4-1.
Table 4-1 Differences between sedimentation processes in the Bohai Sea and the Huanghai Sea at the studied coresites

<table>
<thead>
<tr>
<th></th>
<th>Bohai Sea</th>
<th>Huanghai Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>riverine influence</td>
<td>strong</td>
<td>weak</td>
</tr>
<tr>
<td>current influence</td>
<td>weak</td>
<td>strong</td>
</tr>
<tr>
<td>main transportation form</td>
<td>estuarine turbidity current</td>
<td>(storm generated) mass-flow</td>
</tr>
<tr>
<td>Huanghe sediment input</td>
<td>direct</td>
<td>less direct</td>
</tr>
<tr>
<td>reworking and redistribution</td>
<td>small</td>
<td>large</td>
</tr>
</tbody>
</table>

Conclusion

Through the discussions above it is clear that the sedimentation processes in the Bohai Sea and the Huanghai Sea are the same fundamentally. The main differences in sedimentation processes are largely determined by the distance of the coresites to the river mouth, though local factors can have some impacts on the distribution and reworking of Huanghe sediment. The hydrodynamic conditions decrease outwards from the river mouth, and generally speaking the Huanghe influences, including its normal input and channel switching, are declining in cores from JX91-3B, JX91-2A to JX91-7mG. This decline may not be clearly reflected in mode or median of particle size due to the original sediment features and enhanced mass-flow intensity in the Huanghai Sea, but is obviously shown in sorting and geochemical data. Reworking and redistribution of sediment cannot be neglected, especially for the fine-grained sediment from the Bohai Sea. Despite the differences, sedimentation processes in this region are fluvial, and the Huanghe River plays a dominant part with the channel switching as a practical indicator of its mighty power.
4.3 Sedimentation in the Arabian Sea

- processes acting in the Arabian Sea
The whole Arabian Sea is diversified with various sedimentation patterns, however, the sedimentation in the northwest Arabian Sea is dominated by aeolian process due to lack of big rivers from the surrounding arid lands. Apart from the aeolian process, concerning the sediment, other sedimentation processes such as relocation of sediment, particularly in the form of turbidites, and biogenic process are also common in the Arabian Sea sediments. This section will focus on aeolian processes (4.3.1), mass-flow processes (4.3.2) and sediment sources (4.3.3).

4.3.1 Aeolian Processes

- different from fluvial processes and those on land
Theoretically, aeolian processes can affect a vast area quite uniformly in terms of aeolian dust particle size, because winds can usually move more freely than rivers and do not have distinct boundaries, especially in a flat area like open-sea surface. Many aspects of aeolian processes have been discussed by Pye (1987), but there are some special features when they are considered in the Arabian Sea area.

Geographic restraint
- no riverine and Wadi deposits
Aeolian processes prevail in the Arabian Sea, but the winds are actually not generated there. The northwest Arabian Sea, or the Gulf of Oman, is surrounded by lands where precipitation is so small that no persistent river can be found (Duntton, 1988). Wadi systems do exist around the Arabian peninsula, which may represent the greatly limited fluvial processes in this area. The nearest wadi to the nearshore cores is from the Wahiba Sands to the south of Ras al Hadd (Fig. 4.3-1). It might be influential to coresite of 1733, but unlikely to the other cores as they are protected by a submarine ridge extended seaward from the Ras al Hadd. Flash floods have been observed in that Wadi, but no sand transportation to the Arabian Sea is recorded (Duntton, 1988). Even if the wadi system had been more active in the Holocene
humid interval, it would not have had great impact on the cores, even to core 1733 which is about 100 km from the wadi mouth (Shankar et al., 1987). At the coresite of 1739, it is practically impossible to receive fluvial influences, neither from the Arabia via wadis nor from the Indus River, as it perched on the Murray Ridge.

Accumulation rate: quantity of aeolian deposits
- exponential decline, supported by modelling

Wind will retain its strength as long as the pressure gradient acting on it remains the same. However, as no sediment source is available to the wind across the ocean, while dust keeps dropping out from the wind jet, the concentration of dust should decrease in proportion to the distance it covers. The deposition of aeolian dusts with
distance can be mathematically expressed with an exponential function (formula C1.2-2) as described in Appendix C1.2, given that all constituents of the dust are falling at the same rate. This function allows the dusts to be transported over a long distance after a rapid deposition near the source, i.e. the east coast of Oman in the case of the Gulf of Oman. Using an exponential function, the accumulation rates can be simulated (Table 4-2) for the Arabian cores. It is noticed from the simulation, though not strictly realistic, that the measured accumulation rates do present a general exponential decrease, and even steeper near source. This deposition pattern in the cores near Oman, viz. cores 1735, 1736, 1734a and 1733, is depicted in Fig. 4.3-2, and is similar to the one by Foda et al. (1985) in a much complicated way.

Table 4-2 Relationship between accumulation rate of top sediment and distance from land in the Arabian cores

<table>
<thead>
<tr>
<th>core</th>
<th>distance</th>
<th>accumulation rate</th>
<th>simulated AR*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1735</td>
<td>~12</td>
<td>75</td>
<td>69.4</td>
</tr>
<tr>
<td>1736</td>
<td>23.3</td>
<td>16</td>
<td>15.4</td>
</tr>
<tr>
<td>1734a</td>
<td>27.7</td>
<td>9.23</td>
<td>9.6</td>
</tr>
<tr>
<td>1733</td>
<td>~36</td>
<td>6</td>
<td>5.1</td>
</tr>
<tr>
<td>1739</td>
<td>~300</td>
<td>3.35</td>
<td>3.3</td>
</tr>
</tbody>
</table>

* The simulation formula (C1.2-4) is \( r = 400 \exp(-0.15u)+3.3 \), where \( r \) (cm/ka) is the accumulation rate and \( u \) (km) is the distance from land.

Figure 4.3-2 Relationship between accumulation rate and distance from land in the Arabian cores. Core 1739 is not shown here, but is surely in line with the curve roughly following the exponential law (see data in Table 4-2). Circles indicate simulation accumulation rate data.

Particle size distribution: quality of aeolian deposits

- getting finer with distance

Because larger and heavier grains are prone to drop off from wind, as compared with smaller and lighter grains, the dust will become finer as the wind travels on. When
less and less aeolian dusts remain in the winds, the qualitative (and/or geochemical) aspect of the dust may change as well. Particle size analysis can reveal the physical quality of aeolian dust, but as it is mainly determined by wind strength, little change is expected as long as the wind strength remains constant. This change, if it happens, will be reflected in the decrease of median (Md) or mean (M) of particle size distribution, because although no clear-cut stratification is practically seen in air column, heavy and large particles tend to stay low and have more chance of getting deposited. It is believed the mode can reflect the general strength of transporting force, nevertheless, a declining mode may also result from losing coarse fraction, though wind strength is still the same. The typical particle size parameters of the topcore sediment in the Arabian cores are shown in Table 4-3 and illustrated in Fig. 4.3-3.

Table 4-3 Changes in particle size parameters at the top of Arabian cores

<table>
<thead>
<tr>
<th>Core</th>
<th>1735</th>
<th>1736</th>
<th>1734a</th>
<th>1733</th>
<th>1739</th>
</tr>
</thead>
<tbody>
<tr>
<td>depth</td>
<td>0-1 cm</td>
<td>0-2 cm</td>
<td>0-1 cm</td>
<td>3-4 cm</td>
<td>3-4 cm</td>
</tr>
<tr>
<td>Md (µm)</td>
<td>24.16</td>
<td>20.03</td>
<td>20.05</td>
<td>9.159</td>
<td>12.06</td>
</tr>
<tr>
<td>Mean (µm)</td>
<td>45.55</td>
<td>36.58</td>
<td>38.40</td>
<td>17.21</td>
<td>17.50</td>
</tr>
<tr>
<td>Mode (µm)</td>
<td>30.74</td>
<td>22.28</td>
<td>24.81</td>
<td>10.52</td>
<td>13.04</td>
</tr>
<tr>
<td>Skewness</td>
<td>2.745</td>
<td>2.488</td>
<td>6.701</td>
<td>2.705</td>
<td>1.760</td>
</tr>
</tbody>
</table>

It is worth noting that Md, mean and mode are generally decreasing from core 1735 to 1736, 1734a and then to 1733 and 1739, despite there seems to be inverted
relationship between cores 1736 and 1734a and cores 1733 and 1739. The reasons for
the minor reversals in the relationships are complex. In core 1736, the top sediment
might have mixed finer sediment underneath through bioturbation; and in core 1733
the age of top sediment is not the same as in core 1739 due to top missing. Moreover,
the spatial pattern of monsoonal winds and sediment source may also play a role, i.e.
the top sediments may not be from the same dust source at all (see Chapter 5).

Discussion

- aeolian deposits related to aeolian processes

All the data presented above confirm that the detrital sediments in the Arabian Sea,
top sediments in particular, are basically of aeolian origin and free from fluvial
processes. There is actually no doubt about the origin of the detrital sediment (mainly
silt in the nearshore cores), as satellite data, direct observations and measurements
(e.g. Sirocko and Sarnthein, 1989, Sirocko and Lange, 1991) have already proved
that. Although the deserts may be mostly comprised of sands, there are finer grained
dusts that are transportable to winds. These fine-grained deposits cannot be cleared
from the deserts because they can always be produced under various grain collision
and contacts. The aeolian deposits on sea surface will very likely keep all their
characteristics when settling eventually on seafloor, despite the existence of ocean
current. This is because the spatial deposition is uniform enough, as far as the near-
shore cores are concerned, and the most transportable fine fraction, if carried away,
will be made up of that from the up-current, which is identical.

- particle size parameters as potential indicators of aeolian processes

It is interesting to note that the deposition pattern of aeolian dust over the Arabian
Sea follows generally an exponential law based primarily on aeolian process, and that
the physical characteristics of dust (particle size distributions) are changing with
accumulation rate and distance, though they are within our expectation. The
quantitative analyses, not much sophisticated though, suggest it is possible to use
particle size parameters as indicators of aeolian processes in the Arabian Sea, and to
assess quantitatively, at least in relative magnitude, how the monsoonal wind
behaved in the Arabian Sea in the past.
4.3.1 Aeolian Processes

- terrigenous processes: saltation population

It is also worth noting that terrigenous processes or the boundary conditions, especially those associated with sand dune movement on land are able to influence the nearshore cores, cores 1735 and 1736 in particular. The faster-than-exponentially-rising accumulation rate in core 1735 may be a result of these processes, which can transport coarser sediment by saltation rather than suspension directly to the coresite, though the grains can only have one long jump in the sea. The exceptional coarse grains found in core 1735 (Table 4-3) and a larger proportion of coarse fraction in the bulk sediment may be caused by this saltation.

- catastrophic aeolian process: cyclone deposits

There is another aspect of aeolian process deserving careful consideration, and that is catastrophic cyclone (or heavy storm) in the Arabian Sea. Cyclones are still affecting the Arabian Peninsula occasionally from the Indian Ocean, and usually do not enter deep into the Peninsula, but make a sharp turn to the southwest coast of Iran (Snead, 1968). The cyclones can surely transport very coarse sediment, even coarser than the normal saltation population. It is not very clear whether this had happened more frequently in geological time, though it seems so according to Snead (1966, 1968) and Snead (1993), but the very coarse population found in the lower part of core 1739 (Fig. 2.3-8) suggests this kind of aeolian process might be quite common before 6,000 years ago.
4.3.2 Mass-flow Processes

- inevitable mass-flow

Aeolian sands are well-known for their roundness and incohensiveness because of lack of clay minerals (Pye, 1987). The nature of aeolian sands and their offshore deposition pattern (ref. to section 4.3.1) suggest that an imbalance on the seafloor will eventually occur and the sediment has to be relocated. In the Arabian Sea area where earthquakes are not uncommon, as the Indian subcontinent is subducting under the Eurasia continent (Snead, 1993), mass-flow triggered by earthquakes and other events in the loose sands at the upper slope of continental shelf would be inevitable.

**Recognition of mass-flow deposits (turbidites)**

- criteria

The criteria for identifying a turbidite here will be based on the basic characteristics of a turbidites, i.e. a kind of rapidly deposited exotic sediment normally from a higher position by a turbidity current, and their geochemical significance, e.g. the abnormal profiles of the diagenesis controlled Br and I and some interruptions (see below).

- difficulty and a powerful geochemical tool

The mass-flow, once it occurs on a large scale on the steep continental slope off Oman, will most likely take the form of a turbidity current, producing a classic example of deepwater turbidite system as described by Normark et al. (1993). As the aeolian deposits in the nearshore area is quite uniform, the mass-flow deposits, or turbidites, will not be distinctive from the normal deposits in many circumstances. However, the sedimentation pattern mentioned previously and the environment-related geochemical signatures will reveal the turbidites in the Arabian sediments. Geochemical technique seems to be particularly powerful in identifying turbidites in the Arabian Sea as compared with sedimentational method.

A. Core 1734a

- visual identification (X-ray)

In core 1734a, turbidites can be found in the lower part of core at around 29 cm (Fig. 2.2-2). Though it looks quite homogeneous with naked eyes, a slightly pale wedge of
4.3.2 Mass-flow Processes

sediment is seen in the X-rays of the core which is apparently not in conformity with
the over and under-lying sediment and shows clearly a typical structure of turbulent
sedimentation, i.e. an indication of turbidites.

- particle size analysis and water content evidence
Although Md and mode of particle size distribution show little change at the
turbidites, mean and sorting show obvious drops around 29 cm, indicating the
sediment is finer and better sorted as seen in Fig. 2.3-6. This agrees with the
speculation from the shape and inner structure of the wedge as shown in the X-rays
(Fig. 2.2-2) that this turbidites may be only a distal edge of a much larger one, rather
than a small slump. Moreover, as another indicator of sediment texture, water content
shows a clear spike at that depth (Fig. 3.2-14), suggesting a texture (porosity) change
in sediment caused by the distal turbidites. The looser structure with high porosity is
a natural result of rapid deposition, a typical phenomenon of turbidites. Normally,
when sediment is slowly deposited, processes like winnowing will take effect
together with a good chance of bioturbation and other physical disturbances, which
will lead to the reduction of porosity.

- magnetic evidence
The 3D IRM acquisition curves in Fig. 4.3-4 show simultaneous variations in the
core, indicating the consistency of magnetic composition in terms of magnetic
mineralogy; however, the magnetic minerals are not pure magnetites, though they
may dominate in the core. It is interesting to note that a small trough is seen around
29 cm, which is also demonstrated clearly in other magnetic parameters (Fig. 4.3-5),
indicating the different magnetic properties relating to magnetic minerals. The
decrease of magnetic susceptibility means a lack of magnetic (heavy) minerals and
the intensification of ARM signals implies that the grain size of the magnetic
minerals is finer, both of which support the idea of distal turbidites. Furthermore, the
ratio SIRM/ARM, regarded as a good indicator of grain size, shows clearly the
magnetically fine-grained layer, which could be partly of bacterial origin (Hounslow
and Maher, 1995).
4.3.2 Mass-flow Processes

Fig. 4.3-4 3D IRM diagram for core 1734a

(a) Susc. (um3/kg)  
(b) Xfd (%)  
(c) SIRM (uAm2/g)  
(d) ARM (uAm2/g)  
(e) SIRM/ARM

Fig. 4.3-5 Magnetic properties for core 1734a, susc., Xfd, SIRM, ARM and ratio
4.3.2 Mass-flow Processes

- geochemical evidence

Many element profiles and LOI have shown the troughs or spikes at around 29 cm (Fig. 3.2-14). However, Ca, Br and I, among others, are regarded as the best indicators of turbidites since their downcore trends in the Arabian sediment are quite predictable. Ca is an important element associated with productivity in the Arabian Sea and aeolian deposits from Arabia mainly in form of dolomite (Sirocko and Sarnthein, 1989). These two aspects are coupled in the upwelling system, making Ca concentration in sediment highly indicative. On the other hand, concentrations of Br and I are good diagenetic indicators, which are less affected by other processes except exotic interruptions. Therefore the spikes of Br and I and a Ca trough speak loudly of a turbidite origin.

B. Core 1736

- result of core 1734a applicable to core 1736

The various features outlined above and implied in the datasets may serve as criteria, to some extent, for identifying turbidites in other cores in the Arabian Sea. In light of the closeness between cores 1734a and 1736, these criteria should be applicable to core 1736, though some changes about the individual indicators are expected.

- turbidites prevailing from 25 cm down

From the sedimentological point of view, the lower part of core 1736, from 25 cm downward, is much interrupted, especially when compared with core 1734a. The disturbance is not from bioturbation or other post-depositional processes, because it features in sharp shifts in many profiles rather than smoothing the points. Natural shifts in Md, mean and mode do not seem likely at the time set by its chronostratigraphy, neither for the rate nor for the magnitude (cf. Figs. 3.2-10 and 3.2-13). Water content profile also reveals a rebound at the lower part of core, indicating a looser structure (Fig. 3.2-12a). The variable element profiles at the lower core are best represented by those of Br and I, where spikes and plateaus of Br and I are noticed, which cannot not be the case in normal sedimentation. All the evidence suggests that the lower part of core 1736 is dominated by turbidites, which were not formed in one deposition, nor from the same source area (see below for more detail).
4.3.2 Mass-flow Processes

Significance of the turbidites

- providing information about other areas

Generally speaking, turbidites are not useful in meaning under the study of continuous sedimentation because of their rapid deposition of highly mixed sediment; nevertheless, turbidites can provide information about other parts of an integrated sedimentation system. They provide an opportunity to investigate at one coresite sedimentation processes in a much wider area within certain period, though sound interpretations still depend on the scale and effect of the turbidites.

A. Chronostratigraphical marker

- difficult to apply in practice

Turbidites can serve as an isochron in their influential area theoretically. Although the turbidite at the bottom of core 1736 seems comparable with that in core 1734a, possibly reflecting two locations in one turbidity current, their relationship is unclear, and is not supported by the chronology, unless there is evidence showing a considerable amount of sediment had really been eroded by the later turbidites. The function of turbidites as a chronostratigraphical marker is not very easy to apply in practice, e.g. for close cores like 1734a and 1736, there is chronological problem, but for twin cores like cores 1734 and 1734a, there could be no match of signals. It is notable that similar geochemical and particle size signals for turbidites in core 1734a are not seen in its sister core 1734, where a much smoother transition from bi-modal to uni-modal sediment is seen. The lack of accordance between cores 1734a and 1734 is probably caused by the scale of the turbidite, as the wedge suggested. So the turbidites in core 1734a may not be used for the chronological purpose.

B. Depositional environment indicator

- relative stable depositional environment before and after large scale turbidites

Turbidites in the Arabian Sea do not seem to occur very frequently, as compared with the frequency of earthquakes in the Arabian Sea (Snead, 1993). Large scale turbidites may occur once in a few thousand years (like in core 1734a), but their occurrence may not be a simple periodic phenomenon. Deep-sea turbidites like those in the Arabian Sea are results of both sediment imbalance accumulated over a long period.
and the occurrence of large earthquakes. Earthquake-induced turbidity current can disturb normal sedimentation by depositing turbidites and/or eroding deposited sediment. Since a large earthquake can well balance the relief of seafloor so that following earthquakes may not be able to trigger another round of turbidites before sediment is accumulated to a new height, the earthquake-induced turbidites at a time after a long period of sediment accumulation will mark a special depositional environment and a particular sedimentation period in certain areas.

- unstable depositional environment for small scale turbidites

Small scale turbidites, or sand slides and slumps, are also believed to have occurred in the nearshore cores 1735, 1736 and 1734a, as suggested in the probability plots (see also section 4.4). They may be less associated with tectonic factors, such as earthquakes, as they could also be triggered by unstable depositional environment. Since these turbidites happened around the transition time in these cores (see chapter 5), the oceanographic factor, possibly associated with upwelling current and climatic change in this area, may be responsible for the relocation of sediment.

C. Lateral sediment input

- large scale: older sediments from higher place

The information provided by turbidites is rather limited, and the turbidites are often merely a mixture of certain amount of sediments produced by the nature of turbidity current, however, there are spatial and temporal restraints on the turbidites. Firstly, under most circumstances, turbidites are sediments from topographic highs upslope, and only in special occasions, like in core 1734a, big turbidites could rush onto a relatively higher site under momentum. Secondly, in terms of chronology, turbidites can hardly be younger than the underlying sediment if no erosion occurs and are definitely older than the overlying sediment.

- small scale: tighter restraints

In areas where relatively more frequent turbidites are found, these spatial and temporal restraints are expected to be tighter, i.e. most turbidites will come only from upslope owing to the lack of extravagant sediment failure, and most turbidites will
have similar ages with the contacting sediments, mainly because balance of seafloor relief is frequently adjusted and maintained, and both deposition and erosion take place on a smaller scale. In the Gulf of Oman, this is likely to be the case, and thus provides grounds for further discussion on turbidites in core 1736 where turbidites typical in this area are found at the lower part.

**Turbidites in core 1736**
- a case study

Turbidites in core 1736 are recognised based on their irrational geochemical nature (see section 3.2.4, p. 120). Although they look quite complex, with the help of the clear topographic feature at the coresite (cruise chart) and two well studied cores 1735 and 1734a, it is possible to carry out in-depth study on the turbidites in core 1736 as a case study to address the nearshore deepwater turbidites on continental slope.

A. Characteristics of three turbidites
- comparison with cores 1735 and 1734a

Judging from the criteria set out previously, three turbidites can be identified, namely Turbidites I, II and III from top to bottom respectively. Characteristics of the three turbidites are listed in Table 4-4 in comparison with cores 1735 and 1734a. The geochemical turbidite indicators, Br, I, P/Al, Ca/Al and Mg/Al, along with sedimentological parameter (mode), have combined to pinpoint the three turbidites from 27 cm to 53 cm. The first turbidite is centred at 31 cm, with the second one at 37 cm and the third one at 49 cm. As the alignment (strike) of the valley where the core 1736 is located is in the southeast direction, parallel to the coastline of Oman, there are thought to be three possible source areas, which are the up-valley, landward and seaward sides of the valley. From all the geochemical data presented, the first turbidite is determined to be from the seaward side; and the second from the up-valley and the third from the landward side on the upper continental slope. The modes of particle size distribution also support strongly the determination of the source areas, considering the distances from land and the aeolian deposition pattern in this area (see 4.3.1).
4.3.2 Mass-flow Processes

Table 4-4 Turbidites in core 1736 with references of cores 1735 and 1734a

<table>
<thead>
<tr>
<th>Turbidites</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>1735</th>
<th>1734a</th>
</tr>
</thead>
<tbody>
<tr>
<td>depth (cm)</td>
<td>31</td>
<td>37</td>
<td>49</td>
<td>39</td>
<td>25-30</td>
</tr>
<tr>
<td>range (cm)</td>
<td>27 - 34</td>
<td>34 - 40</td>
<td>40 - 53(+)</td>
<td>10.52</td>
<td>11.71</td>
</tr>
<tr>
<td>mode (µm)</td>
<td>10.52</td>
<td>11.71</td>
<td>13.04</td>
<td>11.71</td>
<td>10.52</td>
</tr>
<tr>
<td>Br (ppm)</td>
<td>300</td>
<td>300 (spike)</td>
<td>300 (plateau)</td>
<td>300</td>
<td>50</td>
</tr>
<tr>
<td>I (ppm)</td>
<td>600</td>
<td>600 (spike)</td>
<td>200 (plain)</td>
<td>125</td>
<td>100</td>
</tr>
<tr>
<td>P/Al (10^2)</td>
<td>2.0</td>
<td>2.0</td>
<td>3.5</td>
<td>5.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Mg/Al</td>
<td>0.68</td>
<td>0.68</td>
<td>0.75</td>
<td>0.8</td>
<td>0.61</td>
</tr>
<tr>
<td>source</td>
<td>seaward</td>
<td>up-valley</td>
<td>landward</td>
<td>landward</td>
<td>seaward</td>
</tr>
<tr>
<td>scale</td>
<td>medium</td>
<td>small</td>
<td>large</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N.B. the reference data from core 1735 are taken from the bottom of core (~40 cm) in order to use records as old as possible, and the reference from core 1734a is taken from the lower part of core (except for the turbidite around 29 cm of about 1.5 cm thick).

B. Br and I indicators

- basic geochemical evidence

Geochemical turbidite indicators, Br and I, can not be easily correlated between the cores directly, because their concentrations in sediment profile may vary from place to place. As seen from the Arabian cores, top sediments are normally highly enriched in Br and I, therefore when turbidity currents occur, the Br and I concentrations in the turbidites can often be higher than those at the depositing sites. Because Br and I are already bound in the sediments, the characteristics of turbidites concerning Br and I are thus retained, despite the later diagenesis which may alter the concentrations in the cores as a whole. From this point of view, Br and I are also good indicators of turbidite origins (Table 4-5), provided that in these Holocene sediments the undisturbed Br and I profiles in the sediments are close to what is observed today, which should be reasonable.

Table 4-5 Br and I (ppm) as indicators of turbidite origin

<table>
<thead>
<tr>
<th>core</th>
<th>Br (top)</th>
<th>Br (bottom)</th>
<th>Turb.</th>
<th>I (top)</th>
<th>I (bottom)</th>
<th>Turb.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1735</td>
<td>550</td>
<td>300</td>
<td>250</td>
<td>125</td>
<td>600</td>
<td>300</td>
</tr>
<tr>
<td>1736</td>
<td>500</td>
<td>150</td>
<td>1300</td>
<td>200</td>
<td>600</td>
<td>300</td>
</tr>
<tr>
<td>1734a</td>
<td>300</td>
<td>50</td>
<td>1000</td>
<td>100</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Turbidite I</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbidite II</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbidite III</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Concentrations of Br and I at lower part of cores are taken from the bottom of continuous sediments. For core 1735, it is around 40 cm; 23 cm for core 1736 and 25-30 cm for core 1734a.
4.3.2 Mass-flow Processes

• role in determining source areas
It is clear that Turbidite III does bear the characteristics of landward sediment, high in Br yet low in I; meanwhile, the Turbidites I and II are excluded from a landward origin. It is noted that both the Br and I concentrations of the turbidites are lower than or similar to those of top sediments in cores 1735 and 1734a, just as expected. The reasons are twofold: they have either undergone certain extent of diagenesis or been mixed rather deep in their original profiles. If the mixing of sediment, or the thickness of sediment failure, plays a key role in this, Br and I should present comparable changes, and the resultant difference may be due to differential diagenesis between the two elements (see below for more detail).

C. Turbidite scales
• turbidite thickness, geomorphology and source areas
These turbidites took place in different scales. Turbidite III is undoubtedly the largest with the base probably still undetected after a thickness of 13 cm. According to Table 4-3, the medium one should be Turbidite I with a thickness of 7 cm and the small one the Turbidite II of 6 cm. As seen from Fig. 3.1-3, the gradient on the landward slope is greater than that on the seaward side, increasing the possibility of a greater sediment failure from land side. Since the valley appears rather longitudinal along the coast and the Al Hajar ash Sharqi mountains (Bramwell, 1977), the gradient along the axis of the valley is believed to be smaller than that of the lateral slopes, therefore turbidite from up-valley could be the smallest in magnitude. Moreover, the imbalance of sediment is also in this order, which is seen in the actual sequence of turbidites.

• Br and I
Furthermore, the Br and I concentrations of turbidites may provide a tentative means of assessing the turbidite scale regarding the thickness of the lost sediment layer at turbidite source. According to I concentration, Turbidite III could move away a layer of up to 15 cm at coresite of 1735, slightly thicker if according to Br concentration. Turbidite I would require a mixing of about 20 cm thick of sediment at core 1734a. Up-valley sediment loss is hard to estimate here, but possibly in the order of that of core 1734a or more.
D. Discussion

- quantification of turbidites

The data available here may not be adequate enough to allow quantification of the deep-sea turbidites in core 1736, however, quantification of the relocation of sediment, both in direction and in magnitude, is theoretically possible and is very important for understanding the sedimentation in aeolian process dominated areas like the Arabian Sea. Using geochemical data, together with sedimentational parameters, to identify turbidites in deep-sea sediments, locate their source areas and access their scales is seen to be quite promising and should be examined and developed further.

- incomplete references, chronology of turbidites

In light of the lack of cores spread out in the area, the core references here may not be complete or ideal. e.g. core 1735 might not be long enough to serve as a perfect reference for core 1736, though it could keep the characteristics as seen in the last few hundred years for a much longer period. The chronology of turbidites has also caused uncertainty in the above comparisons. The boundaries of turbidites are not clear cut depending on different indicators used, and bioturbation may have dampened them, along with diagenesis processes. For instance, at 27 cm in core 1736, the extraordinary Ca peak may not be considered as part of the Turbidite I, because the sediment has clear bimodality, but it does not coincide with the boundary marked by many other elements (e.g. Ba and Sr) with a gap of around 3 cm.

- missing turbidites in core 1735?

There seems to be no obvious turbidites in core 1735, though it should have been affected by the mass-flow processes. This may have four reasons: 1) the core is too young (only about 600 years) to receive one, 2) local topographic feature, e.g. subaqueous plateau, prevents it from having one, 3) the upslope sediment is nearly identical and 4) the turbidites are of rather small scale. Mass-flow processes are actually present all over the continental slope off Oman, but occur at a fairly low frequency and usually individually.
4.3.3 Sediment Sources

- major sedimentation processes
Aeolian processes and mass-flow processes are two major groups of sedimentation processes active in the Gulf of Oman. It is obvious, however, that the aeolian processes are dominant whilst the mass-flow processes only play a minor role. Even though fluvial processes are not likely, the possibility of wadi sediment input to the coresite of 1735 cannot be ruled out, considering the small wadi running from between the mountains Al Jabal Akdar and Al Hajar ash Sharqi to Sur (ref. to Fig. 4.3-1).

- division of study areas
The whole study region in the Arabian Sea can be divided into two areas; one is the near-shore area (Gulf of Oman) and the other is the ‘deep-sea’ area represented by core 1739. The former can be further divided into two small areas; one is to the west of the sub-marine Ras al Hadd (cores 1735, 1736 and 1734a) and the other to the east. They are so divided mainly because the main sedimentation processes and sediment sources may be different within these divisions.

Characteristics of source areas of aeolian deposits

- monsoons and source areas
The seasonally reversing southwest monsoons and the northwesterlies in the Arabian Sea can transport dust from all surrounding areas to the Gulf of Oman, including the Makran of Iran, the Persian Gulf, the Arabia (Arabian Peninsula and Red Sea) and the North Africa (Sahara and Somali) (e.g. Coude-Gaussen, 1984, Sirocko, 1989).

A. Characteristics of original sources
- generally similar if not dolomites, ophiolites and barites
It would be ideal to be able to establish geochemical and mineralogical characteristics of these source areas and then trace these characteristics in the Arabian Sea sediment, however, the general geochemical features of these areas are similar. It should be noted, however, that dolomites (Mg,Ca)CO₃ in the northern and
4.3.3 Sediment Sources

central part of Arabian Peninsula are quite unique in the Afro-Arabian region (Sirocko and Sarnthein, 1989, Sirocko, 1993, Laurent, 1993). Moreover, the ophiolites in Oman, the ultrabasic igneous rocks, are also very distinctive in this region, together with barites (BaSO₄) found mainly along the Red Sea, west coast of Arabian Peninsula, and a little in central area (Laurent, 1993).

- the Wahiba Sands

Most of the Arabian sediments originate from the Arabia (e.g. Sirocko, 1989). There are two main sources of dusts in Arabia regarding the core locations, the Rub al Khali desert in the Saudi Arabia and the nearby Wahiba Sands. It is found in the Wahiba Sands that roughly half the sand is quartz, 30-45% is carbonate of marine origin, and 10-21% is of ophiolitic origin. These materials have been brought into the Sands from the Oman mountains and the nearshore continental shelf by aeolian, marine and fluvial processes (Winser, 1989). Nearshore sediment should have similar composition in light of the short distance and the sediment interchange between land and sea in history.

B. Wind strength influence

- differential deposition of particles

No matter what geochemical characteristics of the original source areas have, the dusts are subject to winds for transportation. Wind can deposit its load differentially in terms of weight and density of the particles, which will have geochemical as well as sedimentological impact. As geochemical composition of dust usually varies with particle size, the geochemical signatures of source sediment may be altered during wind transportation. Geochemical characteristics of some aeolian deposits may even be determined mostly by particle size, unless a particular geochemical signal is large enough. When the characteristics of source areas are similar, the influence of wind strength will become very important.

- sedimentological characteristics relating to source area and wind strength

According to the aeolian transportation pattern, dust particle size decreases with distance from its source area (see also Pye, 1987), while dust sorting will be
4.3.3 Sediment Sources

improved. Theoretically, if wind strength remains the same (ca. 10 m/s), the impact of sources at different distances will follow the description in sub-section 4.3.1, and if the sources are at the same distances from the coresites (ca. 100 km), the wind strength would determine the particle size of dust. Based on these assumptions, effects of the two factors, source distance and wind strength, can be listed in Table 4-6, which also serves as a guideline for identifying dust sources.

Table 4-6 Sedimentological characteristics of aeolian deposits regarding dust source areas and wind strength in the Arabian region

<table>
<thead>
<tr>
<th>source area</th>
<th>(wind: 10 m/s)</th>
<th>wind strength</th>
<th>(source: 100 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>near</td>
<td>coarse</td>
<td>coarse</td>
<td>fine</td>
</tr>
<tr>
<td>far</td>
<td>fine (&lt;20 μm)</td>
<td>fine</td>
<td>coarse</td>
</tr>
<tr>
<td>mean</td>
<td>coarse</td>
<td>coarse</td>
<td>fine</td>
</tr>
<tr>
<td>sorting</td>
<td>poor</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>skewness</td>
<td>low</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>lateral consistency</td>
<td>poor</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>size limit</td>
<td>&lt; 400 μm</td>
<td>&lt; 200 μm</td>
<td>&lt; 400 μm</td>
</tr>
</tbody>
</table>

Main dust sources identified in core

- wind direction influence

Wind direction and wind strength are actually two essential components of a wind vector. Concerning the sedimentary records in aeolian deposits, the changes determined by wind direction can be more fundamental, as it decides where the dust can come from. The wind-direction influence to the sediments will be reflected in the geochemical compositions of sediment, rather than physical parameters. Wind direction is virtually a 3D parameter, and only surface wind (2D) will be stressed here, though its 3D effect will also be noticed in certain places such as the convergence zone of the southwest monsoon and the northwesterlies (Sirocko et al., 1991 and 1993, Chen, 1986).

A. Recent coastal input

- southwest monsoon passing over the coast, the Wahiba Sands

The main constituents of the nearshore Arabian Sea sediment is aeolian derived terrigenous materials. The dust sources for top sediments in cores 1735, 1736 and 1734a are easy to identify, because the present wind strength and dust sources are
fairly clear. Many data show that the present southwest monsoon lands on the coastal area of southeast Oman with a wind speed of ca. 10 m/s (e.g. Atlas et al., 1993). The boundary of the southwest monsoon just passes core 1735 to the west and hence it can certainly transport sands from the nearby Wahiba Sands to these coresites. As the present northeast monsoons are quite weak, ca. 4 m/s (Atlas et al., 1993), and northwesterlies from the Arabia are barred by the southwest monsoon from this area, the uni-modal coarse sediment at the top of cores can only be possible from the Wahiba Sands and the southeast coastal area. Magnetic analysis of sediment from the Gulf of Oman (core 1734a) also suggests a different pattern of magnetic minerals from that of northwest Indian Ocean carried by southwest monsoon (Hounslow and Maher, 1995), and implies a coarse population very likely from the Wahiba Sands (Fig. 4.3-5).

• extra-coarse sands from coast as saltation
Local sediment source often provides extra-coarse sediment to the nearshore cores. A saltation population in core 1735 is present in Fig. 4.3-6 which could be the deposits from gusts blowing seaward from land. This population cannot reach beyond the scope of their first fall in seawater, which is estimated to be up to 8 km when a sand grain is lifted to a height of 1 m (Kukal, 1971). Considering the free fall speed, 16 cm/sec for a 50 μm particle (Kukal, 1971) and a windspeed of 12 m/s, a distance of 12 km (coresite of 1735) will be covered only in 1000 seconds and the particle will fall 160 m during that period. It is quite possible, therefore, for a rather strong wind to lift such particles to that height so that they can reach the coresite of 1735. That is possibly why the particle size distribution in core 1735 is so variable.

• extremely coarse sands and dust storms
The 10 m/s wind velocity of southwest monsoon may not be able to carry coarse particles over 200 μm found in the cores, however, dust storms and blowing dust are quite frequent in the area, at 3.3 days/year and ca. 60 events/year respectively (Middleton, 1986). It should be possible for the dust storms and alike to transport the extremely coarse sediment over 100 km to the Gulf of Oman (Pye, 1987, Tsoar and Pye, 1987) to form the coarse, well sorted, yet laterally variable top sediment.
Fig. 4.3-6 Probability plots of particle size distribution for the Arabian cores
4.3.3 Sediment Sources

- geochemical characteristics of the coastal and top sediments
  Geochemical characteristics of the top sediments can be seen to have, among others, relatively high Mg/Al ratio, yet low Ti/Al, Ba/Al and Zr/Al ratios. Actually, Mg as one typical element for heavy minerals represents a nearby source and the ophiolites influence, and Ti, Ba and Zr may be more connected with minerals in the northern and western areas of the peninsula (Laurant, 1993, Cailleux, 1961 and 1963).

B. Dusts from the Arabia
- sedimentological change in sediments
  Under the distinct top sediments of the cores lies finer-grained uni-modal sediment. This is a change not only in particle size, but more importantly in sediment source. As the mean and mode decreased and lateral consistency improved, the sediment source should be farther away than the Wahiba Sands and/or the wind strength should be weaker than the present southwest monsoon at the coresites. Such a source, therefore, should be in the Arabia or Gulf region, which is in line with the report that the majority of sediments in the Arabian Sea is from the Arabia (e.g. Sirocko, 1990).

- why not a weaker southwest monsoon, but northwesterlies?
  The finer sediment is less likely to be produced by a weaker southwest monsoon for two reasons. Firstly it is quite different from the Wahiba and southeast Oman coast dusts in terms of particle size distribution, in the meanwhile it is hard to explain why the southwest monsoon did not carry Wahiba sands as is seen later. Secondly, simply a weaker monsoon cannot explain the geochemical change in the sediment, because sediment source should not change with wind strength. The element ratios in these deposits have higher Ti/Al, Ba/Al and Zr/Al, but generally lower Mg/Al, in contrast to the Wahiba dusts. The wind strength influence cannot produce this ratio pattern in any way. Actually the dusts can be originally brought up by dust storms, which are found very frequently (~50 storm events/year and up to 20 days/year) in the northern part of the Arabian Peninsula (Middleton, 1986). The dust can then be transported down to the Arabian Sea by the northwesterlies and deposited when climate condition permits.
4.3.3 Sediment Sources

C. Dusts from the Gulf area

- coarse population brought in by northwesterlies

At the bottom of core 1734a, the second normal distribution appears with a mode much coarser than the first one, even exceeding that of the top sediment. This phenomenon in aeolian deposits is common, and the most likely explanation in the Arabian Sea is a mixture of local and far-travelled dust (Pye, 1987). Judging from the shape of the distribution curve and the mode of the coarse and well sorted sediment, the source area could not be too far from the coresite and the wind strength would be stronger than the southwest monsoon at present (Table 4-6). The most likely sediment source is the Persian Gulf area, including part of the northwest coasts of the Gulf of Oman, and the wind should be the northwesterlies.

- geochemical characteristics

As the finer fraction of the sediment is consistent with the upper uni-modal sediment, which is identified as Arabia dusts, the coarser fraction should account for the changes in geochemical characteristics. This coarse fraction is not from the southwest also because Mg/Al remains pretty low instead of getting higher, in the meanwhile Ti/Al and Zr/Al get higher, but Ba/Al lower. Therefore, this must be another sediment source.

D. Dusts from Africa

- southwest monsoon deposits

It is postulated that the top of core 1739 is from Africa as noted by numerous researchers and satellite observations (e.g. Clemens and Prell, 1990, Sirocko and Sarthein, 1990, Atlas et al. 1993). This sediment has unique particle size features, uni-modal, relatively coarse mode, well sorted and relatively high skewness. All these indicate a distant sediment source transported by a strong wind. Actually, the natural boundary of aeolian dust is 50 μm, which is conformed by this sediment. These dusts look like those at the core tops near Oman, but differ in the magnitudes of parameters, such as mean and mode, though sortings are similar. Element ratios are generally high or moderately high. All the sedimentological and geochemical characteristics of the sediment sources for the Arabian cores are listed in Table 4-7.
### Discussion

**A. Data**

- **data in Table 4-7**
  The data quoted in Table 4-7 may only be true of the study area; as we have noticed the particle size may vary along the wind i.e. with the distance from source. However, these variations are largely predictable, at least theoretically, so the data in Table 4-7 can actually be used in another way, i.e. to identify sediment source as well.

- **mode and sorting**
  Mode is selected as a major sedimentological parameter for identifying dust source and wind strength for two reasons. Firstly, in an ideal normal distribution the mean and Md should equal the mode. Secondly, it is difficult to determine the mean or Md of sub-distributions so that these parameters will be better represented by mode. However, it should be pointed out that the mode value used above may not be the one directly given in the distribution diagrams, especially when several sub-distributions merge closely, which results in one merged mode value between the modes of sub-distributions. Sorting is also difficult to estimate, and will often require qualitative evaluation. The same problem exists in the element ratios too. Nevertheless, in most circumstances, the differences are still distinguishable enough to apply the criteria for different source areas, especially when correlating within the cores.

- **an example of mode separation**
  The sample at 24 cm of core 1734a was analysed in order to separate the modes, provided a non-normal particle size distribution is comprised of several normal ‘sub-distributions’. Figure 4.3-7 shows clearly that the apparent modes can differ from the

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**Table 4-7 Sediment sources for the Arabian cores**

<table>
<thead>
<tr>
<th>selected features</th>
<th>Wahiba Sands &amp; southeast Oman</th>
<th>Red Sea &amp; Rub al Khali</th>
<th>North Arabian Peninsula</th>
<th>Pursian Gulf &amp; Gulf of Oman</th>
<th>North Africa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode (μm)</td>
<td>22.3 - 30.7, −110</td>
<td>9.45 - 14.5</td>
<td>−4.46</td>
<td>−27.6</td>
<td>10.5 - 14.5</td>
</tr>
<tr>
<td>sorting</td>
<td>good</td>
<td>medium</td>
<td>poor</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Mg/Al</td>
<td>high (0.63 - 0.8)</td>
<td>medium</td>
<td>high</td>
<td>low (&lt;0.62)</td>
<td>medium</td>
</tr>
<tr>
<td>Ti/Al</td>
<td>low</td>
<td>medium</td>
<td>low</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Ba/Al (10^-4)</td>
<td>medium</td>
<td>high</td>
<td>low</td>
<td>high</td>
<td>medium</td>
</tr>
<tr>
<td>Zr/Al (10^-5)</td>
<td>low</td>
<td>medium</td>
<td>medium</td>
<td>high</td>
<td>high</td>
</tr>
</tbody>
</table>
actual ones. For the coarse sub-distribution, the mode remains the same after the separation, but the fine-grained one is different from the apparent mode, about 5.5 μm instead of 9.45 μm. However, for quick, easy and reliable identification of sediment in practice, the apparent mode can still be useful, since the apparent mode represents a combination of individual modes and the mixing pattern of sediment, which should be consistent for certain sediments. So any change in apparent mode can still reflect relative changes in dust source and wind strength.

![Mode separation on a sample (24 cm) from core 1734a. Note the mode change when two normal distributions overlap.](image)

**E. Methodology and explanation**
- mineralogy, geochemistry and sedimentology

As the rock-forming elements of dolomites (Mg and Ca) and ophiolites (normally Mg, Fe, Ca and Na) are all common elements, it may be difficult to apply conventional mineralogy here to determine the source areas, however, careful comparison of element data and their ratios will be very helpful. It will give more reliable results when combining geochemistry and sedimentology to identify the dust sources and wind strength.
• mechanism controlling element profile: Ba/Al as an example
It is important to identify those elements controlled by aeolian process or biogeochemical process (upwelling). The problem is the elements selected for identification of sediment source may also be influenced by biological activities, endangering the reliability of data interpretation. For example, Ba/Al in some regions is found to be an indicator of palaeoproductivity (e.g. Shimmield, 1992, Breymann et al., 1992), though Ba is not considered as an essential element to most life (Cox, 1995). In the coastal Arabian Sea, however, the Ba/Al is more likely to be determined by sediment source. This is mainly because in continental margins and coastal areas, as in this study, biogenic Ba may not be well preserved, unlike in the deep-sea basins (Breymann et al., 1992). Nevertheless, if Ba is considered an indicator of a particular sediment source from where an efficient upwelling-driving monsoon blows, it will be quite understandable that there is a 'co-incidence' between palaeoproductivity and Ba/Al ratio. In the Arabian cores, Ba/Al is seen either opposite to the palaeoproductivity indicator Ca/Al or having a phase difference (Fig. 5.3-1), therefore Ba/Al and productivity should be de-coupled.

• bimodality
The most striking sedimentological feature in the Arabian cores is the poly-modality. It reflects mixing of different aeolian dusts, but not different processes, e.g. fluvial processes. Bimodality is clear only in cores 1734(a) and 1739, and its absence in cores 1735 and 1736 (possibly at 27 cm) is probably due to their young age. The reason for core 1733 is different. The position of core 1733, slightly off the streamline of the northwesterlies from the Gulf, might have prevented it from accepting such sediment.

• wind direction in the past
Although the palaeo-wind might not have the same path and intensity as it is today, it is thought to be only a matter of path migration and change of its influential scope, but not the basic pattern. Therefore it is still possible to discuss and reconstruct, at least in part, the palaeo-wind field in the Arabian Sea, based on study of present monsoon system (chapter 5).
4.4.1 Transport

General features

- no saltation and traction populations for marine aeolian deposits

Wind transports sediment in much the same way as water, separating the sediment into three transport populations: suspension, saltation and traction (Boggs, 1989). However for marine deposits, saltation and traction populations in aeolian sediment would be missing, since obviously particles dropped in water will not be available to wind again, while riverine sediment could present all the three populations. Exception exists for nearshore cores that can receive direct coastal input, e.g. core 1735 in the Arabian Sea (see section 4.3).

- transport medium: wind and river

The most obvious difference in sedimentation processes in the two regions is the transport medium, river and wind. The difference between the two basic mechanisms have been discussed by many authors (e.g. Pye, 1987). Mainly due to the much smaller density of air than that of water, wind cannot transport coarser sediment than water generally, and the suspension particle size usually falls into the range less than
4.4.1 Transport

50μm, forming a natural boundary (Boggs, 1989, Kukal, 1971, Moldway, 1957). For the same reason, sorting ability of water is higher than that of air during transport, which should lead to better sorting. Nevertheless, as riverine sediment is sorted according to various hydrodynamic conditions at different positions in the transect of a river, the sediment may present a wider spectrum of particle size than the wind-blown sediment, i.e. poorer sorting. On the contrary, wind-blown sediment is usually transported under fewer constraints and present simpler particle size distribution.

Specific features

• most turbid river and strongest monsoons

When comparing the sedimentation processes in the China Seas and Arabian Sea, specific features of the transport force should also be noted. The Huanghe River is the most turbid river in the world, whilst the Indian Ocean monsoons are one of the most dynamic monsoons in the world. Therefore the sedimentation features there may not be very representative for all other riverine and aeolian sediments. The Huanghe riverwater is quite slurry, making mass-flow easier to form and producing some features other riverine sediments do not have (cf. Mississippi River). On the other hand, the strong Indian Ocean monsoons, the southwest monsoon and the northwesterlies, can transport various sands to the Arabian Sea, which are relatively coarser than in other areas (cf. loess area). It should also be noted that cyclones and dust storms in the Arabia and Arabian Sea can also contribute to the aeolian deposits.

• sediment supply

In both regions, transport of sediment has never been a steady procedure. In the long term, both the direction and the quantity of the sediment supply have varied. In the China Seas, the Huanghe River has had frequent channel switchings, and the sediment supply mainly depends on regional climate, especially on the Loess Plateau. On the other hand, the monsoons over the Arabian Sea have even more freedom in changing their directions, and the sediment supply is closely associated with dust source areas rather than the changes in wind strength which is actually also associated with wind direction (chapter 5).
4.4.1 Transport

In sediments

- Lithologic change: sharp vs. vague (lithology)

All the transport features outlined above can be reflected in the sediments from the two regions (see also section 4.4.2). Generally speaking, the lithologic change in the sediment cores is mainly the result of different sediment supply through the two transport forces. In the Bohai Sea, the lithologic change in JX91-3B is sharp and caused by the Huanghe channel switching on its delta, and those in JX91-2A and JX91-7mG are produced by the channel switching between the Bohai Sea and the Huanghai Sea. On the other hand, the lithologic change in the Arabian cores is not quite clear and mainly induced by the swinging of monsoon paths (chapter 5). The intensity of the transport forces seems to have less influence on the lithological change.

- Particle size distribution: two to three populations vs. one (sedimentology)

Probability plots of particle size distribution of the Chinese cores have shown two or three populations in the Huanghe River sediments, in which traction seems to be negligible and under certain circumstance suspension can be predominant, as in off-channel estuarine turbidites in the Bohai Sea. On the contrary, Arabian sediment has shown the major sedimentation feature of aeolian deposit, i.e. only one population, the suspension population, exists as a rather straight line on the plot.

- Sorting: the best vs. the moderate

Although aeolian sands are thought to be the best sorted sediment (e.g. Kukal, 1971), it refers mainly to the sands on land, which comprise mostly of saltation population. This may not be true in deep-sea aeolian deposits where suspension is the only population. In fact, the best sorting in all the cores in this study is found in the channelised sandy layers of JX91-3B, ca. 1.5 as compared to the best of 2.0 in the Arabian core 1739. This affirms the theory that water sorting ability is greater than wind, though the latter may take the advantage of ocean current to gain a better sorting in the Arabian Sea.
• size limit: coarse vs. extremely coarse

It may be wrong to assume all the pristine aeolian deposits at sea should always be finer than 50µm. Due to the strong monsoons, and more importantly the dust storms and cyclones, the particle size in Arabian sediment is often seen exceeding that boundary. In core 1739, a third mode over 100 µm is clearly shown in particle size distribution (Fig. 2.3-11). Although diatoms are abundant in water column, they are seldom found in sediment in the Arabian Sea (Kroon, 1997, personal communication), and neither can the extremely coarse sediment come from fluvial processes. Therefore this mode is believed to be terrigenous, as the sediment has been treated with acetic acid, which can dissolve all the forams (of carbonate). The dust-storm-induced coarse sediment is not found in the Chinese cores, indicating the Chinese typhoons were much cleaner, as they originated at west Pacific and never reached the Bohai Sea and deposited no coarse sediment at JX91-7mG. The ancient climatology in the China Seas might be similar to today’s, but in the Arabian Sea cyclones used to be rampant and have become less severe and less frequent nowadays (Snead, 1993).
4.4.2 Deposition, Reworking and Redistribution

- deposition, reworking and redistribution: general and specific features

Deposition of sediment depends on \textit{in situ} depositional environment, topography, the position in current system or wind field and so on. Reworking and redistribution of sediment can occur shortly after the deposition; but in most circumstances, it takes place long after deposition. For fluvial and aeolian sediments, all these processes can impose different impacts on sediments. When seawater is clean and stable, the depositions of fluvial and aeolian sediments at sea will bear their general features; while the particular depositional environments in the China Seas and the Arabian Sea will impose specific features.

\textit{General features}

- depositing through water column? reflecting \textit{in situ} hydrodynamic condition? and preserving original sediment feature?

The obvious difference in depositions of fluvial and aeolian sediments is that the majority of fluvial sediment can be deposited directly on the seafloor, whilst the aeolian sediment has to pass through a whole water column. It is possible for aeolian dust to deposit in still water, but the fluvial sediment must be deposited in a moving water. Therefore, fluvial sediment can directly reflect the \textit{in situ} hydrodynamic condition, but aeolian sediment can hardly do. This also means the aeolian sediment can preserve the original feature of aeolian dust better than the fluvial sediment can preserve the original feature of river sediment load; because even if there is a weak oceanic current altering the aeolian particle size distribution over a wide area, the original fine-grained fraction being carried away can be possibly compensated by that from other part of the area so that the final distribution of aeolian deposits will remain nearly the same.

- reworking and redistributing while depositing in riverine sediment

In a fluvial dominated area, deposition of sediment is often a process involving deposition, reworking and redistribution. Current can not only transport sediment, but constantly rework and efficiently redistribute it according to the \textit{in situ} hydrodynamic
conditions, though other reworking and redistribution can also occur later on. The deposits will be only the particles that can settle on the seafloor under these conditions, whilst the finer sediment will move on to other places down the current. And that is why the final riverine sediment can barely indicate the original features of the river sediment load. The aeolian sediment, however, is firstly deposited in rather still water and then reworked by various mechanisms (bioturbation in particular) and redistributed by stronger current.

- **Sediment preservation**

Kukal (1971) found preservation of sediment generally higher in deep-sea (90%) than on open shelf (50%). Actually, riverine sediment on shelf, although reworked intensively at the beginning, can be well preserved in the long term. On the other hand, although aeolian sediment can be preserved in short term, it is easily disturbed, causing mass-flow (often turbidity current) at the edge of continental shelf or other similar geometric features.

**Specific features**

- **Huanghe and monsoonal deposition**

The turbid Huanghe River can make direct deposits in the Bohai Sea through an estuarine turbidity current and the Huanghai Sea through a mass-flow. Deposition in the northwest Arabian Sea, in particular the Oman margin, is a simple process, as aeolian processes are far more important than current.

- **Reworking and redistribution**

Physical reworking is the major form of sediment reworking in the China Seas, though some bioturbations may help in this regard too, but their intensity is relatively low especially when weight-intensity is considered; whilst in the Arabian Sea bioturbation is dominant, though very little if any disturbance can be found at least in the upper part of core 1735. Redistribution in the China Seas is mainly caused by stronger hydrodynamic conditions than those under which the sediment was deposited, e.g. channel switching and storms; whilst in the Arabian Sea it is simply because the narrow and steep continental shelf cannot allow the imbalanced

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deposition of aeolian dust off shore going on forever. Speaking in general, in the Bohai Sea redistribution of sediment is rare, and in the Huanghai Sea, it mainly happened on the old sub-aqueous delta and took the form of mass-flow. In the Arabian Sea, redistribution of imbalanced sediment on the shelf is often achieved by turbidity currents, as sediment failure is not difficult to start due to the lack of clay minerals and hence the cohesion in aeolian deposits (Pye, 1987).

**In sediments**

- **210Pb data**
  The significance of general features in the depositions (whether through water column or not) is reflected in the 210Pb records, though not very clearly in other sedimentary records. As much of the fluvial sediment did not deposit through the whole water column, the 210Pb accumulation has little to do with the 210Pb concentration and distribution in seawater, so it is unclear how much 210Pb is from the seawater and how much from the original sediment or somewhere else. The total excess 210Pb method, therefore, cannot be applied on the Chinese sediments at all. On the other hand, 210Pb in the Arabian Sea has a much definite meaning, and as a step further, scavenger problems can be discussed.

- **ultra-fine fraction**
  Ultra-fine sediment (10-11 μm) is found relatively abundant in the China Seas, which appears as a small section on top of normal suspension section on the probability plot (Figs. 4.1-2 and 4.2-6). This section cannot be found in the Arabian cores, and it is very likely associated with the relatively high suspension content in the China Seas owing to the clay-rich Huanghe River input. As a matter of fact, this ultra-fine fraction is not normally deposited, because it can be redistributed at any time. It exists in the sediment because it becomes a part of the ambient seawater, and there is no cleaner water to wash it away. Its existence in the estuarine sandy layers in JX91-3B confirms its status in seawater and sediment, while the Arabian seawater lacks the ultra-fine fraction.
4.4.2 Deposition, Reworking and Redistribution

• bimodality: reworking and preservation
Bimodality is another important aspect to note in the comparison of the China Seas and the Arabian Sea. The difference between the depositional environments in the China Seas and the Arabian Sea is that bottom current in the Arabian Sea is not so active as in the China Seas, mainly due to the greater water depth, hence reworking by bottom current is negligible in the Arabian Sea. Therefore the bimodality of the Arabian sediment can reflect faithfully two monsoons of different strengths at one time. However in the China Seas, physical disturbance of sediment is active and the sediment is intensively reworked, especially in the Huanghe estuary, therefore, bimodality in China Sea sediment reflects a depositional environment largely determined by the finer mode and the deposition of coarser fraction cannot be a persistent one. For instance, in the extreme estuarine condition in JX91-3B, although there is fine-grained fraction in the original Huanghe sediment, no bimodality is found when coarser sediment is deposited, helping make the sandy layers 'event' strata. In terms of time, the bimodality in the Chinese region reflects deposition at different times, while in the Arabian Sea it can be done at the same time.

• turbidites
Generally speaking, normal turbidites are rapidly-deposited highly-mixed sediment under one transporting force at a particular location, so it is difficult to distinguish them among equally highly-mixed aeolian sediment, as in core 1736. The Arabian turbidites are classic deep-sea turbidites and the turbidites in the China Seas have received much influence from the turbid Huanghe River and present specific features. They are recognised with the help of hydraulic analysis together with particle size analysis. As for the mass-flow in the present Huanghai Sea, the evidence is the rather coarse fraction in the sediment and the suspension profile.
4.4.3 Discussion and Summary

- various aspects of sedimentation processes

Although the sedimentation processes addressed previously are mainly in terms of sedimentology, it is often found that impact on sediment geochemistry is more essential for identifying different processes, e.g. the turbidites in the Arabian Sea. Rock magnetism also helps distinguish changes in sedimentation processes, e.g. in the Huanghai Sea and the Arabian Sea. Other non-sedimentological indicators used in the discussion include foram assemblage in the Bohai Sea and radioactive nuclei ($^{210}$Pb) accumulation.

- comparison procedure

Fluvial and aeolian processes in the China Seas and the Arabian Sea have been discussed and compared in two levels and four aspects. The first level is general feature comparison, which applies to all riverine and aeolian deposits, and the second one is comparison between specific sediments from the China Seas and the Arabian Sea, which bears fingerprints of certain depositional environments. These general and specific features differ in four main aspects of sedimentation process, transport, deposition, reworking and redistribution. As for the other main aspect, erosion of sediment source, will be discussed on in chapter 5.

- transport and deposition: their effects

Transport is important here due to its direct linkage with sediment supply, which determines the sedimentation in both regions. Generally speaking, river can transport much more sediment to the sea than wind, owing to its greater erosive and transport power. In fluvial sediment dominated area, accumulation rate is generally greater than that in aeolian sediment dominated area, ca. an order of magnitude higher in the China Seas than in the Arabian Sea. This also influences the geomorphology of the two areas. The broad continental shelf in the China Seas is actually a feature of long-term fluvial deposition with abundant sediment supply. Although the tectonic control of the Arabian Peninsula continental shelf does not provide the basic condition for a broad shelf, the rather low accumulation rate there is still responsible for the relief of
seafloor in the west of the Murray Ridge as compared to the east of the ridge where the enormous submarine Indus fan is developed.

- reworking and redistribution, and other minor processes

Reworking and redistribution of sediments are often seen associated with drastic events such as channel switching, storms and mass-flow, e.g. in JX91-7mG in the Huanghai Sea and core 1736 in the Arabian Sea, though less intensive but rampant bioturbation also plays a major part in deep-sea sediment. However, other gentler processes are still possible, such as particle-by-particle wafting of sediment from topographic highs and slopes to small basins (Ruddiman, 1997). Because such processes may mix relocated particles with normal deposition, it is difficult to tell how important they are in the whole procedure of sediment redistribution in the two regions. Moreover, it should be noted that there are also aeolian deposits in the China Seas, and it may not be comparable to the riverine sediment, but may contribute more to the suspension content in the seawater.

- comparison of sedimentation processes

The sedimentation processes in the China Seas and the Arabian Sea provide a case study to investigate the two most important sedimentation processes, fluvial and aeolian processes. Comparison of sedimentation processes in the two regions is summarised in Table 4-8.

<table>
<thead>
<tr>
<th>Table 4-8 Sedimentation processes in the China Seas and the Arabian Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>China Seas</strong></td>
</tr>
<tr>
<td>H. Estuary</td>
</tr>
<tr>
<td>Transport</td>
</tr>
<tr>
<td>Deposition</td>
</tr>
<tr>
<td>Hydrology</td>
</tr>
<tr>
<td>Particle size</td>
</tr>
<tr>
<td>Reworking</td>
</tr>
<tr>
<td>Mass-flow and pattern</td>
</tr>
</tbody>
</table>

- determining and influencing factors at several levels

Sedimentation processes are determined and influenced by many factors at different levels. Table 4-9 lists some important factors at each level which determine or influence the sedimentation processes. Human factors are not included in the list as
they usually take effect through more than one of the natural factors combined. The higher the level is, the less direct the factors are, but more fundamental. As the scale of the influence decreases, the diversity of factors increases.

<table>
<thead>
<tr>
<th>Level</th>
<th>Determining and influencing factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>external</td>
<td>earth's orbital forcing</td>
</tr>
<tr>
<td></td>
<td>solar insolation</td>
</tr>
<tr>
<td>global</td>
<td>glaciation and deglaciation</td>
</tr>
<tr>
<td></td>
<td>sea-level change</td>
</tr>
<tr>
<td></td>
<td>palaeoclimatic change</td>
</tr>
<tr>
<td>regional</td>
<td>albedo on the Qinghai-Tibetan Plateau</td>
</tr>
<tr>
<td></td>
<td>monsoon system</td>
</tr>
<tr>
<td></td>
<td>humidity and aridity</td>
</tr>
<tr>
<td></td>
<td>precipitation and river runoff</td>
</tr>
<tr>
<td>local</td>
<td>sediment source and composition</td>
</tr>
<tr>
<td></td>
<td>river channel switching</td>
</tr>
<tr>
<td></td>
<td>wind direction and strength</td>
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<td></td>
<td>oceanic current</td>
</tr>
<tr>
<td></td>
<td>seawater composition</td>
</tr>
<tr>
<td>in situ</td>
<td>position in turbidity current or mass flow</td>
</tr>
<tr>
<td></td>
<td>position in wind-field</td>
</tr>
<tr>
<td></td>
<td>physical disturbance and bioturbation</td>
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<tr>
<td></td>
<td>seafloor relief and slope</td>
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<td></td>
<td>water depth</td>
</tr>
<tr>
<td></td>
<td>biogenic activities</td>
</tr>
</tbody>
</table>

* brief chapter summary

In this chapter, sedimentation processes in the Bohai Sea, the Huanghai Sea and the Arabian Sea are identified, characterised and discussed from various points of view. This is done following ‘transect’ lines from estuary to shallow water and to shallow continental shelf (in China region) and from continental slope to deep water (in Arabia region). The two lines are not connected because of the basic differences in the two regions: fluvial processes in the China Seas with strong influence from the Huanghe River and its channel switching, and aeolian processes in the Arabian Sea associated with changing southwest monsoons and northwesterlies with influences from coastal area and dust storms. It is believed a better understanding of the fluvial and aeolian processes in the two regions will help identify and interpret the two types of sediment and reconstruct the relevant palaeoenvironments.
Chapter 5. Temporal Variations of the Sedimentation Processes and Palaeoenvironmental Reconstruction

- short term and long term temporal variations

Based on the spatial characteristics of the sedimentation processes in the Chinese and Arabian regions (chapter 4), the objectives of this chapter will be to explore the temporal variations of the sedimentation processes since the Late Pleistocene and their palaeoenvironmental implications, and to reconstruct the palaeoenvironments in the two regions, in ware of the interaction between environment and human activities. The temporal variations can be divided into short term (~1 year) and 'long' term (~100 year) variations. The short term variation can only be examined in the Bohai Sea, taking advantage of the detailed historical records, while the long term variations will be studied in cores from both regions.

- section content and connection

The study of short term variations at the Huanghe estuary (section 5.1) will be related to the recent soil erosion on the Loess Plateau. Sections 5.2 and 5.3 will discuss the long term variations of sedimentation processes in the China Seas and the Arabian Sea respectively. Section 5.4 will try to correlate the palaeoenvironmental changes between the two regions, and reconstruct trans-continental palaeoenvironment over Eurasia since the Late Pleistocene. A general summary will be given in section 5.5. This chapter will try to answer questions concerning 'why', i.e. to establish the internal mechanisms of the palaeoenvironmental changes over Eurasia.

- methods

Geochemical (elements) and rock magnetic (magnetic susceptibility and \( X_{(d)} \)) data will be used to establish the physical and geochemical mechanisms of soil erosion on the Loess Plateau and sedimentation in the Bohai Sea, with the help of statistical analysis of PCA and hydraulic records of the Huanghe River in the last 60 years. This helps to identify the Huanghe influence in the Bohai and Huanghai Seas since the early Holocene and the sedimentation processes without the direct influence from the Huanghe River when channel switching occurred. In the Arabian region, geochemical
and sedimentological data are combined with terrestrial data (seifs in the deserts) to reconstruct the palaeomonsoonal variations both in direction and in strength. The palaeoenvironmental changes in the two regions will be associated with the palaeoclimate (albedo) on the Tibetan Plateau.

5.1 The Huanghe Estuary: Recent Soil Erosion of the Loess Plateau

- linkage between land and sea

It has been recognised in chapter 4 that the sediment input from the Huanghe River and the Huanghe channel switching are two determining factors for the sedimentation processes in the Bohai Sea. At the Huanghe estuary this variation of sediment input has actually reflected the original variable soil erosion of the Loess Plateau. An improved understanding of sedimentation processes at the estuary is essential to develop a linking framework between the marine and the terrestrial records.

5.1.1 Geochemical and Palaeomagnetic Analyses

- in-depth analyses

A pure sedimentary approach as applied in chapter 4 would not tell the full content of the sediment input related to soil erosion, since physical properties of the Huanghe sediment at different times are almost identical in terms of sedimentology. Other more in-depth analyses, e.g. rock magnetic and geochemical analyses, are required to tell the true story about the history and the reasons of soil erosion, through the geochemical and rock magnetic indicators of soil erosion in the estuarine sediment.

Four groups of elements

- element profile pattern

Looking at the geochemical data obtained for JX91-3B (Fig. 5.1-1), we can find a common pattern for many major and trace elements which is very much lithology-controlled, but there are some other elements, e.g. P and Ti, which present a different pattern and dissimilar from Sr or Al (Chen and Shimmield, 1997).
Fig. 5.1-1 (a) XRF major elements for JX91-3B
Fig. 5.1-1 (b) XRF trace elements for JX91-3B
5.1.1 Geochemical and Palaeomagnetic Analyses

- PCA and four groups

To examine the inter-element correlation, principal component analysis (PCA) will be applied, which was successfully used by Li (1982) and Shimmield and Mowbray (1991) to analyse geochemical data. Fig. 5.1-2a shows the 3D results of the analysis, together with bi-plots for the principal component pairs: pc2 vs. pc1, pc3 vs. pc1 and pc3 vs. pc2 (Chen and Shimmield, 1997). From Fig. 5.1-2 we can see four groups of elements: the first one is that of Si, Na and Zr, the second one is that of Al and many other elements, the third is that of P, Ti and La etc. and the fourth is mainly for Sr.

**Three sedimentation processes**

- Element group and sedimentation process

Element group is usually associated with a particular sedimentation process, especially where biogeochemical processes are not prevalent. As the sedimentation process in the Bohai Sea is mainly of a physical one, it actually cannot change the chemical composition of the original sediment itself, though it will certainly help create a particular depositional environment with certain geochemical characteristics. The way it affects element profile is that it can selectively transport and deposit certain sediments, rework and redistribute it until a special element pattern is made.

- Channel switching process: the first two element groups (Si and Al)

The first two element groups (Fig. 5.1-2a), represented by Si and Al respectively, contain mostly lithogenic elements and are quite in line with the lithology, particle size profile and other physical parameters, e.g. water content. Si and Al vary conversely in pattern, mainly because sand (quartz--Si) and mud (clay--Al rich) are opposite to each other in sediment. As they are lithology-controlled, they must be directly related to the Huanghe channel switching (chapter 4). Actually they should belong to one big group: the lithogenic group, which is a primary group (pc1).

- Sediment supply process: the third element group (P)

The third group (represented by P) is very different from the first two and has nothing to do with the lithological changes, which cannot be explained through any of the four main aspects of sedimentation processes (ref. to chapter 4). Therefore it must be
Fig. 5.1-2 PCA results of XRF major and trace elements for JX91-3B. (a) 3D diagram, (b) pc3 vs. pc2, (c) pc3 vs. pc1 and (d) pc2 vs. pc1. Distribution of these elements is determined by three processes quantified by pc1, pc2 and pc3. Two of the components, pc1 and pc3 are related, but pc2 is independent. Si, Al, P and Sr are four representatives of four groups of elements controlled by these processes.
associated with the origin of the sediment: erosion of sediment source. The sediment supply from the Huanghe River is a collection of sediments eroded in its whole catchment, which may vary chemically due to different erosion processes. This element group determined by these processes can therefore be labelled as a soil erosion group. This is not to say, however, that deposition of this group is completely independent of sedimentation processes, though it is not affected by them in general.

- redistribution of biogeochemical deposit: the fourth group (Sr)
The fourth element group actually consists of only one or two elements with Sr as its representative, which is seen to be of a secondary process. In fact, Sr is closely associated with shells in the China Seas (Zhao and Yan, 1994), and the spike of Sr indicates the initial flushing of the riverwater on the tidal flat at a new river mouth (chapter 4, also Chen and Shimmield, 1997). As Sr is a biogeochemical element, it should not be simply regarded as of a physical process. As the (benthic) biological activities are rather low (chapter 4), Sr at the coresite of JX91-3B would not be much affected by local Sr and must be related with sediment reworking and redistribution.

**Magnetic susceptibility and its frequency dependence**

- two types of records

Although the magnetic minerals in loess are mainly minerals, we do not have the IRM acquisition curves for JX91-3B to confirm it; however, the IRM data from JX91-2A (ref. to Fig. 5.2-2) suggest it is almost true. Fig. 5.1-3 shows the magnetic susceptibility and its frequency dependency ($X_{fd}$) for JX91-3B, together with typical element profiles and particle size data (Chen and Shimmield, 1997). Two different types of magnetic records are shown: the magnetic susceptibility is rather lithology-independent while its frequency-dependence is quite lithology-controlled. When compared with geochemical data, magnetic susceptibility is seen to be quite consistent with the typical elements from the P group, though it reveals more detail owing to a smaller sampling interval, whilst the $X_{fd}$ is quite in line with the Si and Al groups.
Fig. 5.1-3 Profiles of representative elements Si(\%), Al(\%), P(\%) and Sr(ppm), magnetic susceptibility X(S.I.) and its frequency dependence Xfd(\%), and mean(μm) of particle size distribution for JX91-3B. It can be seen that Si, Al, Xfd and mean are associated with lithology, while Sr is related to shell layers, and P and X are in good agreement but independent from the others. The three sandy layers indicated by hatched areas are dated by Chen and Shimmield [5].
5.1.2 Relationships and Mechanisms

- two groups of processes: sedimentation processes in the Bohai Sea and soil erosion on the Loess Plateau

The geochemical and magnetic data fit into three groups: lithogenic group including Si, Al and X_{ld}, soil erosion group of P and magnetic susceptibility, and Sr group. They are mainly associated with two groups of processes, the normal sedimentation processes in the Bohai Sea, Huanghe channel switching in particular, and the sediment supply from the Huanghe River, mainly soil erosion on the Loess Plateau.

- focus on soil erosion

As the sedimentation processes at the estuary are fairly clear, the focus of the whole procedure from erosion, transport, deposition, reworking to preservation will be on erosion (on the Loess Plateau), relating to the P group parameters. The soil erosion processes involve mainly physical and chemical processes which will be discussed accordingly, though biochemical processes will also be discussed where necessary.

*Physical processes*

- concerning detrital part of sediment

Physical processes affect only the detrital part of the sediment, which is chemically stable during erosion, transport and deposition. Suppose the physical properties of these terrigenous grains change very little during transport, the physical processes should be able to connect the erosion directly with the deposition. As some elements in the P group are thought to be associated with topsoil (see below), it is desirable that the relationship of these elements with topsoil should be established before the erosion of these elements is discussed.

A. Relationship

- loess and soil: definition

Soils on the Loess Plateau are divided into ordinary soil and loess, a kind of soil developed under cold and dry climate (Zhao, 1991). The loess part is usually barren or scarcely covered with vegetation, while the soils, short for 'ordinary soils' here, is either covered by trees or grass or cultivated as farmland. The loess account for most
of the Huanghe sediment, and virtually forms the background for the soil's contribution, which presents a quite different element inventory from the loess.

**AI. elements**
- **P and topsoil**
  Some elements are known to have a closer relationship with topsoil than with loess, which are either biochemically active (P) or redox-sensitive (Mo). Being a representative of P group, phosphorus is also a typical biochemical element essential to plants and relating to the topsoil. It is enriched in topsoil through complex mechanisms. It is easily precipitated in unavailable forms to biota in soil with poorly crystalline forms of Fe and Al, as their anion absorption capacity is typically greater (Schlesinger, 1991). Moreover, as clay minerals can be enriched by weathering processes (Bronger and Heinkele, 1990), soils can certainly increase the ability of absorbing free P. Furthermore, for agricultural production on the Loess Plateau, a great deal of phosphorus is added to the farmland with traditional (organic) fertilisers, mainly manure, in the early days and synthetic fertilisers after the 50's, which cannot be neglected. As the majority of phosphorus is firmly bound to particulates in the topsoil, they are subject to physical erosion later on. Contrary to the situation in topsoil, P in loess suffers more from leaching and frequent mechanical and chemical erosion owing to lack of protection from vegetation. So even if there is no absolutely substantial P concentration in topsoil, the low level of P in loess will make the P input from the topsoil a distinguishing signal.

- **Mo and topsoil**
  As another essential trace element, molybdenum is a constituent of several enzymes where the possibility of cycling between Mo(+4) and Mo(+6) states is important. An important such enzyme, nitrogenase, is used by bacteria that fix atmospheric N₂ into organic nitrogen; and those for reduction of sulphate and nitrate are just other examples. Mo is thus essential for the biological utilisation of nitrogen and sulphur, and in the environmental cycling of these elements (Cox, 1995). Apparently Mo should present a higher content in soils and topsoils than in loess.
5.1.2 Relationships and Mechanisms

A2. magnetic susceptibility

- susceptibility enhancement in topsoil

Susceptibility enhancement in soils and topsoils is a very common feature in soils world-wide (Thompson and Oldfield, 1986, Maher and Talyor, 1988, Heller and Evans, 1995), and has been noted and analysed particularly for the Chinese loess (Zhou et al., 1990, Maher and Thompson, 1991, Maher and Thompson 1992, Maher et al., 1994). The responsible ferromagnetic minerals for the extra magnetic susceptibility are believed to be maghemite and magnetite, the top two minerals with strong susceptibility. These two minerals can be formed from iron oxide or oxyhydroxides by repeated oxidation-reduction cycles during soil formation (e.g. Butler, 1992 and refs. therein). It is also postulated that the ultra-fine magnetites being formed in the topsoil as a result of burning or bacterial activities have contributed greatly to this enhancement (e.g. Thompson and Oldfield, 1986 and refs. therein). Initially free Fe accumulates in amorphous and poorly crystallised forms, known as ferrihydrite, but with increasing time, most Fe is found in crystalline oxides and hydrous oxides (e.g. goethite and hematite), which may involve bacteria (Schlesinger, 1991, Fassbinder et al., 1990). All these processes relating to the susceptibility enhancement take place mostly in soils, topsoil in particular. The relationship between magnetic susceptibility and topsoil is further confirmed by observations on the Loess Plateau (Sun and Wei, 1991), where iron-oxide content and magnetic susceptibility are found obviously higher in the palaeosols than in the loess. Obviously, all the carriers of the magnetic susceptibility are detrital and subject to physical erosion.

B. Erosion

- rain: the eroding force, protection: the key factor

Physical erosion is a complicated process, and depends on the type of soil (loess or soil), the vegetation protection, the gradient of the slope and the type of erosion etc. (Chen and Shimmield, 1997, White et al., 1993). However, it is normally the rain drops that start the erosion, damaging the surface structure of the loess and soil first, and then forming erosive flows and streams during and after rain. Therefore, vegetation protection of soil seems to be the most important factor to consider.
5.1.2 Relationships and Mechanisms

- how can soils be protected from rain by vegetation?

Soils, unlike pristine loess, are normally covered with vegetation on the Loess Plateau. Vegetation can protect soils in many ways, such as:
1. reducing the collision impact of raindrops on soil,
2. absorbing rainwater through leaves,
3. increasing permeability of soil to help drain rainwater,
4. holding soil with root system,
5. increasing surface roughness and
6. dispersing flows.

- topsoil erosion and rainstorm

Therefore the soil area can be greatly protected by vegetation from the damage and erosion of rain fall, whilst in loess area erosion is almost inevitable whenever rain falls. However, during heavy rainstorms, both areas can be eroded significantly (e.g. Zhao, 1991). While the erosion of loess is somewhat proportional to the total rainfall, the erosion of soil would appear much more catastrophic when a threshold of rainfall is surpassed; so the appearance of topsoil-related elements and minerals in the final sediment would be able to indicate an exceptionally heavy rainfall or storm, which would cause a big flood on the plateau. Concerning the area affected, loess erosion mainly happens in gullies, while topsoil erosion on top of the hills; therefore topsoil vs. loess erosion can reflect the sheet vs. gullying erosion.

- formation of topsoil erosion signal

Despite a greater amount of erosion, a heavy rainfall can cause little changes in the general physical properties in the final sediment, because
1. the loess has a very consistent composition over the plateau,
2. topsoil only consists a small fraction of the total erosion, even if soil is presumed to be very different from loess chemically, and
3. stronger current can hardly break down the fine-grained sediment even a little further or carry unproportional amount of coarse particles.
5.1.2 Relationships and Mechanisms

Therefore in terms of physical processes, the topsoil-related elements, such as P and Mo, and magnetic susceptibility will be able to indicate the topsoil erosion caused by rainstorm out of the loess background.

- **signal recorded**

Transport of the detrital part of eroded sediment is so efficient, considering the turbid and furious Huanghe River and the relatively fine-grained sediment, that the topsoil-related sediment can be promptly deposited in the Bohai Sea together with its loess background. However, the deposition is still subject to sedimentation processes in the Bohai Sea, which will sort out the Huanghe sediment according to the particle size (Chen and Shimmiel, 1997). Due to the extraordinary characteristics of the topsoil erosion signals in many aspects, they are recorded in the estuarine sediment finally.

- **decouple of magnetic susceptibility and $X_{fd}$**

It seems to be a puzzle that magnetic susceptibility and $X_{fd}$ is decoupled in the estuarine sediments, because it was thought that high magnetic susceptibility should be associated with fine-grained magnetic minerals, i.e. they are coupled, as on the Loess Plateau. As a matter of fact, this is a perfect example to show how sediment source and sedimentation processes imposed their influences on the sediments. Magnetic susceptibility and mineralogy on the Loess Plateau have been studied in many aspects (e.g. Liu, 1985, Guo et al., 1998, Sun et al., 1998, Torii and Fukuma, 1998, Chlachula et al., 1998, Maher, 1998, Sun et al., 1997, Liu et al., 1995, Evans and Heller, 1995), and the basic conclusion is that magnetic susceptibility is enhanced in topsoils and palaeosols on the Loess Plateau. Detailed study (e.g. Zheng et al., 1991) revealed that this is true on the whole spectrum of grain size, though the enhancement may vary with the size. It should be pointed out in particular that the magnetic-mineral concentration is more than four times higher in palaeosol than in loess in terms of $X_{fd}$ (Zheng et al., 1991) in all the grain size catagories, suggesting that magnetic susceptibility can be used as an overall indicator for topsoil erosion. Therefore, in the Huanghe estuarine sediments, no matter fine-grained or coarse, topsoil erosion will definitely produce a high signal. As the sedimentation processes will determine what size of sediment can be deposited, $X_{fd}$ will be in line with the
overall particle size, but magnetic susceptibility can still reflect the topsoil erosion independently over all the size scale, making the two parameters decoupled. It is interesting to note that the $X_{50}$ in mud is fairly high (up to 8%), which is certainly a signal originating from topsoil where ultra-fine magnetic minerals are particularly enriched (e.g. Maher and Taylor, 1988, Zhou et al., 1990). As the Huanghe estuarine sediments are directly deposited from the river rapidly and the sediments are poor in organic matter, alternations to the original magnetic signals by biogenic, authigenic and diagenetic processes are negligible.

**Chemical processes**

- **scope**

Chemical processes mainly control the erosion, transport and deposition of chemicals either in dissolved form or occluded form. Organic matter will also be included in this category as non-detrital material. Although detrital part comprises the majority of the Huanghe sediment, the chemical process controlled constituents can also play a role, especially when concerning the trace elements, like REE.

A. Elements subject to chemical erosion

- **P and REE (including Th and Y)**

The distinct elements subject to chemical erosion are phosphorus and REE (Rare Earth Elements). The REE to be discussed here include only three out of the ten elements (Lanthanide), namely La, Ce and Nd. As thorium is frequently found in association with the lanthanide elements in mineral monazite (La, Ce, Th) PO$_4$, and yttrium usually along with lanthanides in minerals such as xenotime (Y, Ln)PO$_4$ (Ln is used to represent a combination of lanthanides), Th and Y are often regarded as REE (Cox, 1995), particularly the chemically similar Y. Since all the five elements behave quite similarly as shown in Fig. 5.1-1, it is very likely that all REE in the estuarine sediment are mainly controlled by the same process from beginning to end.

- **chemical processes concerning P and REE within soils**

The main ores of the REE are the phosphates, which tend to undergo rapid weathering involving chemical as well as biological processes in soils (e.g. plant
5.1.2 Relationships and Mechanisms

released phosphatases). Once the phosphorus is released, it goes to biota (organic P) or exists in non-occluded forms, like that from apatite weathering. It is found at later stages of weathering and soil development that occluded and organic P dominate the forms of P remaining in the system, and almost all available P is found in a biogeochemical cycle in the upper soil profile (Wood et al., 1984). Therefore phosphorus in topsoil is quite vulnerable to chemical erosion with runoff. On the other hand, the cations released from the phosphate weathering may be scavenged by organic matter, iron oxide minerals and clay minerals, especially the former in most cases. It should be stressed that hydroxide (-OH) radicals are often negatively charged and can attract and bind cations (Schlesinger, 1991), making the iron oxyhydroxide in soils an important host of the REE.

- topsoil indicators
In addition to the enrichment of P in topsoil, the REE are also found as REE peaks and REE/Al peaks in soils in comparison with ordinary loess (e.g. Taylor et al., 1983, Weber et al., 1996), suggesting both of P and REE indicators of topsoil.

B. Processes in chemical erosion, transport and deposition

- chemical erosion: elements, organic matter and occludes
P and REE in soils can be eroded chemically as well as physically with detritus during heavy rainfall. This is because soils would be saturated with rainwater which can wash out the elements in ionic form in the interstitial water in soil (soil solution) and organic matter and occluded materials in soils (e.g. iron oxyhydroxide) on which P, REE and many other topsoil related elements are attached. This chemical erosion, once it occurs, can have an extended effect because of the light weight of the organic matter and another effect known as hysteresis, the result from an initial flushing of highly concentrated waters that accumulated in the soil pores during low flow period (Schlesinger, 1991).

- transport: changing to insoluble form
The output of chemical erosion would undergo chemical changes during transport. Most river waters are supersaturated with dissolved CO₂, which causes river waters
to be slightly acid. Meanwhile, rivers usually carry low concentration of dissolved inorganic phosphorous (Meybeck, 1982). Under the acid conditions, the phosphorus would bind to Fe-hydroxide minerals and is transported in the load of suspended sediments (Meyer, 1979), which is insoluble at high redox potential (Schlesinger, 1991). Decomposition of organic matter in riverwater contributes significantly to the chemical process during transport, which produces a slightly acid solution, and in the meantime releases the absorbed elements and transfers them to inorganic carriers, making some of them insoluble. On the other hand, the rate of plant production in large rivers is often limited by turbidity, so these systems usually retain an overall dominance of allochthonous materials (e.g. Cai et al., 1988) and P would be unlikely to be involved in another biogeochemical cycle. Therefore P, very likely REE as well, will be changed in part from dissolved and occluded forms to insoluble forms and be transported with other detritus.

- deposition
Deposition of chemically transported constituents is normally taking place at the estuary. Upon mixing in the higher pH of seawater, phosphorus may desorb from suspended particles (Chase and Sayles, 1980), and a great part of the released phosphorus will precipitate with the abundant Ca at high pH (~7) at the Huanghe estuary or coprecipitate with REE (Byrne et al., 1996). Moreover, the oxyhydroxides of iron will go through dehydration to maghemite or magnetite from occluded form and brings down the P, REE and alike to sediment. Of course the topsoil elements can also precipitate with other minerals, especially the clay minerals. Therefore no matter how complex the chemical processes are, the original signals carried by P, REE and magnetic minerals (including those in occluded forms e.g. iron oxyhydroxides) from the topsoil erosion on the Loess Plateau will be eventually recorded in the Huanghe estuarine sediment.

**Relationships**
- typical indicators with other elements
In the discussion of physical and chemical processes, only magnetic susceptibility and typical topsoil-related elements have been examined. In fact, there are found to
be good interrelations within all the P group elements, and close relationship between the elements and iron-bearing minerals.

- Ti and Nb with Fe
  The only two elements in the P group not mentioned above are Ti and Nb. Neither of them has biological role, but both normally occur with iron in Fe-Ti oxides and columbrite (Fe, Mn)Nb₂O₆ (Cox, 1995), therefore they may also be involved in processes concerning iron oxides in soil, which also determine the magnetic susceptibility of soil.

- Ti in FeTi oxide: bond to ferromagnetic minerals
  By far the most important ferromagnetic minerals in nature are FeTi oxides, which are actually a group of minerals (solid solution). Titanomagnetites have higher magnetic susceptibility in the FeTi oxide series, and can be altered by two processes, exsolution and low-temperature oxidation (Butler, 1992).

  1) Exsolution yields Ti-poor crystals surrounded by Ti-rich region. The resulting composite grain will have fine-grained crystals of ferromagnetic, Ti-poor titanomagnetite surrounded by paramagnetic, Ti-rich titanomagnetite, which effectively decreases grain size of ferromagnetic particles.

  2) Low-temperature oxidation of titanomagnetites produces cation-deficient titanomaghemite, which is ferromagnetic.

Both these processes can increase the magnetic susceptibility by producing ultrafine (up to 0.02 μm) titanomaghemite and maghemite in soils and bond Ti tightly with ferromagnetic particles. Although the ultrafine-grained magnetic minerals of bacterial origin in soils are found to be pure magnetite (e.g. Maher and Taylor, 1988), in the Huanghe estuarine sediment, they do not seem to account for the overall susceptibility, especially in sandy layers, as indicated in Xfd (Fig. 5.1-3). As there is no trace of sulphides in the estuarine JX91-3B, unlike JX91-2A, the inorganic magnetic minerals in the original soils on the Loess Plateau, which appear to be somewhat anomalous (Eyre and Shaw, 1994), may be more responsible for the susceptibility signal in JX91-3B. Since Ti is usually found in FeTi oxides, but Fe is one of the most abundant elements in the crust and exists in many iron-bearing but
non-magnetic minerals. It is not surprising that Fe does not appear in the P group along with magnetic susceptibility and Ti.

- Iron-bearing minerals and ferromagnetic minerals

An important fact found in many soils and soil-derived sediments is the presence of ultrafine iron oxides in the superparamagnetic size range (e.g. Mullin, 1977, Maher and Taylor, 1988), which have distinctively high susceptibility (Thompson and Oldfield, 1986). Fe is playing an active part in their production, as Fe can become relatively soluble when it is involved in chelation reactions with organic matter (Huang, 1988). Four more processes may demonstrate further the versatile role of Fe in soil relating to production of ferromagnetic minerals, while serving as hosts for many elements (Butler, 1992, Maher, 1995):

1) formation of maghemite (and sometimes magnetite) from iron oxides or oxyhydroxides by repeated oxidation-reduction cycles during soil formation.
2) natural burning in the presence of organic matter, converting paramagnetic Fe-bearing minerals to maghemite.
3) dehydration of lepidocrocite (αFeOOH), a common iron-oxyhydroxide weathering product of iron silicates.
4) ultrafine magnetite formed by bacteria.

- conclusion

It may be proper to say that it is iron in various forms and minerals that brings the P group together through complex physical and chemical processes which are still not well understood. The relationship between P, REE, Ti and ferromagnetic minerals can be established in soils; on the contrary, no such relationship can be expected in loess. Therefore, magnetic susceptibility, P, REE and Ti in the Huanghe estuarine sediment can be regarded as genuine indicators of topsoil erosion on the Loess Plateau.
5.1.3 Correlation with Hydraulic Records of the Huanghe River

- comparison between indicators and hydraulic records: necessity and possibility

The above discussions have established the relationship between soil erosion and geochemical and palaeomagnetic parameters, confirmed the P group elements and magnetic susceptibility as indicators of topsoil erosion on the Loess Plateau. If all these are true, the indicators should present a good agreement with the recent hydraulic records of the Huanghe River. The comparison between indicators and gauge readings is possible owing to both the high resolution chronostratigraphy established for JX91-3B in Chapter 3 and the precious records of the Huanghe River sediment and water discharge since 1920 AD (Wang, 1980). As the downcore magnetic susceptibility profile is more densely sampled, it should be an ideal representative of the P group.

*Water discharge and sediment load*

- what to compare in hydraulic records? both in the long term

In terms of topsoil erosion, sediment loads seem more important than the total water discharge, because moderate rainfalls have no significant effect on topsoil erosion, but the total precipitation (water discharge) may be even greater. It is possible that one or two very erosive rainstorms can result in huge topsoil erosion, while not necessarily making a flooding year. However, a flooding year should see relatively more sediment eroded, just as shown in Fig. 5.1-4, though not necessarily more topsoil. Nevertheless, in the long term the sediment load and water discharge are seen to be in line with each other and both can be regarded as hydraulic indicators of topsoil erosion, despite the variable ratio between them.

*Correlation*

- chronology and sedimentary records

JX91-3B has been dated at a resolution of a year or so, with very accurate dates at the boundaries corresponding to the channel switchings. However, it may be that the accumulation rates within the homogeneous layers are not as consistent as the particle size data would suggest, particularly when the sedimentation was interrupted,
5.1.3 Correlation with Hydraulic Records of the Huanghe River

Fig. 5.1-4 Annual sediment load ($x10^8$ t) and water discharge ($x10^{10}$ m$^3$) of the Huanghe River over the last 70 years (Wang, 1980, Qin and Li, 1986) with magnetic susceptibility.

say 1938-1947, and sediment supply varies (Fig. 5.1-4). Therefore chronology within the layers may be flexible to some extent. Since the average sedimentation rate for the upper part of JX91-3B is determined as around 1.5 cm/y, and the sampling interval is about 2.3 cm for susceptibility, every flooding year with larger sediment load should therefore be sampled, though the ordinary year might be missed due to less sediment load.

- well correlated: relationship confirmed

Based on these, the correlation between the two profiles is carried out and not surprisingly, the magnetic susceptibility peaks are correlated very well with the flooding years (Chen and Shimmield, 1997). The relationship between the geochemical and palaeomagnetic indicators and topsoil erosion on the Loess Plateau is thus confirmed.
5.1.4 Discussion and Conclusion

• other elemental records of topsoil erosion
It is improper to say that the lithogenic elements cannot reflect topsoil erosion. In fact, when topsoil erosion happens, there must be more loess erosion, though not vice versa sometimes. The extra intensive erosion may produce certain signals but less significant because of the primary influence from the channel switching. These minor signals may be responsible for the secondary variations in the lithogenic element profiles, which are obviously not suitable for indicators of topsoil erosion.

• topsoil erosion of other areas
Special areas protected either by vegetation or geomorphologic feature can also contribute to the topsoil signals as observed. No matter what area it is, the basic characteristic should be that it can only be eroded by rainstorms and alike. Such an area may be found in the Inner Mongolia, to the north of the Huanghe River but still within the catchment, where REE ores seem to be abundant. As the primary purpose of this study is not to restrict the eroded region, the wording of ‘topsoil erosion on the Loess Plateau’ should only be regarded as the mainstream of the discussion.

• different from other topsoil erosion
This flood-related topsoil erosion pattern is different from the hysteresis pattern found in many other rivers, which occurs during rainfall, especially during seasonal flooding (e.g. McDiffett, 1981). This is mainly because the topsoil erosion discussed here shows the yearly changes and is not limited in dissolved ions, and actually it is mainly in particulate or occlude form.

• relationships valid only at estuary
Although during flooding years the sedimentation processes in the Bohai Sea can affect a greater part of the sea, this influence is limited mainly because the turbidity current might not be able to go much further (>100 km off shore) and more active biogenic activities and diagenesis may also damage the magnetic signals especially those carried by fine grained magnetic minerals. So the signals of topsoil erosion on the Loess Plateau remain mainly an estuarine feature of the Huanghe sediment.
5.1.4 Discussion and Conclusion

• estimate of chemical deposition

Ancient delta plain sediments in the North Sea have been studied by Hauger and Lovlie (1992) through the acid dissolution experiment (HCl treatment). It suggests that chemically reactive iron, e.g. iron oxyhydroxides, is responsible for 90% of the magnetic susceptibility, and the remainder is carried by single domain magnetite grains of detrital origin. This shows us how important the reactive Fe can be, however, as seen from Figs. 5.1-3, 5.2-2 and 3, much of the Bohai magnetic susceptibility is of detrital origin (magnetite and titanomagnetite, chapter 4) and is little influenced by the chemical deposition.

• conclusion

After all, geochemical and palaeomagnetic studies of the Huanghe estuarine sediment revealed the short-term temporal variations of the sedimentation processes in the Bohai Sea and the sediment supply by the Huanghe River from the Loess Plateau. With the help of principal component analysis of the XRF major and trace elements, together with detailed measurements of magnetic susceptibility and its frequency dependency (Xfd), four groups of elements are identified, represented by Si, Al, P and Sr respectively with the addition of magnetic susceptibility to P group and Xfd to Si group. The two kinds of main processes controlling the estuarine sediments are identified as the dominant sedimentation processes in the Bohai Sea (Si, Al, Sr and Xfd) and soil erosion processes on the Loess Plateau (P and magnetic susceptibility). Relationships between soils on the Plateau and magnetic susceptibility and P group elements are established, and physical and chemical processes concerning erosion, transport and deposition of the topsoil related materials are discussed. Soil erosion on the Plateau is linked to the precipitation pattern and various mechanisms are explored. Indicators of topsoil erosion on the Plateau have been determined as magnetic susceptibility, P, Ti and REE. A comparison made between magnetic susceptibility and Huanghe hydraulic records over the past 70 years confirms the relationship between the topsoil erosion and estuarine sediment records as indicated by the geochemical and palaeomagnetic indicators.
5.2 Palaeoenvironment in North China, the Bohai Sea and the Huanghai Sea since the Holocene

- four influential factors and section arrangement

Sedimentation processes in the Bohai and Huanghai Seas have been influenced mainly by four factors in the Holocene, viz. channel switching of the Huanghe River, sea-level fluctuations, climatic changes and anthropogenic activities. The last two factors are the main content of Chapter 5; and the first two, though already discussed in Chapter 4, will be summarised again in 5.2.1 to construct an event stratigraphy for the Bohai and Huanghai sediments. Long term temporal variations of the Huanghe River and the oceanography of the seas will be examined in 5.2.2, followed by discussion on palaeoenvironmental changes on land in 5.2.3.

5.2.1 Event Stratigraphy

- definition and difference from chronostratigraphy

Event stratigraphy, as defined with sound dates, is virtually different from chronostratigraphy, though in some circumstances they are thought identical. Generally speaking, event stratigraphy focuses on spatial sequences based on events (presumably wide-spread) while chronostratigraphy relies on temporal sequences based on dates (chapter 3). The link between the two lies on the fact that events are usually synchronous in all the individual sites within a certain area, though not always so (ref. to section 5.3). They will appear the same only when stratigraphical markers are definitely isochrons. Comparison between the two may result in a better understanding of the changing rate of an event in time domain and the spatial features of the event in a certain region.

- event stratigraphy in the Bohai and Huanghai Seas: Huanghe channel switching

As the Huanghe River plays such a key role in the sedimentation in the Bohai and Huanghai Seas, the sediments from the two areas can be correlated and connected through the Huanghe River and the Huanghe channel switchings between the Bohai and the Huanghai Seas, which serve as the most prominent events in this region.
5.2.1 Event Stratigraphy

During most of the history of the Huanghe River, at least during the last 4000 years, the Huanghe River has been taking one main course, i.e. flowing either to the Bohai Sea or to the Huanghai Sea, and more importantly the Huanghe sediment has never ceased depositing in the seas. Therefore a continuous event stratigraphy (mainly on JX91-7mG because of its longer time span) can be established through identification of channel switching signals in the sediments from the two seas, based on the successful applications in JX91-3B, and the event stratigraphy will look similar to the chronostratigraphy.

**Channel switching signals**

- geochemical signal: Ca and Sr: Bohai - Huanghai

Channel switching signals are recognised in JX91-3B as sharp lithogenic change in sediment. As the river influence in the central Bohai Sea and the Huanghai Sea would be much smaller than that at the Huanghe estuarine, the sedimentological parameters used in JX91-3B may not be fully applicable in JX91-2A and JX91-7mG. However, geochemical channel switching-related signals can still be identified for event stratigraphy. At 19 cm in JX91-7mG, there are exceptionally high Ca and Sr spikes, which are not shown in other element profiles (Figs. 3.2-5 and 4.2-7). For Ca, the spike seems consistent with the Huanghe-absent pattern, but only higher; on the contrary the Sr spike is opposite to the general pattern. The strong signal is possibly an outcome of an independent process, which mimics those in JX91-3B, suggesting strongly a biogenic origin. In fact, it is quite likely that the Ca and Sr spikes are also caused by intensive initial flushing over the tidal flat in the Bohai Sea by the Huanghe River when it switched back from the Huanghai Sea. According to the chronostratigraphy, this signal was possibly about 20 years later than 1855 AD, because the main river channel at the rivermouth was only formed around 1875 AD (Pang and Si, 1979). It is very likely the Ca, Sr-rich very fine-grained sediment was brought to JX91-7mG by the current flowing out of the Bohai Sea to the Huanghai Sea. This event can be related to the lower Sr spike in JX91-3B, which is caused by initial flushing of the Bohai seafloor. This is supported by the magnitude of Sr, both of which are around 230 ppm.
• thin muddy layer in JX91-7mG

It is obvious in Figs. 2.3-3 and 3.2-4 that from 70 cm to 77 cm of JX91-7mG the sediment appears very similar to the muddy top, though apparent sediment mixing occurred. This kind of change looks almost the same as that in JX91-3B. This muddy layer is regarded as deposit of a short period about 34 years if the same accumulation rate as in the top layer is applied. This event is not well documented unfortunately. Since the intensity of the signal is relatively weak as compared with the top layer and the similar layer at around 320 cm, there can be three possibilities: 1). channel switching on the old Huanghe Delta in the Huanghai Sea, 2) a partial channel switching, i.e. one branch to the Bohai Sea and the other to the Huanghai Sea, and 3). a breach of the river. It is worth noting that one of the most catastrophic floods and breach of levee in history happened in September 1642 which claimed 340,000 lives in Kaifeng (Zhou, 1986, Zhou, 1990) and this could be the result. This muddy layer (ca. 7 cm thick) is detected with a smaller interval in subsampling (2 cm), and there could be other similar signals downcore, though not revealed by the 10 cm interval subsampling.

• downcore muddy layer: Huanghe River to Bohai Sea; sandy layer: to Huanghai Sea

Since 2270 BC, the Huanghe River had continuously flowed into the Bohai Sea, only during 6th - 1st century BC a small branch of the river might have entered the Weishan Lake (e.g. Ren et al., 1985, Liu and Walker, 1989). This long period of absence of the Huanghe River in the Huanghai Sea is similar to the present situation, and can be well represented by the muddy layer around 320 cm. Therefore the upper boundary (310 cm) of the muddy layer can be set at 1128 AC, while the lower boundary (340 cm) at 2270 BC. There are no historical records about the river course before 2270 BC on the Great North China Plain, which the river would traverse if into the Bohai Sea. This may suggest the river had possibly used a course further south to enter the Huanghai Sea. As expected, sediment below 340 cm in JX91-7mG showed uni-modal distribution pattern again, which is typical for the direct influence from the Huanghe River. The thickness of this layer is about 30 cm, and it possibly accounts for a period from 8,500 yr BP to 4260 yr BP, during which time there is no evidence to show that the Huanghe River entered the Bohai Sea.
5.2.1 Event Stratigraphy

- peat as indicator of Huanghe presence

It is postulated that the Huanghe River drained into the Bohai Sea in early Holocene, as $^{14}$C dating of the peat in the Bohai Sea and North Huanghai Sea area normally falls into 11,000 - 8,500 yr BP (Qin et al., 1989). The muddy layer at 370 cm is likely to be responsible for that period. Before 11,000 yr BP, the Huanghe River might have run into the Huanghai Sea, because uni-modal pattern is clearly shown in the sediment from 380 -390 cm. At the bottom of JX91-7mG (392 cm), the only peat in JX91-7mG, implying the presence of the Huanghe River, is dated as 11,900 $^{14}$C yr BP. In fact, seismic acoustic survey in the south Huanghai Sea has revealed various buried old channels by Holocene sediment (e.g. in Fig. 5.2-1) dated by $^{14}$C as late Pleistocene or the beginning of Holocene, roughly the same time when the widespread peat is formed (Qin et al., 1989).

![Fig. 5.2-1 Buried Huanghe channel by Holocene sediment in the Huanghai Sea (extracted from Qin et al. 1989).](image)

- magnetic support

Generally speaking when the sediments are direct deposits from the Huanghe River, the magnetic susceptibility is higher as shown in Fig. 4.2-5 for JX91-7G (60 - 210 cm), which is basically a result of channel switching from 1128 AC to 1855 AD. In the Bohai Sea, the magnetic mineralogy of JX91-2A indicated in IRM acquisition curves in Fig. 5.2-2 shows the dominance of magnetites, making the magnetic parameters in JX91-2A (Fig. 5.2-3) easier to interprete. The relevant channel switching changes (ref. to Table 3-5) is also recognisable, e.g. the top 10 cm (relatively high in direct deposits) vs. 10-45 cm (relatively low in indirect deposits).
5.2.1 Event Stratigraphy

Fig. 5.2-2 3D IRM diagram for JX91-2A

Fig. 5.2-3 Magnetic properties for JX91-2A, susceptibility, SIRM and ARM
Sea-level changes

- not an effective ‘event’, but can influence the sedimentary records

Sea-level changes cannot be regarded as an effective event for the Bohai and Huanghai sediments simply because the sedimentary records are difficult to compare due to the difference in water depth and hence the responses. In the case of transgression, the coastal area would move inland, making the rivermouth further away from the coresite and consequently decreasing the hydrodynamic impact from the river; in the meanwhile fresh riverwater will be less influential in determining the chemical composition of seawater and the redox conditions, making the sedimentological, geochemical and biogenic indicators less representative. More importantly, low sea-level would expose the seafloor and no channel switching would be directly recorded, except in the peat.

- transgression: the possible ‘event’

Transgression may be the only possible event to the Bohai and Huanghai sediments which happened in the late Pleistocene and early Holocene. As there have not been many transgressions obvious in the sediments, an event stratigraphy would be difficult to establish. The transgression signal can be seen clearly in the geochemical profiles at the base of JX91-2A (Fig. 5.2-4), where the gradual change to the present geochemical state is seen, though it is not so clear in JX91-7mG (Fig. 3.2-6), owing to the sparse subsampling and Huanghe influence. Because of the difference of water depth, ca. 40 m, the transgression occurred obviously at different times in the Huanghai Sea and the Bohai Sea. Estimated from the sea-level change curve (Fig. 3.2-4), the rising of sea-level from ca. -75 m to -30 m took about 3000 years, close to the time span roughly from 11900 yr BP in the south Huanghai Sea to 8,500 yr BP in the central Bohai Sea, confirming the transgression event at the bases of the two cores.

- channel switching event stratigraphy

Although event stratigraphy of the Bohai and Huanghai sediments is mainly based on the Huanghe channel switching, there are other events that help to establish the event
5.2.1 Event Stratigraphy

Fig. 5.2-4 (a) XRF major elements for JX91-2A
Fig. 5.2-4 (b) XRF trace elements for JX91-2A
5.2.1 Event Stratigraphy

stratigraphy. These events should be able to influence the sedimentation in the two seas in the same or a similar way, e.g. the runoff of the Huanghe River, regional and global changes, apart from the sea-level changes (Fig. 3.2-8). The event stratigraphy for the Bohai and Huanghai Seas is therefore given in Table 5-1 based on channel switching information from both historical records and the inference from previously established channel switching indicators.

Table 5-1 Event stratigraphy for the Bohai and Huanghai Sea sediments

<table>
<thead>
<tr>
<th>Event (channel switchings)</th>
<th>age (a BP)</th>
<th>Bohai</th>
<th>Huanghai</th>
<th>quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>water/sediment interface</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>a</td>
</tr>
<tr>
<td>formation of single course in 1875 AD*</td>
<td>116</td>
<td>12**</td>
<td>19</td>
<td>a</td>
</tr>
<tr>
<td>channel switching to Bohai in 1855 AD</td>
<td>136</td>
<td>14**</td>
<td>25</td>
<td>a</td>
</tr>
<tr>
<td>total switching to Huanghai in 1484 AD</td>
<td>507</td>
<td>45</td>
<td>232</td>
<td>b</td>
</tr>
<tr>
<td>partial switching to Huanghai in 1128 AD</td>
<td>863</td>
<td>140</td>
<td>292</td>
<td>a</td>
</tr>
<tr>
<td>total switching to Bohai in 10 BC</td>
<td>2000</td>
<td>220</td>
<td>325</td>
<td>b</td>
</tr>
<tr>
<td>partial switching to Huanghai in 602 BC</td>
<td>2600</td>
<td>230</td>
<td>335</td>
<td>b</td>
</tr>
<tr>
<td>earliest record into Bohai Sea, 2278 BC</td>
<td>4,270</td>
<td>275</td>
<td>350</td>
<td>b</td>
</tr>
<tr>
<td>River entrance to the Huanghai Sea</td>
<td>8,500</td>
<td>395</td>
<td>370</td>
<td>c</td>
</tr>
<tr>
<td>River through the Bohai Sea area</td>
<td>11,000</td>
<td></td>
<td>380</td>
<td>c</td>
</tr>
<tr>
<td>River to Huanghai Sea (terrigenous peat)</td>
<td>11,900</td>
<td></td>
<td>392</td>
<td>a</td>
</tr>
</tbody>
</table>

NB. Stippled area indicates direct deposits from the Huanghe River, and lightly stippled area for partial such deposits. Depths are for the lower boundaries of Huanghe direct deposits.
* The initial flushing resulted in the dispersion of tiny shell fragment (exceptionally high Ca and Sr) to the Huanghai Sea through the along-shore current.
** estimated according to magnetic measurements (Chen, 1994).
1. the Central Basin, JX91-2A; 2. the South Huanghai Sea, JX91-7mG.
5.2.2 Variations of the Huanghe River and Current System

- two influences: Huanghe River and current system

The event stratigraphy for the Bohai and Huanghai Seas enables the sediments to be correlated through major sedimentation process rather than time. However, each channel switching is not simply a repeat of the previous ones. There are obvious changes in the sedimentation since the beginning of Holocene, but it seems difficult to distinguish whether the influence is from the Huanghe River (sediment supply) or the current system (transport and deposition etc.) or both. The sedimentary records need to be examined for the two influences.

The Huanghe River

- similar depositional environment in Early Holocene

As the direct Huanghe deposits in the Bohai Sea are not available until 4270 yr BP (Table 5-1), the main information about the Huanghe River in the Early Holocene and early Mid-Holocene would only be found in JX91-7mG. The sediment in the lower part of JX91-7mG looks quite similar to its upper part (e.g. Figs. 2.3-3, 3.2-4 and 4.2-7), especially the similar channel switching signals in terms of sedimentology, indicating that the hydraulic conditions and local depositional environment at early Holocene are similar.

- geochemical and mineralogical differences

However, at that time the geochemical characteristics of Huanghe sediment might not be the same as today. Many element profiles generally show a continuous trend down to the bottom of core, except at the channel switching points, which is believed to be caused by mineralogical changes rather than biogeochemical processes. An example of the geochemical change is found in the profile of Ca, one of the Huanghe indicative elements, which does not show a peak at 320 cm as the recent two channel switchings do, though the ratio Ca/Sr still suggests a Huanghe origin rather than other sources (Zhao and Yan, 1993). Fig. 4.2-4 shows more clearly the changes in ferromagnetic minerals, especially in magnetic susceptibility and ARM.
5.2.2 Variations of the Huanghe River and Current System

- Water discharge effect: Mn

As another aspect of hydrology of the Huanghe River, the water discharge, however, is more difficult to assess. A possible way is to examine its effect on seawater dilution and/or redox condition. Redox sensitive Mn and Mn/Al ratio in JX91-2A serve as indicators of foram assemblage associated with the channel switching and seawater dilution, and can get enriched in sediment as authengenic Fe-Mn oxides (unclear magnetic properties) under oxidising environment (Zhao and Yan, 1994). It is possible that Mn in JX91-7mG in the Huanghai Sea would be able to reflect similar changes. In JX91-7mG, it seems that Mn is controlled by channel switching, and that the indirect input from the Huanghe River can contribute ca. 50% of Mn concentration; however, it is not so in early Holocene, though there is also fine-grained fraction in the sediment. This possibly means the channel switching might have little impact on the water mass in early Holocene when the Bohai Sea was actually exposed (sea-level below -30 m) and the Huanghai Sea was much smaller. Since the channel switching did impose an impact on the sediment (fine-grained fraction) and a generally higher Mn was present at that time, the little impact on Mn can be possibly interpreted as a smaller water discharge and oxidising environment in the Huanghai due to the shallow water.

Current system

- The Huanghai Current: early Holocene

The Mn profile in JX91-7m can also be used for current system analysis (ref. to Fig. 4.2-1). When the earliest channel switching occurred at 11,000 yr BP, the sea-level was about -70 m, and the water depth in the Huanghai Trough was about 10 m; however, the Huanghe River mouth was at least 200 km from JX91-7mG, and it would be difficult for the small river flume to transport even the fine-grained sediment that far. There must have been a current in the Huanghai Trough at that time, which could be the initial stage of the present Huanghai Current, flowing down along the west coast of the old Huanghai Sea and transporting the fine-grained sediment. As the water was deeper on the east side of the trough, the old Huanghai Current would possibly first enter the Huanghai Sea from its east side, also under Coriolis force, and then flow anti-clockwise in the trough.
5.2.2 Variations of the Huanghe River and Current System

- the Huanghai Current: later
Riverwater is normally oxidising due to oxygen dissolved in raindrops and during transport, which would influence the shallow Bohai Sea easily, but for the Huanghai Sea from 8500 yr BP on, the redox condition would be mainly determined by the current system. When the Huanghe River entered the Huanghai Sea, the along-shore current from the Bohai Sea today would be weakened, and riverwater jet from the rivermouth to the east would be strengthened, together with that of the Changjiang River; to form the only one giant circular current, instead of two, in the south Huanghai Sea. At that time riverwater, or diluted seawater, was actually less available to JX91-7mG, though mass-flow could be quite active, leading to a more reducing environment at JX91-7mG enclosed by the current and hence lower Mn concentration.

- Korushio Current
The Huanghai current is a branch of the Korushio current originating from the tropical West Pacific (ref. to Fig. 4.2-1). It is suspected that during the last glacial time, the west branch of it was blocked at the shallow Shima Strait; however, it might still be possible to enter the Huanghai Sea area through the Huanghai Trough. From the early Holocene, that branch, though rather weak as compared with today, has been active in the Huanghai Sea.

- discussion
Unfortunately, the sedimentary records here can hardly give more detailed information about the Huanghai Current and Korushio Current variations in the Huanghai Sea in early Holocene owing to the low accumulation rate then and a sparse subsampling interval of 10 cm. It has been noted many datasets can actually lead to the same conclusion, such as channel switching, fine-grained fraction, Mn and Huanghai Current, making it possible to understand phenomenon with various aspects. A good understanding of the sedimentary records will surely help to understand the palaeoenvironmental changes on land.
5.2.3 Palaeoenvironmental Changes in the Chinese Region since the Holocene: Natural and Anthropogenic Influences

Recent sedimentation history is always mixed with natural and anthropogenic influences. It is an ordeal to separate the two completely, and actually it is impossible due to the nature of interplay between them. However, speaking of time before 5,000 yr BP, the palaeoenvironmental changes are mainly of natural processes in the China region; and after that, particularly 2500 yr BP, the anthropogenic influences also play a part. As the changes of sedimentation processes and palaeoceanography in the Bohai and Huanghai Seas could lie basically on land, directly or indirectly, the following will therefore focus on palaeoenvironmental changes in the China region suggested in the sedimentary records from the Bohai and Huanghai Seas.

Natural influences

- accumulation rates in the Bohai and Huanghai Seas

Land erosion of North China, especially the Loess Plateau is the main cause of the Huanghe sediment supply in the Huanghai Sea and the Bohai Sea, though redistribution of previously deposited sediment may also contribute to some particular cores. Calculated from the chronostratigraphy and event stratigraphy (Table 5-1), the accumulation rates in the two seas since the Holocene are listed in Table 5-2.

<table>
<thead>
<tr>
<th>Date from to (yr BP)</th>
<th>accumulation rate (cm/a) Bohai Sea</th>
<th>Huanghai Sea</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 136 0</td>
<td>0.10</td>
<td>0.18</td>
<td>recent</td>
</tr>
<tr>
<td>2 507 136</td>
<td>0.08</td>
<td>0.56</td>
<td>medieval</td>
</tr>
<tr>
<td>3 863 507</td>
<td>0.27</td>
<td>0.17</td>
<td>Late Holocene</td>
</tr>
<tr>
<td>4 4,270 863</td>
<td>0.07</td>
<td>0.015</td>
<td>late Mid &amp; Late Holocene</td>
</tr>
<tr>
<td>5 8,500 4,270</td>
<td>0.03</td>
<td>0.005</td>
<td>early &amp; late Mid-Holocene</td>
</tr>
<tr>
<td>6 11,000 8,500</td>
<td>0.003</td>
<td></td>
<td>Early Holocene</td>
</tr>
<tr>
<td>7 11,900 11,000</td>
<td>0.01</td>
<td></td>
<td>Late Pleistocene</td>
</tr>
</tbody>
</table>

NB, Heavily stippled areas indicate direct Huanghe input, and the lightly stippled ones for partial input and clear ones for indirect input.
5.2.3 Palaeoenvironmental Changes in the Chinese Region since the Holocene:
Natural and Anthropogenic Influences

- **before 5,500 yr BP**
  It is seen that the accumulation rate in early Holocene is rather low, comparable to that in the deep-sea, though the sea-level was much lower. The relatively high accumulation rate in the late Pleistocene is mainly because of the transgression, when redistribution of coastal sediment might be playing an important role. In the Mid-Holocene, the accumulation rate was still rather low, though the Huanghe River deposited directly in the Huanghai Sea and should raise the rate. The rather small increase, however, indicates the total sediment supply possibly remained roughly the same during this period. Therefore the land erosion in Early Holocene and early Mid-Holocene might be fairly small.

- **after 5,500 yr BP**
  At the beginning of late mid-Holocene, the intensity of land erosion might not be too far from that in earlier time, but after 4270 yr BP, the accumulation rate is seen to be increasing rapidly. This is not only reflected in the Huanghai Sea, where the accumulation rate was expected to be around 5 cm/ka, but also in the Bohai Sea, where the accumulation rate more than doubled that for transgression deposits. The late Holocene saw the accumulation rate soaring to the recent level or even higher (Table 5-2). This suggests a substantial increase in land erosion after about 4300 yr BP, and it is very likely to be caused by human activities in North China rather than purely natural processes, though increased precipitation together with an intensified deforestation might also play a role.

**Anthropogenic influences**

- **population from the Mid-Holocene**
  Human activities in North China are concerned mainly with the agricultural development on the Loess Plateau, which was accompanied by destroying previous vegetation. The intensity of the anthropogenic influences should be roughly proportional to the total population, though human's abilities increased more significantly in later periods. The population in China in the last 5000 years can be found in Table 5-3 and depicted in Fig. 5.2-5.
5.2.3 Palaeoenvironmental Changes in the Chinese Region since the Holocene:
Natural and Anthropogenic Influences

Table 5-3 Population in China since 4500 yr BP

<table>
<thead>
<tr>
<th>Year (AD)</th>
<th>population (million)</th>
<th>Year (AD)</th>
<th>population (million)</th>
<th>Year (AD)</th>
<th>population (million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2205 BC</td>
<td>13.55</td>
<td>1290</td>
<td>58.83</td>
<td>1910</td>
<td>368.15</td>
</tr>
<tr>
<td>221 BC</td>
<td>20.00</td>
<td>1393</td>
<td>60.54</td>
<td>1912</td>
<td>405.81</td>
</tr>
<tr>
<td>2</td>
<td>59.59</td>
<td>1578</td>
<td>60.69</td>
<td>1928</td>
<td>474.79</td>
</tr>
<tr>
<td>105</td>
<td>53.25</td>
<td>1685</td>
<td>101.71</td>
<td>1931</td>
<td>421.70</td>
</tr>
<tr>
<td>122</td>
<td>48.69</td>
<td>1724</td>
<td>126.11</td>
<td>1937</td>
<td>438.40</td>
</tr>
<tr>
<td>140</td>
<td>49.15</td>
<td>1741</td>
<td>143.41</td>
<td>1947</td>
<td>455.59</td>
</tr>
<tr>
<td>280</td>
<td>16.16</td>
<td>1751</td>
<td>181.81</td>
<td>1949</td>
<td>541.67</td>
</tr>
<tr>
<td>581</td>
<td>44.50</td>
<td>1762</td>
<td>200.47</td>
<td>1954</td>
<td>602.66</td>
</tr>
<tr>
<td>607</td>
<td>46.01</td>
<td>1790</td>
<td>301.48</td>
<td>1964</td>
<td>704.99</td>
</tr>
<tr>
<td>740</td>
<td>48.14</td>
<td>1795</td>
<td>297.00</td>
<td>1969</td>
<td>806.71</td>
</tr>
<tr>
<td>755</td>
<td>52.91</td>
<td>1812</td>
<td>333.71</td>
<td>1974</td>
<td>908.59</td>
</tr>
<tr>
<td>1080</td>
<td>33.00</td>
<td>1834</td>
<td>401.00</td>
<td>1981</td>
<td>1000.72</td>
</tr>
<tr>
<td>1110</td>
<td>46.73</td>
<td>1840</td>
<td>412.81</td>
<td>1988</td>
<td>1110.26</td>
</tr>
<tr>
<td>1223</td>
<td>76.81</td>
<td>1845</td>
<td>421.35</td>
<td>1995</td>
<td>1200.00</td>
</tr>
</tbody>
</table>

Fig. 5.2-5 Population in China since 4500 yr BP (China’s Population, 3/7/1995)

- 2500 - 5500 yr BP: also geochemical support

Although the total population in China about 4500 yr BP had reached 13.55 million, and agriculture had started, the anthropogenic influences remained at a low level. Later in this period, however, saw the beginning of the famous Warring States in Chinese history, when the land began to suffer large scale deforestation. Forest burning was widely used as an important attacking and defending method (personal communications with Prof. Yang Zigeng, 1994), and there was an increasing demand for timber in construction and for fuel. Therefore land erosion should have started about 2500 yr BP (ref. to Table 5-2), though the ‘Big Flood’ in China, as in other part
of the world as mentioned in the Bible, began about 2000 years earlier. The generally small land erosion in the whole period is also reflected in Ca, which presents a trough instead of an expected peak during this period, contrary to most elements. If the high Ca at the top is due mainly to the fine-grained loess sediment, the lack of Ca might indicate the absence of such sediment. Instead, as topsoil is leached of Ca, this may also indicate the topsoil erosion accounted for a larger proportion in the overall sediment. Although this looks similar to the present topsoil erosion geochemically, it is not so considering the small absolute amount of sediment deposited. However, this might suggest the beginning of deforestation on the loess Plateau.

- after 2500 yr BP: magnetic support

The population surged at around 2000 yr BP, nearly tripled within 200 years, posing greater pressure on the ecosystem on land. The characteristic of Chinese agriculture is mainly farming rather than herding, so the vegetation on the Loess Plateau must be destroyed at a greater pace. The most powerful country at that time (as seen in the famous Qin Dynasty Terra Cotta in Xi’an) was on the now Loess Plateau, therefore the human activities must have contributed largely to the worsening of environment on the Loess Plateau. This process continued to today and can be seen in magnetic susceptibility of JX91-7G, which, similar to that in JX91-3B and JX91-2A, shows the soil erosion history by the rising trend in the core, on top of the first order variations caused by Huanghe channel switching (Fig. 4.2-5).

- continental aridity and precipitation.

The accumulation rates in the Bohai and Huanghai Seas are seen to be increasing since the Late Pleistocene, except very recently due to strengthened river harnessing. This is definitely a result of increasing soil erosion, but may not necessarily be due to increasing water discharge. Actually, turbidity of the river accounts for much of the increase. Seen from Table 3-4, the fresh water foram only appears once about 4200 years ago, indicating the water discharge might have never exceeded that since then, which is in line with the conclusions made from studies on pollen etc. on the plateau (Fig. 5.2-6). It has been noted that the coarsening of the sediment after the transgression occurred following the appearance of the typical yellowish Huanghe
sediment, possibly suggesting the intensification of human activities about 4,000 years ago. From the increased erosion, we can infer that the vegetation on the plateau decreased, very likely owing to the actual declining in precipitation or more arid climate on the plateau. Human activities have definitely played a part in the continental aridity, very likely through deforestation and over-grazing.

Figure 5.2-6 Temperature on the Loess Plateau since 10,000 yr BP (Sun et al., 1991)
5.3 Palaeoclimatology and Palaeoenvironment in the Arabian Sea since the Late Pleistocene

- section arrangement

Similar to the structure of Section 5.2, event stratigraphy will be established for the Arabian cores in 5.3.1, and the monsoonal variations will be examined in 5.3.2 based on the event stratigraphy and chronostratigraphy, followed by the interpretation of sedimentary records in terms of palaeoenvironmental changes in the Arabian region in 5.3.3.

5.3.1 Event Stratigraphy

- event stratigraphical markers: related to monsoonal variation and maybe secondary

In Arabian sediments comprised of genuine aeolian deposits, the event stratigraphy can be established on the basis of the monsoonal variations. Generally speaking, almost all of the stratigraphical changes in sediments from the Gulf of Oman are directly associated with monsoonal variations, either in wind speed or in wind direction (dust source), which usually relate to each other in the Arabian Sea (see also 5.3.2). It should be noted that the event stratigraphical markers associated with monsoonal variations may not be synchronous in every part of the sea, and sedimentary records of the monsoonal events may not be purely 'physical' either. Unlike the emphasis placed on chronostratigraphy, geochemical data will be applied more extensively to reveal the secondary changes of oceanographic responses to the monsoonal variation, mainly coastal upwelling system. Terrigenous signals used in core correlation have been correlated using absolute concentrations of element, whilst biogeochemical signals would be correlated using element ratios mainly, which can show the extent of relative changes, enrichment or depletion.

*Events in the Arabian Sea (Gulf of Oman)*

- identification of four Arabian events

The events can be classified according to the extent of the monsoonal variation, however, for the purpose of establishing correlation between the Arabian cores in the
5.3.1 Event Stratigraphy

whole region, local events, e.g. coastal dust storms, will not be included. The big events are mainly reflected in geochemical data and particle size parameters. Known from the chronology of the Arabian cores (chapter 3), core 1739 would have recorded a peak of foraminifer at about 9000 yr BP as suggested in many cores in the Arabian Sea (Prell, 1989). Although no palaeontological work has been carried out, the calcium concentration in core 1739 can represent the relative content of forams in bulk sediment (chapter 3), and Ca/Al can be regarded as an indicator of intensity of upwelling, rather than a simple dilution effect. This should be the oldest event in all the Arabian cores here and can be called Arabian Event I. Another distinct feature in core 1739 is the rapid shift of particle size distribution from poly-modality to unimodality, which can also be found in core 1734(a). This must have indicated an abrupt change in aeolian processes and should be chosen as the second event, AE II (Arabian Event II). Although only a continuous decline of Ca or Ca/Al is noticed in core 1739 (Figs. 3.2-18 and 5.3-1), there is a drastic drop in the nearshore cores, and the foot of the Ca plateau can be considered a marker of this event, AE III. The occurrence of uni-modal coarse sediment in the nearshore cores can be regarded as the fourth event, Arabian Event IV.

Event stratigraphic markers
- direct and indirect (or inferred) markers

The primary features of the Arabian events, applied as above to define these events, can also serve as event stratigraphic markers; however, in the case when these markers are not so distinct, other relevant subsidiary markers may also be used. Cr/Al, for instance, can serve as an indicator for the mountainous input from the northeast mountain area of Oman (Shimmield and Mowbray, 1991, and Shimmield, personal communication). As a matter of fact, more event markers can be determined based on the already-known mechanisms rather than direct correlation. As these events are associated with the monsoonal variation, other monsoon-related markers, e.g. Sr/Al, may also serve as a marker similar to Ca/Al in the Arabian Events I and III, due to the association between Sr and biogenic calcium carbonate seen also in the Bohai Sea (section 5.1) (Fig. 5.3-1).
Fig. 5.3-1 Typical geochemical ratios for the Arabian cores
5.3.1 Event Stratigraphy

- main markers used
The main event stratigraphic markers are listed in Table 5-4. They are either associated with the most distinguishable features in the Arabian Sea, the upwelling and palaeoproductivity, or are seen as clear sedimentational signals, which can hardly be affected by sediment disturbance or other minor processes.

Table 5-4 Features of the events in the Arabian Sea since deglaciation

<table>
<thead>
<tr>
<th>Event</th>
<th>descriptions</th>
<th>primary markers</th>
<th>other markers</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>forams peak</td>
<td>Ca/Al (or Ca) peak</td>
<td>Sr/Al</td>
</tr>
<tr>
<td>II</td>
<td>ITCZ*</td>
<td>bi- to uni-modality</td>
<td>Cr/Al</td>
</tr>
<tr>
<td>III</td>
<td>vanishing of upwelling</td>
<td>decline of Ca/Al (or Ca)</td>
<td>Sr/Al</td>
</tr>
<tr>
<td>IV</td>
<td>Wahiba sands input</td>
<td>coarse uni-modal</td>
<td>Zr/Al, Ti/Al</td>
</tr>
</tbody>
</table>

* InterTropical Convergence Zone: the zone along which the wind systems of the two hemispheres converge.

Event stratigraphy

- establishment
Event stratigraphy for the Arabian cores can be established according to the event stratigraphic markers (Table 5-4) in conjunction with the chronostratigraphy (chapter 3). It is worth noting that the depths of these events cannot be made very accurate due to the discrete nature of the points, and the dates derived from the chronostratigraphy are only the best estimates.

Table 5-5 Event stratigraphy for the Arabian cores with dates

<table>
<thead>
<tr>
<th>Event</th>
<th>1735 depth</th>
<th>1735 date</th>
<th>1736 depth</th>
<th>1736 date</th>
<th>1734a depth</th>
<th>1734a date</th>
<th>1733 depth</th>
<th>1733 date</th>
<th>1739 depth</th>
<th>1739 date</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>II</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>3 cm 40 a</td>
<td>3 cm 188 a</td>
<td>6 cm 650 a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Depth is in cm down the length of core and date is in calendar years BP.

Discussion

- ‘moving’ event
The event stratigraphy in the Arabian Sea looks quite different from the chronostratigraphy. It is clear that the same event can happen at different times in different places. The general spatial pattern of the major events on time scale is moving landward from central Gulf of Oman to the Peninsula, though at different
paces. This moving spatial pattern of event is apparently due to the migration of the southwest monsoon across the Gulf of Oman.

- **example: core-top coarsening**

Another clear example for the difference between event stratigraphy and chronostratigraphy is from the core tops of 1735, 1736 and 1734a, where abrupt coarsening of sediment is noticed. If the boundary of this coarsening is taken as an isochron marker, higher accumulation rate in core 1734a than in cores 1735 and 1736 will be inferred, which is against the observations in nature (e.g. Sirocko and Sarnthein, 1989). Actually, they were switched at different times (chapter 4), though they are indeed the same processes. Therefore, although a signal is produced by the same event, it may not be at the same time.

- **other events**

There are a number of other minor events in the sedimentary records of the Arabian cores, which are not classified in Table 5-4, but may have special significance, e.g. the landing of the southwest monsoon on the Arabian Peninsula (5.3.2) and dust storm or cyclone deposits.
5.3.2 Monsoonal Variations

- two aspects: direction and strength

Combination of the event stratigraphy and the chronostratigraphy enables us to examine the monsoonal variations in the Arabian Sea since the Late Pleistocene, in two aspects, the monsoonal direction and strength.

- major players: the southwest monsoon and northwesterlies

The seasonally reversed southwest and the northeast monsoons are two key players acting at different times in a year. In summer time, the southwest monsoon is accompanied by the northwesterlies in the Gulf of Oman. Due to the weakness of the northeast monsoon in winter time, the southwest monsoon and the northwesterlies become the two major monsoons in the Arabian Sea. This scenario was believed to be continuous from the past, at least from the Late Pleistocene (Sirocko et al., 1991, Clemens and Prell, 1990, Duplessy, 1982). The relatively weak northwesterlies is actually an array of monsoons from the Mesopotamia (Makran), the Gulf, the Arabia and the Red Sea, and it is often neglected in studies of the ancient Arabian monsoon system. As we will see, although the northwesterlies and the southwest monsoon did not play in the Arabian Sea exactly like yin and yang, they have been determinants to each other, either in their position and direction or in their strength.

**Wind direction**

A. Present windfield

- present 3D wind-field

The southwest monsoon and the northwesterlies merge at their boundary after the latter turns about 90° to southwest. It is noted that part of the northwesterlies are still blowing toward the Indian sub-continent at a greater altitude over the southwest monsoon, though the surficial winds become parallel (e.g. Sirocko et al., 1991).

- present ITCZ

This boundary at the northwest flank of the southwest monsoon and southeast flank of the northwesterlies is known as the ITCZ today (Intertropical Convergence Zone)
5.3.2 Monsoonal Variations

(e.g. Sirocko et al., 1991). The ITCZ generally tends to be distorted northwards over land in the northern summer, because the continental masses heat up faster than the ocean in summer and cool faster in winter (Open University, 1993).

B. Palaeo-windfield

• palaeowind direction: recent change

As seen from the sedimentary records, particularly the dust source-related records, the palaeowind direction must have been different from today’s. An example is from the top sediments in the nearshore cores, where both the geochemical and particle size characteristics have changed. Wind strength itself could not cause such changes, so the wind direction in association with dust sources must be different, and hence the palaeowind must have blown more easterly to avoid the Wahiba Sands.

• the Late Pleistocene: northerly winds

Geochemical data show a significant change (e.g. Ba/Al) in the lower part of core 1739. Since Ba/Al shows different relationship with Ca/Al in cores 1739 and 1734a (Fig. 5.3-1), Ba/Al may be more related to dust source rather than biogenic activities in the Gulf of Oman; so at the beginning of deglaciation, ca. 14,000 yr BP, the northwesterlies might have blown further east and taken control of the Gulf of Oman, making deposition of the Red Sea dust impossible at the coresite of 1739. Meanwhile, the exposed Persian Gulf and the southern Iran might have provided a lot of coarse dusts (chapter 4). The winds at that time might have been more like ‘northerlies’ rather than northwesterlies in the Gulf of Oman, and the ITCZ would be far south to the coresite (ref. to Fig. 5.3-3a).

• support of the ‘northerlies’: terrestrial records

It is difficult to find evidence in the sediments to directly indicate palaeowind direction, though dust source indicators are good for that. However, such evidence is relatively easy to obtain on land with more reliability. Sand dunes are considered to have long or short memories depending on their ability of holding the shape. A consistent and strong wind can maintain a dune ridge, which cannot be modified by gentler succeeding winds. The huge ridges of the central Wahiba Sands, also termed
5.3.2 Monsoonal Variations

Fig. 5.3-2 Palaeo-windfield recorded in the Arabian deserts (a) central Iran near Kerman, (b) eastern and (c) southern Rub al Khali desert in the Arabian Peninsula (Short et al., 1976).

mega-memory dunes, probably remembered the winds of the last glacial periods (Winser, 1989). Such linear dunes, also called longitudinal dunes or seifs, are widely found in Arabia (Figs. 1.1-5 & 5.3-2), which are created normally in areas of uniform sand accumulation under generally high velocity winds of variable direction (Boggs, 1987). Therefore the seifs in the Wahiba Sands, the Rub al Khali and Iranian deserts
Fig. 5.3-3 Summer Indian palaeomonsoon over the Arabian Sea since the late Pleistocene
5.3.2 Monsoonal Variations

(c) 6,000 yr BP

(d) recent
5.3.2 Monsoonal Variations

have actually shown the high wind speed and the northwesterly direction in central Iran, northerly direction in the Wahiba Sands and northeasterly direction further inside the Arabian in the last glaciation. As the last glaciation is well comparable to any previous glaciations in all indices (e.g. Clemens and Prell, 1991, Shimmield and Mowbray, 1991), all these seifs are in fact relics of the last glaciation. It is quite clear that the wind direction changed around the peninsula from northwesterly to northeasterly, and it can be postulated that the wind direction in the Gulf of Oman should be mainly northerly or slightly northwesterly in the west (Fig. 5.3-3).

• deglaciation period: northwesterlies

This ‘northerlies’ seemed to change its direction rapidly as deglaciation went on, since dusts from the Arabia began to appear at the coresites at ca. 13,000 yr BP or earlier. The northwesterlies began to dominate the northwest Arabian Sea since then and remained rather stable in the Gulf of Oman, though under the pressure from the gradually building-up southwest monsoon in the south (Fig. 5.3-3b). As the sedimentary records are mixed with signals of wind strength and ITCZ, the ITCZ migration across the Arabian Sea is rather difficult to determine. Nevertheless, it would be mainly in the central Arabian Sea aligning northeast (ref. to Sirocko et al., 1991) with a possible intrusion into the peninsula due to a possible split of the northwesterlies. It is still possible that the ancient southwest monsoon played a part in the sedimentation, though winter monsoons were also responsible. Cyclones seemed quite common during the deglaciation time.

• from the Mid-Holocene: southwest monsoon

Global deglaciation is thought to have terminated in early Holocene, but maybe not until mid-Holocene in some areas like the Tibetan Plateau. Palaeomonsoon in mid-Holocene is hard to determine from only a few scattered coresites, but it may be better recorded on land. As a general indicator of the palaeomonsoon position, the past ITCZ may be traced according to the records on the Indian sub-continent, where the southwest monsoon has served as the main moisture supplier (Singh et al., 1974, Swain et al., 1983, Ely et al., 1996). The first appearance of southwest monsoon at coresite of 1739 occurred at about 5500 yr BP, well in line with the land records
5.3.2 Monsoonal Variations

about the migration of rainbelt in India. Since 5,500 yr BP, the southwest monsoon has dominated the coresite of 1739 and moved on to further west to the northwest of Arabian Sea (Fig. 5.3-3 c and d). The northwest flank of the southwest monsoon reached the coresite of 1733 at about 2,500 yr BP and the coresite of 1734a at about 500 yr BP (Table 5-5). It is seen to be moving further west at present according to the sedimentary records in the nearshore cores 1735, 1736 and 1734a.

C. Palaeo-ITCZ

- migration of ITCZ

The migration of ITCZ across the Arabian Sea seems to be a continuous process since LGM (the Last Glacial Maximum) (Van Campo, 1986, Bryson and Swain, 1981), though it is believed the pace may vary in different periods, and short-term reverse of movement might also occur. However, no obvious evidence is available so far to identify the short term reversals, due to the resolution of the sedimentary records and the small scale and time-span involved. Generally speaking, the ITCZ migrated fairly rapidly from the Indian continent to the Arabian Peninsula, taking 22°N (as at Ras al Hadd) as a reference line. If the front between the southwest monsoon and the northwesterlies left India at ca. 6000 yr BP, it is reasonable for it to reach coresite of 1739 at ca. 5000 yr BP, and land on the Arabia at ca. 2.5 ka and then traverse the Wahiba Sands at ca. 500 yr BP. The movement of on land, however, has slowed down significantly in the last few hundred years.

Wind strength

- southwest monsoon: three stages

The other aspect of the windfield change in the Arabian Sea is wind strength, which used to be stressed on so much that it was used to explain all the main phenomena in this area (Prell, 1984, etc.). The strength variation of the southwest monsoon seemed more important than that of the northwesterlies, because it responds more sensitively to the palaeoenvironmental changes in the Arabian Sea. The wind strength of southwest monsoon seems to have experienced three major stages, A) since the last deglaciation till mid-Holocene (ca. 14,000 - 8500 yr BP), B) the whole mid-Holocene (8500 - 2500 yr BP) and C) the whole late-Holocene from 2500 yr BP to present.
5.3.2 Monsoonal Variations

A. Deglaciation and the early Holocene (Core 1739)

- Time span and depth range

This period spans from 14,000 to 8500 yrs BP. The only core from the Arabian Sea bearing the records of this period is core 1739. At 37 cm, the core is dated at 11,000 calendar years BP, so the bottom of core can be derived as 14,000 calendar years BP, and the depth for 8500 yr BP is about 28.6 cm. The last deglaciation is believed to start around 14,000 and lasted about 6 ka (Williams et al., 1993). During the glacial period, wind speeds were generally higher by a factor of 1.3 to 1.6 (Petit et al., 1981), and in the transitional deglaciation period the wind strength must have changed drastically with events including the Younger Dryas and maximum solar insolation.

- AE I

AE (Arabian Event) I is characterised by a peak of productivity in the whole Arabian Sea around 10,000 yr BP. This event is widely speculated (e.g. Prell, 1984) to be a result of a stronger southwest monsoon at the beginning of the Holocene, based mainly on foraminiferal records in sediment cores from central and south Arabian Sea. However, this conclusion may not be universally correct, because the sites of these cores did not cover the whole Arabian Sea, especially the sensitive north Arabian Sea (Gulf of Oman), and it was drawn rather unconvincingly (see below).

AI. a much stronger southwest monsoon?

- Two possible evidence: solar insolation and albedo on the Tibetan Plateau

It is hard to imagine the southwest monsoon was so much stronger in proportional magnitude as indicated by the foram signals. The declining Ca/Al might be related to the solar insolation, but not necessarily to the strength of southwest monsoon, in light of other ways to produce a stronger upwelling in the Arabian Sea (see below). However, it is right to point out two major processes in this regard: the solar insolation and the albedo on the Tibetan Plateau (Prell, 1984).

- Logic problem: was it the southwest monsoon?

It is calculated that the solar insolation culminated around 10,000 yr BP and the upwelling indicator, Globigerina bulloides, reached its maximum around 9000 yr BP.
5.3.2 Monsoonal Variations

(e.g. Prell, 1984, Naidu and Malmgren, 1995). Considering the relatively small delay of the foraminiferal maximum, it is quite reasonable to infer that the maximum upwelling was associated with the solar insolation, but the question is how this happened. Although the monsoon prevailing in the Arabian Sea today is the southwest monsoon, it is not logically correct to assume that the palaeomonsoon system was the same in the past. To make a stronger southwest monsoon reasonable, the albedo on the Tibetan Plateau has to be smaller than it is today, but this is not supported by records from the Tibetan Plateau (section 5.4). The strength of southwest monsoon could reach a small peak around 10,000 yr BP, but for a different reason (see below).

A2. a more efficient way?

• blow smarter, not harder

As the upwelling system in the Arabian Sea is mainly wind-driven, it is logically sound to assume the upwelling in the Arabian Sea was also driven by monsoons in the past. It is quite true that the forams, *G. bulloides* in particular, are indicators of the strength of the upwelling system, so at about 10,000 years BP, it is very likely the wind-driven upwelling in the Arabian Sea had reached its maximum. Nevertheless, it is not necessary to postulate a stronger southwest monsoon for the maximum. In fact a stronger upwelling can be produced either by an enhanced wind strength or in a more efficient way, i.e. different monsoons with favourable direction. Therefore the efficiency of wind-driving should also be considered in the build-up of an upwelling system, which seems to be often neglected unfortunately.

• efficiency changes with wind direction: coastal Iran as an example

Wind direction relative to coast line is important in driving coastal upwelling, as this determines the driving efficiency. Because of this, upwelling is not found in every monsoon-dominated coastal area, no matter how strong the wind is. The south coast of Iran shows a narrow upwelling centre (Fig. 5.3-4), which cannot be driven by the southwest monsoon (Fig. 5.3-3d); instead, it is actually driven by the northwesterlies from the middle east. Although the northwesterlies in that area is relatively weak, the intensity of upwelling in terms of productivity is not weaker than that off Oman.

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Ekman effect in low latitude

The present upwelling system off Oman is mainly sustained by the so-called Ekman effect, which is actually originated from the Coriolis force (ref. to Appendix B8). Apparently, concerning the transportation of surface water offshore, the Ekman effect is much less efficient than the direct transportation by offshore wind, because the Ekman effect is actually a secondary effect of the initial surface water movement (see also Appendix B8). Moreover, Coriolis force has no horizontal components on equator and a small component near equator, which means Ekman effect is even smaller than it is at high latitude. In fact, the surface current in the Arabian Sea is quite in line with the wind field with little typical Ekman effect (e.g. Bearman, 1991). Therefore the northwesterlies, blowing at a much better angle than the southwest monsoon at the Oman coast and an outward angle at southern Iran coast, are believed to be much more efficient in driving the upwelling system. According to Fig. 5.3-1, the northwesterlies is dominating the Gulf of Oman, and must have driven a much stronger upwelling system than the present one off Oman around 10,000 yr BP.
A3. wind strength estimation

- misleading upwelling intensity to wind strength

As seen in the example of the northwesterlies at the Iranian coast where wind-driving efficiency plays a key role, it is hard to estimate wind strength of monsoons based on the upwelling intensity, because wind direction has to be considered as well. Moreover, orbital parameter change can also influence the *in situ* wind strength.

- orbital influence: advance of the southwest monsoon

Wind strength during this period (post-glaciation and early Holocene) was relatively stable, as seen in the particle size distribution. However, a careful examination reveals a finer fine-grained fraction at the time of maximum upwelling. This can be interpreted as a weakening of a northwesterlies' branch from the Arabia under the influence of a stronger southwest monsoon, but earth orbital change at that time has made it more complicated. It is widely accepted that the change in the earth's orbital parameters is the driving force of the palaeoenvironmental change, among which precession of the earth is the most important one in Quaternary. Astronomical calculation shows the obliquity of the earth's axis is changing between $22^\circ$ and $24.5^\circ$ periodically every 41 kyr, and at about 9000 years ago the obliquity reached its maximum at $24.5^\circ$ (Milankovitch, 1920, Berger, 1976, Berger, 1978). This means the Tropic of Cancer moved over 110 km up north during this period, shifting the general position of the southwest monsoon northward. Therefore it is difficult to tell whether a stronger southwest monsoon is a result of this shift of position or simply due to a stronger heat low in south Asia, or both.

- relatively stronger southwest monsoon at 10 ka BP

The precession period is 25.7 kyr and the hiatus is in summer time at around 10,000 yr BP, hence the southwest monsoon could be stronger generally at that time, which is confirmed by Naidu and Malmgren (1996). However, it does not necessarily mean the northwesterlies were weaker. The increase of fine fraction of the sediment at that time may only indicate the change in general position of the southwest monsoon owing to the obliquity change. In fact, the intensification of heat low in southeast Asia can drive a stronger northwesterlies too.

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5.3.2 Monsoonal Variations

- position of the southwest monsoon and continental heat low: varying wind strength

The northward movement of the northwestern front of the southwest monsoon during the early Holocene is also observed in the west Arabian Sea (Sirocko et al., 1993). It is estimated that the continental heat low was strongest during this time (Kutzbach and Guetter, 1986), however, the northernmost position of the southwest monsoon (Sirocko et al., 1993) may not be a natural result of this intensification, and the latitudinal position of the continental heat low determined by orbital parameters may also be responsible (section 5.4.2). As the solar insolation decreased and obliquity of the earth axis reduced in the late early Holocene, the southwest monsoon withdrew to further south and decreased its strength, but not to what it was at the beginning of deglaciation. The strength of the southwest monsoon during early Holocene might be modestly stronger than it was at the beginning of deglaciation, but the upwelling signals and the frontal positions have led to exaggeration of its strength.

B. Mid and late Holocene

• a transitional period

This period saw the rapid transition of the Indian Ocean monsoonal system over the Arabian Sea. This is the period when many palaeoclimatic events occurred and the climate for the present day was settled.

B1. wind strength in different periods

• early Mid-Holocene

The southwest monsoon gradually diverted the northwesterlies to blowing east and bringing dust from north Arabian Peninsula to coresite of 1739 as shown by a dramatic drop in Ba/Al. This phenomenon was also noticed by Sirocko et al. (1993) further south in the Arabian Sea. Wind strength began to increase continuously at the beginning of mid-Holocene, and at around 5500 yr BP a drastic shift in wind strength took place at coresite 1739.

• AE II

This event did not impact significantly on sediment geochemistry, which shows a smooth transition, but on the particle size parameters. Wind strength of the southwest...
monsoon at that time should be stronger than before, though might not be stronger than the Arabian northwesterlies. The intensification of the southwest monsoon at ca. 5500 yr BP is possibly related to the albedo change on the Tibetan Plateau (see section 5.4), which strengthened the heat low in south Asian significantly, produced a much southwest monsoon and shifted its position in the Arabian Sea to further north.

- **late Mid-Holocene**
  
  From 5500 yr BP, the southwest monsoon began to dominate the north Arabian Sea. Wind strength at coresite of 1739 remained quite stable in the rest of the mid-Holocene, though fluctuation is seen both in geochemical indicators (Ti/Al) and particle size parameters (e.g. Md).

- **Late Holocene**
  
  The late-Holocene saw the continuing strengthening of the southwest monsoon in north Arabian Sea, indicated clearly in greater Md and better sorting of particles, though variable and generally smaller Ti/Al, Zr/Al and Cr/Al ratios are also seen during this period (Fig. 5.3-I). The geochemical data can be better interpreted as changes in sediment sources rather than wind strength, because particle size distribution is determined directly by its transporting wind. Geochemical wind strength indicators (e.g. Ti/Al) should be used only in sediments from the same source, so that relative wind strength can be shown.

- **recent**
  
  In the last millennium, the strong southwest monsoon has dominated most of the north Arabian Sea, except the west Gulf of Oman. As we can see, the most recent southwest monsoon is very likely the strongest since late Pleistocene, taking advantage of the small albedo on the Tibetan Plateau and the wide-spread continental low surface air-pressure from the plateau to the middle-east (section 5.4). However it may still not be able to produce the largest upwelling system in the Arabian Sea; on the contrary, the windfield change under the growing southwest monsoon might have been creating a monsoonal pattern in the Arabian Sea that limits the scope of the upwelling system and even the development in some areas.
5.3.2 Monsoonal Variations

B2. wind strength in cores

- core 1734a

It is interesting to note the influence of southwest monsoon in the Gulf of Oman, as revealed in core 1734a. The coarsening of particle size upward in the nearshore cores reflected the strengthening of the southwest monsoon and the northwesterlies combined. At coresite of 1734a, after the termination of the coarse dust input in the lower part of core is a period of relatively weak wind. This period lasted about 1000 years before a strengthening of the southwest monsoon at the coresite about 1400 yr BP, as calculated from the trough from 20 to 13 cm in Ti/Al and Zr/Al profiles. Once it became stronger, it evaded coresite 1736 and finally destroyed the upwelling system in the west Gulf of Oman as seen today (Fig. 5.3-4).

- support from Himalayan lake records

Interestingly, similar records are found in the Himalayan lakes which are susceptible to southwest monsoonal condition. It is found that from c.a. 580 BC to 300 AD the region experienced precipitation similar to the present; whereas from 300 AD to 1400 AD, the monsoon was relatively subdued (Kumumgar et al., 1995). This means the southwest monsoon strengthened at ca. 2.5 ka BP and lasted for about 900 years, and then weakened for 1100 years. They generally agree with the sedimentary records in core 1734a, where wind strength (of the northwesterlies) weakened at ca 2.4 ka BP for 1000 years and got strengthened for 760 years (13 - 6 cm in Zr/Al and Ti/Al). This generally good land-sea correlation between the two records confirms that the southwest monsoon determines the regional climatic system across the Arabian Sea to the Himalayas and also controls the northwesterlies from the Arabia.

- the recent western Gulf of Oman

From 560 yr BP, the southwest monsoon obviously increased its strength and made the southeast flank of northwesterlies deposit Wahiba sands in the nearshore coresites. In period when the northwesterlies dominated the nearshore area, core 1734a had coarser sediment than cores 1735 and 1736. This is possibly because the stronger northern flank of the northwesterlies blew quite straight downward from the Gulf, while the weaker southwest flank, after being diverted by the southwest monsoon, blew to the sea near the Wahiba Sands.
5.3.2 Monsoonal Variations

- **core comparison: landing of the southwest monsoon on the Peninsula**
  
  It is found at the southeast side of the Wahiba Sands that the sand dunes are being propelled inland at an average rate of 10 m annually, and left the coast some 4 ka ago. This is possibly the earliest time when the northwesterlies began to be forced back. Whilst this movement of sand dunes may be driven by the south branch of the northwesterlies being compressed by a stronger southwest monsoon, it is not necessarily the time when the southwest monsoon touched the Arabian land. The major confrontation of the two monsoons might happen before the southwest monsoon landed on the peninsula. Since dust is normally transported along the streamline of windfield, seen from the location of core 1739 relative to the peninsula, the termination of Arabian dust and initiation of southeast Oman coastal dust from this coresite should be regarded as approximately the same time as the southwest monsoon landed on the peninsula. This signal can be found at 8 cm in core 1739 in Zr/Al and Ti/Al profiles (ref. to Table 4.3-5), which is about 2.4 ky BP.

- **landing signal in core 1733**
  
  Similar signal should also be found in core 1733, as it locates near the strip-like area along the landing zone. The signal at 11 cm in core 1733 may be produced by the landing southwest monsoon, dated at around 1.8 ky BP. As Wahiba Sands is further west to the southwest monsoon streamline than to the southeast coast, the Wahiba dust should appear later in the nearshore cores, e.g. 650 years BP in core 1734a. The first touch on the peninsula by the southwest monsoon seems to have different dates depending on the core locations, however, the core 1739 can best reflect the landing and the time of the first landing since deglaciation should be around 2.4 ky BP.

- **the Yin Yang pattern**
  
  It seems whenever the southwest monsoon was relatively weakened, the northwesterlies would outplay it and changed its path to further east accordingly; and *vice versa*. These two summer monsoons form a pattern similar to the *Yin-yang* in the Gulf of Oman. It is not appropriate to say which monsoon is active and which is passive. In fact, both of the monsoons are reacting to the climatic change on the surrounding land, especially the south and southeast Asia.
C. Monsoonal variation since the late-Pleistocene

- final result
When the variation of wind strength is considered together with wind direction, the monsoonal variation in the Arabian Sea since the late Pleistocene can be best figured out (Fig. 5.3-3), with the help of the analysis on the continental heat low.

- difficulties involved
The monsoonal variation in the Arabian Sea is difficult to determine from only a couple of cores. In fact, two scenarios can result in \textit{in situ} monsoonal variation:

1) The whole wind-field is shifted, usually driven by earth orbital forcing. If the wind-field is not universally constant (as in this case), the shift will cause apparent monsoonal variations, many of them may be inconsistent and sometimes contrary in different coresites, though the actual process is straightforward and simple.

2) The whole wind-field is changed. If only wind strength changes, things will be quite predictable. However, in many cases, wind direction is the most changeable factor and is normally associated with changes in wind strength. In fact, the two normally change together, making the sedimentary records at individual coresites more difficult to compare and correlate.

If all the variations are mixed together, care must be taken in interpreting the records of monsoonal variations in sediment.

\textit{Further discussion}

A. Stronger southwest monsoon in the past?

- maximum upwelling ≠ strongest southwest monsoon
A stronger southwest monsoon was proposed to be directly based on the maximum of an upwelling indicative foraminifera \textit{G. bulloides}. As a matter of fact, even though a stronger wind-driven upwelling was recorded at that time, it does not necessarily mean a stronger southwest monsoon. The southwest monsoon was assumed to be the cause of the stronger upwelling probably because it is currently the predominant monsoon in the Arabian Sea. However, if the northwest monsoons were taken into account, the explanation could be equally satisfactory. Moreover, when considering the cause for the stronger upwelling, the northwesterlies would do even better. We
can only say that there was an enhancement of upwelling at around 9,000 yr BP in the Arabian Sea, and it was monsoon-driven and associated with solar insolation, but not that the palaeo-monsoon must be the same southwest monsoon as observed today.

- doubtful model value

It has been noted that some palaeoclimate model yielded a stronger southwest monsoon (Kutzbach et al., 1993), however, the model values need to be examined and even the model itself, because most models are 2D instead of 3D, which is apparently incapable of tackling problems raised by 3D orographic effect (geographical high), which plays a very important part in the Indian monsoon system.

- no much smaller albedo on the Tibetan Plateau

The cause of a stronger southwest monsoon is ambiguous, and relies on a smaller albedo on the Tibetan Plateau (Prell, 1984). However, as the temperature on the Tibetan Plateau was still rather low, possibly 6 °C below present as estimated from the Loess Plateau (Fig. 5.2-6), it is almost impossible that the albedo could be much smaller than it is today.

- no obvious decline in wind strength

Moreover, a derived decline in the strength of the southwest monsoon is against observation. There was no evidence showing the albedo on the plateau has been increasing since 9,000 years ago, because no obvious advance of glaciers in mid and late Holocene is found and the observation seems to be just the opposite. Even though the albedo on the plateau had reached its minima sometime in the Holocene, i.e. more land area than present had been exposed, it is hard to explain why the ice-cover area can keep expanding since then.

- misleading foram count

If the magnitude of foram count could really represent to some degree the strength of the southwest monsoon, is it appropriate to say that the present day southwest monsoon is the same as 12,000 years ago, or the albedo on the plateau today is the same as 12,000 years ago? The foram count is sometimes misleading. Actually, the
strength of the monsoon does not have to be stronger at around 9,000 yr BP to make the peak of the forams, especially *G. bulloides*. The other possibility, the northwest monsoon, could also keep the upwelling going, more efficiently. As the northwest monsoon blows perpendicular to the coast line of the Oman southeast coast, it can drive surface water directly away offshore, much more efficient than the weak Ekman effect. The upwelling driven by the northwest monsoon can even reach a wider range in the Arabian Sea and hence produce a much stronger upwelling signal.

• support from other forams

In fact, a study on *G. truncatulinoides*, a species living preferentially in the subtropical gyre system, reveals that the northern part of the Arabian Sea presents a much higher abundance than in the rest of the NIO (Northern Indian Ocean), and in eastern NIO almost no faunal change is found at the transition from the LGM to deglaciation (McKenna and Prell, 1994). This means no dramatic change of the southwest monsoon in the late-Pleistocene and a low profile of the southwest monsoon in the Arabian Sea.

B. Stronger northwesterlies in the past

• northwesterlies derived upwelling centre

A stronger northwesterlies in the past can also be reflected in the upwelling pattern in the Arabian Sea. If the 9000 yr BP peak of the upwelling indicative foram is observed throughout the whole Arabian Sea, and in the southern Arabian Sea the magnitude is similar to or even higher than the Oman coastal area, it may be viewed as hard evidence for a stronger southwest monsoon, however, the signal of the peak was weaker or even disappeared in the southern Arabian Sea and off Somali (Prell, 1984). This implies that the upwelling system ca. 9000 yr BP was not produced by the southwest monsoon in particular, let alone a solely stronger southwest monsoon, and unlike the present one, it was likely centred just off Iran in the Gulf of Oman.

• northwesterlies after retreat

Although the northwesterlies is now no longer a surface wind since it was driven almost completely off the Arabian Sea, they are actually always there, because winds
5.3.2 Monsoonal Variations

blowing to the equator are a natural phenomenon in atmospheric circulation known as the Hardley circle. At present, the northwesterlies are still blowing on top of the southwest trajectory (Sirocko and Sarnthein, 1989). When the northwesterlies climb up over the southwest monsoon, the wind strength would be reduced, and coarse sediment would drop out considerably. It is reasonable to speculate that once the northwesterlies reached the height, it would become rather 'clean', and if the finer particles dropped into the underlying stronger southwest monsoon, they would be carried away. This is possibly why little typical northwesterlies' deposits have been found in core 1739 since the monsoonal switching.

C. Relationship between the monsoons

- complicated and cannot be described by one variable

Monsoonal variation in the Arabian Sea is very complicated. There were at least two summer monsoons interplaying in this area, and apparently one variable (e.g. wind strength of the southwest monsoon) is not enough to describe this complex monsoonal system. It seems the interpretations and modelling of the Indian monsoons are over-simplified. Actually the monsoon system in the Arabian Sea since the late-Pleistocene may have its own characteristics different from those in the previous glacial-interglacial cycles. It is noted that although a coherence of marine and terrestrial records during interglacial intervals due to the monsoonal southwesterlies was concluded, the two are not quite in phase (a phase difference of 3 ka) and coherence did not appear at all during the last interglacial (Prell and Van Campo, 1986). This suggests the processes operating in the Arabian Sea may not be as simple as they appear today.

- in the north Arabian Sea

In glacial time, the wind-driven upwelling was significantly low off Oman, which might indicate a decrease in strength of the monsoons, but the interglacial high was not necessarily due to the southwest monsoon in the whole Arabian Sea. In the north Arabian Sea it is possible that the southwest monsoon had never played a key role as compared with the northwesterlies except during the last 5000 years, and in the coastal area off Iran the northwesterlies are actually still in hold.
5.3.2 Monsoonal Variations

• winter monsoon
The sea surface temperature in the northern Indian Ocean was lower during the last glaciation (Sarkar et al., 1990), but the temperature on land was believed to be even lower than that of today, resulting in overall stronger winter monsoon. Based on the same fact, Asia summer monsoon are therefore thought to be weaker (Duplessy, 1982). It is true if the ‘summer monsoon’ refers only to the southwest monsoon, but as the northwesterlies were also present in summer, which was actually stronger than it is today, it may not be appropriate to say all the summer monsoons were weaker.

D. Significance of bimodality
• why no bimodality in core 1733
As defined previously the event of monsoonal switching (AE II) occurred about 5500 yr BP at coresite of 1739 and 2400 yr BP at coresite of 1734a. There ought to be a similar monsoon-switching signal (disappearance of the second mode) in core 1733, however, because of the long distance from the land in one hand, and the relative position to Ras al Hadd on the other, this signal may not be well exposed, though it is implied in the particle size distribution.

• one modality-transition, two different significances
This monsoonal switching (AE II), however, bears different significance for the coresites of 1739 and 1734a. In core 1739, the particle size change is believed to be associated directly with the strengthening of the southwest monsoon, whilst in core 1734a, it is indirectly associated with the southwest monsoon. This is because the northwesterlies and the southwest monsoon are not compatible, and the sediment pattern remains till present day in core 1739, whilst in core 1734a, the finer fraction is seen to continue only to the upper part of core (6 cm), where Arabian dust dominates. So the modal changes in both cores 1739 and 1734a are related to the strengthening of the southwest monsoon, but at different times, suggesting a rapid withdrawal of northwest monsoons in the Gulf of Oman.
5.3.3 Palaeoenvironmental Changes in Arabia since the Late-Pleistocene

- results of the monsoonal variations
The monsoonal variations in the Arabian Sea have resulted in changes in three scenarios. The most obvious one is the migration of the coastal upwelling centre in the north Arabian Sea, and the other two are aridity and climate, and human activities in this region.

Migration of the upwelling centre in the Arabian Sea
- determined by wind
Shimmield et al. (1992) studied the coastal upwelling system in the world and noticed that it cannot be generated everywhere. Upwelling system in the Arabian Sea is basically wind-driven, but this does not mean that where there is a wind, there is an upwelling system. The upwelling system is controlled primarily by wind-direction relative to the alignment of the coastal line, which determines the existence of coastal upwelling (see Appendix B8). Meanwhile, the wind strength will determine the scope and intensity of the upwelling system.

- effect of wind-direction in the north Arabian Sea
The coast lines in the north and northwest Gulf of Oman and the Arabian Peninsula align in different directions; however, their dips are mostly in three direction: south (off Iran), east and northeast (west of the Gulf of Oman) and southeast (off Oman), i.e. in the east 'hemisphere'. Therefore, under the Coriolis force (Appendix B8), easterly winds (including northeast and southeast winds) can hardly produce coastal upwelling in the above areas. In fact, easterly winds can only drive surface water downward while moving laterally, a process just opposite to the upwelling. As an extreme example, northerly winds can drive the surface water off a south-facing coast, e.g. off Iran, however, according to the Ekman effect, the underlying water would move southwesterly on a horizontal plane, so a contour current might have been generated rather than an upwelling. Therefore, to produce an upwelling system in the west and north Arabian Sea, westerly winds are required.
5.3.3 Palaeoenvironmental Changes in Arabia since the Late-Pleistocene

• late-Pleistocene: lack of upwelling

The wind direction in this period was mainly northerly, which is supported by the sand dunes in the peninsula. The sand dunes or seif dunes (uruq) at the southern flank of Ar Rub al Khali desert (18° N, 49° E) indicate strongly northeasterly winds, and so do the seif dunes at the east flank of the desert (21° N, 53° E) (Short et al., 1976), though the cusps of Wahiba seif dunes run more vertically from north to south. These seif dunes are believed to have been formed during glacial time, when the wind-strength was much stronger (Winser, 1989). However, sedimentary records in the Arabian Sea show little evidence of an upwelling system in the Arabian Sea at the beginning of deglaciation, ca. 14,000 yr BP (Prell, 1984, and this study). Apparently, the main reason is the wind direction, which was just not right for an upwelling. In fact, even the wind on land was northerly, it would become slightly northeasterly as it travelled on under the Coriolis force, making an upwelling impossible:

• deglaciation: upwelling building up

Shortly after the deglaciation began, the dominant wind in the Arabian Sea changed rather rapidly from northerlies to northwesterlies. Under this favourable wind direction, the upwelling system in the Arabian Sea was soon built up. As the northwesterlies is the most efficient wind in driving an upwelling system, the maximum upwelling in the history since the late-Pleistocene is seen to happen in this period. The first upwelling centre was along the southern coast of Iran and then joined in by that off Oman at around 9,000 yr BP to form the maximum upwelling in the Arabian Sea.

• mid and late-Holocene and future

As the wind became more and more northwesterly, the upwelling centre would then expand and move to the west of Gulf of Oman at ca. 6000 yr BP. Since the northwesterlies became less stronger and the southwest began to take control of most part of the sea, the scale and intensity of the upwelling started to decline. As the northwesterlies further retreated under the pressure from a stronger southwest monsoon in late mid-Holocene and changed more or less to easterly in the Gulf of Oman, the upwelling centre moved deeper in the Gulf of Oman and finally lost its
5.3.3 Palaeoenvironmental Changes in Arabia since the Late-Pleistocene

ground and vanished there. In the meanwhile, another upwelling centre was created off Oman under the stronger southwest monsoon, especially when it merged with the northwesterlies and landed on the Peninsula in the late-Holocene as we see today. It can be predicted that if the southwest monsoon goes further into the peninsula and blows into the west of Gulf of Oman, the upwelling centre will be able to expand over the Ras al Hadd to the west Gulf of Oman again, because the southwest monsoon blows in favour of an upwelling off the northeast coast of Oman.

• relationship and timing in cores

It is interesting to examine the relationship between the collapse of upwelling system in the west Gulf of Oman and the southwest monsoon's influences. The collapse of the upwelling system seemed to be more consistent in time than the actual dust source change. As indicated in Ba/Al profiles, the increase of Ba/Al, which implies a contribution from the Arabia and Red Sea dust, arrived at coresite of 1733 at 2.8 ka BP (17 cm), well before the collapse of upwelling at 2.5 ka BP, while at coresites of 1734a and 1736, they appear at 2.4 ka BP (22 cm) and slightly over 1 ka BP (17 cm) as compared with 2.0 ka BP and 1.3 ka BP for collapse of upwelling respectively. The apparent manner of vanishing of the upwelling system in the Gulf of Oman depends on the position of the cores. In central Gulf of Oman (core 1739), this appears as a continuous decline, whilst in the west of Gulf of Oman, it is much more abrupt. The upwelling system is seen to collapse before the actual streamline of the southwest monsoon crossing the coresites. It is worth noting that the low LOI (e.g 11 cm in core 1733) indicates much more terrigenous sediment with no sign showing turbidity current origin, therefore suggests a possible aftermath of upwelling collapse in west of Gulf of Oman. It is also interesting to note that in core 1734a, the Ca/Al peak coincides with the vanishing of the second distributional mode, whereas in core 1739 they do not occur synchronously. This suggests the coastal upwelling at core 1734a may be directly related to the northwesterlies, but at the central coresite of 1739 upwelling relies mainly on the northwesterlies which took advantage of the maximum solar insolation at around 10,000 yr BP. The Ca/Al peaks in the two cores can be correlated based on similar palaeoceanographic and palaeoclimatic conditions, but not directly on time.
5.3.3 Palaeoenvironmental Changes in Arabia since the Late-Pleistocene

- impact on other parts of the sea

The migration of the southwest monsoon produced less impact on the oceanographic conditions in the central area of the Arabian Sea than in the west of Gulf of Oman. As the upwelling centre moved from the coastal area of Iran and off Oman to the west of Gulf of Oman and then to the present position off Oman, the path formed a part of a circle centred roughly at coresite of 1739. Therefore little signal of this migration can be detected in south Arabian. As the upwelling driven by the northwesterlies was much stronger than that by southwest monsoon in the Gulf of Oman and off Oman in early Holocene, the impact would reach a wider range of the Indian Ocean and be recorded at a number of cores from northwest and even central Arabian Sea as the maximum upwelling. This migration has been completed in a quite short period and seems stuck on land. This is because the ITCZ is relatively easy to move across sea area, and largely influenced by orographic factor and a balance is usually found along the coastal line. Since the most distinctive effect of upwelling mainly concerns in the upper water layer, the submarine features of the Murray Ridge plays little part in it, though it may influence the path of the intermediate water supply.

Aridity and climate in the Arabia and its vicinity

- since late-Pleistocene: mid-east and Arabia

Arabia today is characterised by its severe aridity, which was not always so in geological time. A study on a drill core from the Azraq Basin approximately 150 kilometres east of Amman in Jordan revealed palaeoclimatic changes over the last 500,000 years (Greg, 1992). It shows climatic deterioration sets in and a period of aridity is the dominant phase during the Late Pleistocene up until about the time of the glacial maximum at 21,500 yr BP. Climatic improvement following this period may correspond to the early Holocene Pluvial. The uppermost section shows a return to present-day arid conditions. This long-term palaeoclimatic change is typical in Mid-east and Arabia, which is also seen in the Wahiba Sands. Land investigation in the sands near Ras al Hadd revealed the quaternary history of the sands (Winser, 1989). It is clear that a relatively humid interval in the Holocene was followed by an arid period of more rapid erosion till today (Winser, 1989). Dates for a snail found
5.3.3 Palaeoenvironmental Changes in Arabia since the Late-Pleistocene

between the linear mega-dunes and a mollusc found within old swamp deposits near the coast confirmed the existence of vegetation and lakes in the Wahiba Sands in the mid-Holocene period 7,000 years ago (Winser, 1989).

- roles of the southwest monsoon and northwesterlies

Seen from the Arabian cores in this study, it is possible the time for the aridity to set in is around 5500 yr BP, which coincides with the disappearance of the second and coarser mode in core 1739 and hence a shift of the southwest monsoon after the retreat of the northwesterlies. As seen on the peninsula today, the windfield is never a part of the southwest monsoon. Considering a stronger northwesterlies in glacial and post-glacial time and early Holocene, the southwest monsoon might have never been the main moisture supplier deep into the peninsula, and the northwesterlies should be directly responsible for the climate in Arabia. The northwesterlies has a close connection to the Mediterranean and Caspian Sea, which might be a major moisture source to that area in early Holocene. Even seen from the present meteorological map of mean surface winds over the earth (Lamb, 1972), the summer winds across the Arabian Peninsula is apparently connected with the mid-latitude westerlies, which are originating in the north Atlantic and passing through Britain and much of the Europe, including the Mediterranean Sea, to join the equatorial westerlies. This connection might have been enhanced in the early and early mid-Holocene when winds were stronger. More importantly, more moisture would be available in this moisture source area during the global Holocene Pluvial, and the stronger northwesterlies could transport moistures further to the Arabian Peninsula and North Africa, where it helped sustain high lake level throughout this region at that time (e.g. Kutzbach and Street-Perrott, 1985). According to the pollen studies (Roberts and Wright Jr., 1993), in mid Holocene, the Arabian region had warmer winter and wet summer, which is surely an indication of more moisture supply.

- wind strength and humidity

It should be noticed that a stronger southwest monsoon cannot bring more moisture from Indian Ocean to the Makran and Mesopotamia, nor to the Arabia; on the contrary, it can possibly lower moisture supply from the northwesterlies. It is likely
that the slightly finer fraction of the sediment in core 1739 at around 9,000 yr BP would be a signal of an *in situ* weaker southwest monsoon, preceding the humid period. Although it is argued that dust-flux reflects changes in wind transport, rather than aridity in tropical Atlantic (Ruddiman, 1997), the wind strength and humidity are closely associated in the Arabian Sea. In fact, the monsoonal change in the last 600 years, i.e. the landing of the southwest monsoon on the peninsula (Table 5-4), had brought more arid climate to the southeast coast of Oman, as reflected in a miniature depicting Muscat in 15th century (Fig. 5.3-5).

Figure 5.3-5 Miniature of Muscat in the fifteenth century. Note the small river flowing across the city is now dried (extracted from Winser, 1989).

• cyclone and moisture transfer
The existence of cyclones in the Arabian Sea is revealed by the extremely coarse sediment in the middle of the Gulf of Oman. As observed today, cyclone often occurs at the transient time of the northeast and southwest monsoons (Snead, 1991), i.e. when the wind strength is relatively weak. As the atmospheric gradient between the sea and land is building up rapidly, but no efficient transmission (e.g. the southwest monsoon) is available, an extreme form of such a transmission, cyclone, will be inevitable. In terms of heat and moisture transfer from low latitude to mid-latitude, the southwest monsoon and cyclone serve the same purpose in the climate system, and obviously cyclone does it in a more fierce way than the southwest monsoon, but
5.3.3 Palaeoenvironmental Changes in Arabia since the Late-Pleistocene

lasts shorter. The climate conditions in the present transient time are that the relative temperature difference is building up but not so great as in summer time. These climate conditions might stay longer in summer time in the Arabian Sea from the late Pleistocene to early mid-Holocene, when the temperature and sea surface temperature were lower, therefore cyclones would have prevailed at that time. The Wadi system widely seen in the Arabian desert might have been developed in the flash floods caused by the cyclones, which would land on the peninsula more frequently than they do now, in light of the weaker low-pressure attraction from the south and southeast Asia. However, it is still not clear how much this cyclone process had contributed to the moisture supply to the Arabian area.

**Human activities**

- interacting with the environment

Human activities can definitely pose a significant impact on environment, as is seen today, but the extent and process of this impact in the past are unclear in many places, though it is thought to be less significant before human civilisation around 7,000 yr BP. In return, environmental change can affect human activities and human civilisation as well. Therefore the human activity-environment scenario is actually an interacting one.

- human activities to environment

Since the environment on the Tibetan Plateau, the main attraction to the southwest monsoon, has remained rather stable in the last few millenniums, the southwest monsoon should not have changed very much. However, the southwest monsoon was still seen to get strengthened and advanced further to the west of Gulf of Oman during this period. In addition to the natural trend on land globally, the extra driving force of the monsoonal system in the Arabian Sea is likely to be associated more or less with human activities, in mid-east (Mesopotamia) and India and Pakistan in particular. This anthropogenic influence could take effect as early as the earliest human civilisation, though natural process on the continent, the Tibet Plateau in particular, was still a major player. The civilisation in Mesopotamia around 7,000 yr BP saw a great damage to the ecosystem, leading to numerous abandoned villages on
barren hills, which used to be covered with forest. The deforestation and
desertification of the Indus catchment at a later time are also caused by human
activities there, one of the earliest civilisations in the world. In Europe during the
Roman Period about 2000 years ago, the climate around the Mediterranean changed
to a warmer but more arid one, which is also thought to be associated with human
deforestation (e.g. Terral and Arnold-Simard, 1996). All these human activities
greatly changed the local environment and imposed influence on regional climate,
resulting in more variable and more arid climate, which would increase the low air-
pressure on land in summer and strengthen the Indian monsoon.

Favourable climate and environment are essential for human survival and
development. An important factor of these is water, and hence forest, mild whether
and food. In the Indo-Arabian, it is not a coincidence to find the civilisations are
following the mid-Holocene humid period. That period is around 8,000 yr BP in
Mesopotamia and around 6,000 yr BP in the Indus Plain. There is evidence that in
early civilisation during 7,000 - 12,000 yr BP much more rain had been carried to
Oman. Rock paintings of elephants, crocodiles and pastoralists with huge herds of
goats and camels in part of Arabia and the Tassili N’Ajjer mountains of the Sahara
are some of the evidence (Winser, 1989). The Arabian civilisation had fully taken the
advantage of the monsoons, also known as the trade winds, to trade with other part of
the world around the Indian Ocean. However, no archaeological evidence shows such
a maritime communication between Arabia and India before 5,500 yr BP, though
land route is found through Makran, not a desert at that time (Snead, 1991). In the
Indo-Pakistan, the southwest monsoon played a vital role in fostering the civilisation
there, transporting the essential monsoonal rain to that piece of land in early mid-
Holocene. However, the intensive human activities at the earliest civilisations around
the Arabian Sea had changed local eco-environment by deforestation, farming, over-
grazing and so on, which in turn helped deteriorate their living environment and
largely destroyed their civilisations in the end. A similar pattern can also be seen on
the Loess Plateau in China, though the Chinese civilisation continued to thrive in
other part of the country.


**Discussion**

- **Ba/Al:** not a palaeoproductivity indicator

When upwelling in the Gulf of Oman is discussed, it is worth noting that the geochemical ratio Ba/Al in the Gulf of Oman sediment is not necessarily an ideal indicator of palaeoproductivity or intensity of upwelling, though in Arabian sediment from further south it appears to be linking with other palaeoproductivity indicators (Shimmield, 1992). It is possible, however, in both cases the Ba/Al ratio only indicates the sediment source or wind direction, especially in coastal areas, because in the Arabian Sea the wind bringing in more Ba, i.e. the northwesterlies, can also drive a stronger upwelling. Nevertheless, the two may not always agree with each other. As seen in the Gulf of Oman, higher Ba/Al ratio is accompanied by lower Ca/Al, e.g. in core 1734a, contrary to that in core 1739. Biogenic Ba may be important in some areas where effective preservation persists, however it is also found to co-vary with bottom-water Ba, involving mainly chemical reaction (Lea and Boyle, 1989), therefore 'biogenic Ba' might not be a simple indicator of palaeoproductivity. The 'excess Ba' cannot be applied on the Gulf of Oman sediment due to the collapse of the upwelling system there; actually, no or very little 'excess' Ba can be identified in the sediments. Generally speaking the Ba/Al in the Arabian cores in this study is lithogenic and related to dust sources.

- **Conclusion**

It is seen that the monsoonal variation in the Arabian Sea is complicated with many interacting factors and has various impacts on the regional palaeoenvironment and palaeoceanography, with factors and impacts not limited to the Arabian Sea area though. Generally speaking, the windfield in the Arabian Sea is determined by the interaction of the southwest monsoon and the northwesterlies since late Pleistocene, which originates mainly from the albedo change in south Asia under orbital forcing, global warming and human activities. These variations were not happening at the same pace, and it seems the maximum solar insolation at ca. 10,000 yr BP and monsoonal shift around 5,500 yr BP are the two most important factors outlining the history of the Indian Ocean monsoon system and upwelling since late Pleistocene.
5.4 Palaeoenvironmental Changes Over Eurasia

- significance of land-sea correlation
Consideration of palaeoenvironmental changes should entangle both marine and land records, as the land-sea-atmosphere interaction belongs to an integrated earth system controlling all the surface processes. As the most distinct mid-latitude orographic feature on earth, the Tibetan Plateau stands in the middle of the two peripheral regions of the Eurasia continent and has been acting as an atmospheric pivot since its uplift (Molnar et al., 1993). Information from the land, particularly the Himalayas, the Tibetan Plateau and the Loess Plateau, will be vital for understanding the sedimentary records and palaeoenvironment over the Eurasia. Records since the late-Pleistocene from the Tibetan Plateau and other part of East Asia will hence be discussed in 5.4.1, and those from Afro-Arabia and Indo-Arabia will be presented in 5.4.2. Connections and teleconnections will be addressed in 5.4.3 and discussion and summary will be given in 5.4.4.

5.4.1 The Tibetan Plateau and East Asia

- the Tibetan Plateau
The Tibetan Plateau is officially called the Qinghai-Tibet or Qinghai-Xizang Plateau, which locates in southwest China covering a vast area of about 2 million square kilometres, equivalent to the areas of Germany, France, Italy and Britain combined (Ren et al., 1985). Because of its mid-latitude location and its tremendous altitude, it plays a key role in determining the climate over Eurasia and even the world. The impact of the plateau is materialised mainly through the albedo change on the plateau, which is associated with temperature, precipitation and glacier activity.

Albedo on the Tibetan Plateau
- two main factors: temperature and precipitation
Albedo on the plateau is determined mainly by the coverage of alpine glaciers, ice-caps and snowfield (Fig. 5.4-1), which has the highest albedo in nature. The coverage of snow and ice is controlled by two main factors, temperature and precipitation, both
of which are changing with regional and global climate. In late Pleistocene global
deglaciation was switched on, which must have impacted on the alpine conditions;
however, the response from the Tibetan Plateau might not be prompt and
straightforward, and the albedo change on the plateau would differ from that of the
temperature.

• delay of deglaciation on the Tibetan Plateau
It is known that the last deglaciation was turned on at different times in different
places. For instance, the deglaciation in Newfoundland is believed to have begun
only a few centuries before 10 ka BP (MacPherson, 1996), although deglaciation in
Europe started as early as 14,000 yr BP (e.g. Williams et al., 1993). Generally
speaking, the higher the latitude, the later the deglaciation. The increase of latitude is
somewhat equivalent to the increase of elevation in terms of climate condition, and
the deglaciation on the plateau could be thus delayed.

• reason for the delay
One main reason for the delay in deglaciation is the low temperature on the plateau in
late Pleistocene because of its high elevation. It is noted that sea surface temperature
(SST) in the transition from the Last Glacial to Holocene rose ca. 8 °C as converted
from a 5 % change in δ18O change (Weber and Flohn, 1984). Moreover, during the glacial
period temperature could drop by 10 °C or more in middle latitude (Goossens and
Berger, 1987). On the Loess Plateau, northeast to the Tibetan Plateau, the palaeo-
temperature at the beginning of Holocene was also estimated about 10 °C lower than
present (Zhao et al., 1991). Therefore, it is quite likely the temperature on the Tibetan
Plateau from the LGM up to the beginning of the Holocene was about 10 °C lower
than present. Calculated from the average gradient of temperature vs. height, i.e. 0.5
°C per 100 m, the 10 °C drop will bring the snowline about 2,000 m down from
where it is now. The present snowline on the plateau stands at 6,200 m (Ren et al.,
1985), so the glacial period snowline would be just 4,200 m above sea-level, which is
below the average height of the plateau by over 300 m; if so, the deglaciation at the
beginning of Holocene on the Tibetan Plateau would be almost impossible.
5.4.1 The Tibetan Plateau and East Asia

• snowfield and glacier

Joint surveys by a Sino-French team in 1980 (Mercier and Li, 1984) and a Sino-British team in 1985 (Chang et al., 1988) had failed to provide hard evidence for large scale ice-caps or ice-sheets as postulated before for the glacial time. It is thought that low precipitation on the plateau was responsible for this, especially when it is compared with the active and low altitude glaciers on the south side of the Himalayas. At present the precipitation over 5,000 m is only about 50 mm per year. The moisture transported from ocean to land was much less at glacial period (Berger, 1981) and it was much drier (only 30-70% precipitation of today) on the plateau (Shi, 1997), though alpine glaciers were seen to be abundant (Jin, 1989). It is quite possible that, despite the low precipitation, patches of snow-field could be formed on the plateau, as seen beside the Broder ice-cap in north Canada now (MacPherson, 1996). As the present perma-frost zone on the plateau is generally below 5000 m, the snow field on the whole plateau before the deglaciation would last a considerable time in a year, which can also effectively reduce the intensity of the heat low in summer (Barnett et al., 1988). At higher elevation, ice-sheets were still able to accumulate and glaciers were found advancing to cover a wider region before Holocene.

• relationship between temperature and precipitation

Under such a climatic and orographic condition, the global deglaciation could have a rather different impact on the albedo on the plateau. The climate pattern on the plateau in the last 160 ka BP was alternating between cold-dry and warm-wet (Xue et al., 1997). A more humid condition in west Tibet is reported in early Holocene (e.g. Winkler and Wang, 1993), however, if the temperature was not high enough, which was very likely at the beginning of Holocene, more precipitation would only help increase the snow-ice coverage. In fact it is notable that the snowline of the East Rongbuk glaciers on the dry northeastern slope of the Mount Qomolangma (Everest) is located at 6,200 m above sea-level, while that of the Aze Glacier (29°N) in the humid southeastern part of the Himalayas is only 4,600 m above sea-level, with its end extending to an extremely low altitude of only about 2,500 m, penetrating into mixed conifer and broadleaf forests (Ren et al., 1985). The similar situation is also
found in South America (Luu, 1980). Therefore a wetter and slightly warmer climate might not result in a large scale deglaciation on the plateau, but likely the opposite, and the albedo on the Tibetan Plateau could not have been reduced very much from the glacial time at the beginning of Holocene, and almost impossible to be even smaller than it is today under a relatively warmer and dryer climate.

- **glacial condition in early Holocene**

In early Holocene, when the global temperature rose, temperature on the plateau might also increase, but together with precipitation (e.g. Winkler and Wang, 1993). However, generally speaking, glacial conditions still persisted on the plateau in the early Holocene (around 9,000 yr BP), or even more serious in terms of glacial activity. That is because the increased precipitation had fed the glaciers and in the meanwhile raised the lake-levels in Tibet, which could sustain the glacier advance in return (Li, 1997). In early Holocene (8,000 - 10,000 yr BP), the perma-frost zone in northeast Tibet was found only 3,200 m above sea-level, about 1,000 m lower than today (Li and Wang, 1997). Therefore although temperature and precipitation on the plateau increased significantly in early Holocene, glaciers and snow-field did not retreat accordingly (if not advanced), which could hardly make the albedo on the plateau smaller, hence the heat low on the plateau would not be significant.

- **deglaciation at ca. 6,000 yr BP**

As seen from the palaeotemperature on the Loess Plateau (Fig. 5.2-3), over 1,000 m lower than the Tibetan Plateau, a sharp rise up to modern condition is recorded around 8,000 yr BP. This progress should happen on the Tibetan Plateau at similar and possibly later time. Sedimentary records and Indian terrestrial records suggest this shift could possibly be around 6000 yr BP and is aslo confirmed by the flooding in the Changjiang Middle and Lower Reaches Plain from about 6.8 to 4.9 ka BP (Zhu *et al.*, 1997). The lag of warming up on the Tibetan Plateau of around 2,000 years is reasonable, considering the rate of warming on the Loess Plateau is about 8 °C in 3,000 years and a temperature difference between the two plateaus of over 5 °C. It is likely that at the time of deglaciation, the perma-frost zone had moved above the average height of the plateau, so that the large patches of snowfield disappeared
5.4.1 The Tibetan Plateau and East Asia

synchronously and ice-sheet thinned and glaciers retreated. As the plateau is rather flat, the rate of the deglaciation would be quite high. As typically shown in Fig. 5.4-1, the glacier receded in Holocene, leaving a large terminal moraine, and the snow-field disappeared from the dark plain at the foreground (Kidd and Molnar, 1988). All these processes could significantly decrease the albedo on the Tibetan Plateau rapidly, making a powerful low air-pressure as seen today.

Fig. 5.4-1 Geomorphology of the Tibetan Plateau near the Burhan Budai. A terminal moraine is seen left by the receded glacier in Holocene, and the dark plain at the foreground is almost snow-free at present. Note the contrast of albedo between the plain and the glacier and snowfield (from Kidd and Molnar, 1988).

• reasonable timing

This date of 6000 yr BP for the deglaciation is reasonable. It is estimated that continental ice-sheets in the northern hemisphere need about $10^4$ years to build or decay (Flohn, 1987), as for the transition between glacial and interglacial climates. It is reasonable to say that the snow-ice cover on the plateau was largely melted away some 8,000 years after the general deglaciation on the low-altitude continent, considering the much longer period for it to form and the high elevation of the plateau. Previous studies on lakes in west Tibet confirmed the history of the palaeoenvironmental change on the plateau (Winkler and Wang, 1993). The large
scale deglaciation on the plateau is reflected in the marine and land records throughout Eurasia. The rapid shifts of Indian Ocean monsoonal system and the continental aridity are also proof of the rapid albedo change on the plateau. All these rapid changes in palaeoenvironment over Eurasia around 6000 yr BP are also naturally connected (see below).

**East Asia**

- **warming**
As represented by the palaeoclimate change on the Loess Plateau, the other parts of China experienced a rapid warming of the climate and an extensive sea-level rise at coastal areas. The sediment input into the China Seas began to increase rapidly from the Mid-Holocene, indicating an increasing land erosion possibly due to a greater water discharge with increasing anthropogenic influences.

- **abrupt cooling around 5,000 yr BP**
However, as indicated in many sources, e.g. Yang Zigeng (1994), the warming in East Asia was often intercepted by abrupt set backs. The most commonly noted one was at ca. 5,000 yr BP in China, which can be correlated with records from Japan and Korea and hence considered a regional (far east) phenomenon. This phenomenon can also be correlated with the Elm Decline in Europe about the same time. Palaeoenvironmental records suggest a drastic change around 6000 yr BP on the Loess Plateau (Fig. 5.2-3), and a cooling around 4.9 ka BP in the Changjiang middle reaches (Zhu *et al.*, 1997), which may be relevant despite the gap in chronology.

- **climate-control factors**
As the moisture from the south is largely blocked by the Himalayas, the humidity of the Loess Plateau will mainly rely on the moisture from the southeast, i.e. the west Pacific or more closely the marginal seas. It is postulated that the warm and humid period on the Loess Plateau may be associated with an intensified Asian monsoon system, in which the Himalayas and the Tibetan Plateau might play a role.
5.4.2 Afro-Arabia and Indo-Arabia

- regional low pressures

This region includes the south Asia, the Middle East, the Arabia and the North Africa around the Arabian Sea. The environmental characteristics of this region are largely controlled by the Indian monsoons, which are determined mainly by the heat low in the south Asia and the Tibetan Plateau. However, the most outstanding low pressure in south Asia today covers an area from the Indo-Pakistan, Iran, Mesopotamia to part of the Gulf, but not the Tibetan Plateau itself (e.g. Bartholomew et al, 1899, Shea, 1986), though the later contributes a great deal to the Indian monsoons.

Albedo in the Indo-Arabia
- significance of the Himalayan orographic feature

The albedo on the south side of the Himalayas (Indo-Pakistan) seems to be playing a very important role in the monsoon system, together with that of the Persian Plateau, though the variation on this lower plateau may not be so great. The orographic feature of the south side of Himalayas directs the warm air-flow up the slope, similar to the 'continental slope' in coastal upwelling system but different in the driving force. On the Himalayan slope, the heated-up land surface can create a much warmer hence lighter air sheet as compared to the cooler lateral air mass. As temperature in air column has a gradient of about -0.5°C per 100 m upward, but no such gradient exists on land surface temperature on a mountainous slope, or even a slightly positive one as solar energy is less absorbed by air at higher elevation, this air upwelling along mountain slope can create a powerful low pressure for the Indian monsoons.

- Himalayas

The albedo on the Himalayan southern slope is mainly determined by ice and snow cover and alpine glacier activities as well as the consequent ecological effects. Undoubtedly, the glacier activities influenced by global climatic change would greatly affect the albedo on the slope. As the higher the elevation, the more intensive the air-upwelling process, the albedo changes at high elevation should account for a considerable part of the total albedo on the slope. That is possibly why alpine glaciers...
are particularly important to climate changes, regionally and even globally. As the determining factor of the Indian monsoon, the glacier activities in Himalayas should be regarded as the initiator of the regional climatic changes, however, their variations can possibly only be driven by external forcing, i.e. earth orbit forcing, and should be among the first to respond to the forcing and therefore a starting point of the complex feedback.

- Persian Plateau and Makran
Owing to the smaller elevation (about 3,000 m above sea-level), the Persian Plateau is much less important than the Himalayas. The albedo on this plateau and in Makran area is mainly determined by vegetation, which is believed to have changed greatly in Holocene. Due to further deterioration of environment on the plateau and in Makran in mid-Holocene (deforestation and desertification), possibly as a consequence of other major changes such as the monsoonal change and human activities, this area became more and more arid and was finally transformed into another significant continental heat low in summer time, which strengthened the southwest monsoon and attracted it further west across the west Gulf of Oman.

**Solar insolation**

- significance
Total solar insolation is equally important as albedo in determining the regional palaeoclimate. Albedo in this region determines the pattern of the heat low, while solar insolation determines the strength of these low-pressure cells.

- melting glaciers and rising temperature
Maximum solar insolation occurred about 10,000 yr BP. It could directly reduce the albedo on the south side of Himalayas by melting some of the glaciers and snowfield, and hence could greatly enhanced the low-pressure there. More importantly, it raised the temperature extensively in this region, making the low-pressure even more powerful.

- effect of the maximum obliquity
As this maximum solar insolation is associated with the maximum obliquity of the earth axis, 1° more than the present obliquity, the land tropical area (Tropic of Cancer) would extend over 110 km up north. This distance is quite significant to the steep Himalayan slope north of Indo-Pakistan. Moreover, the change of angle of the sun will make the absorption of solar energy by the south facing slope more efficient. As a matter of fact, the general slope of the southern Himalayas can reach 3° as calculated from an elevation of 8 km over a horizontal distance of 150 km at about 27.5° N. Considering that the maximum obliquity of the earth’s axis is 24.5°, and that the whole southern slope of Himalayas is equivalent to a belt at 27.5°-3° = 24.5° N in terms of the angle to the sun, when the sun moved to the Tropic of Cancer at 24.5° N, a broad area including the southern Himalayan slope would be practically put in the ‘tropical’ zone. Because of the vast area involved, an extraordinarily strong heat low would be created, and hence a generally stronger southwest monsoon and stronger northwesterlies, and consequently a maximum wind-driven upwelling. As this period did not last long, the palaeoenvironment in the Indo-Arabia started going back to normal pretty soon, but was still followed by various consequences.

• on the Tibetan Plateau

It remains unclear whether this angle change of the sun had significantly changed the climate on the Tibetan Plateau, because it seems mainly determined by global atmospheric condition. The maximum solar insolation might not have warmed up the atmosphere so quickly and it might take a few thousands years to do that. Once the heat low in the Indo-Pakistan is backed up by the vast Tibetan Plateau, it can be argued that the southwest monsoon would certainly be strengthened, even exceeding the one 10,000 years ago. The solar insolation seems to be irrelevant to the heating up of the Middle East deserts, which happened in mid-Holocene.

**Palaeoenvironment in Indo-Arabia**

• late Pleistocene to early Holocene

In late Pleistocene, albedo on the southern Himalayan slope would be rather high due to the wide spread glaciers and snowfield. The heat low would locate on the low latitude of the Indian sub-continent, and the southwest monsoon would be active only
5.4.2 Afro-Arabia and Indo-Arabia

at low latitude originating from the centre of the north Indian Ocean. In the meanwhile, attracted by the heat low in north Africa (see below), northerly and northeasterly winds were blowing across the Arabian Peninsula and the northwest Arabian Sea. After global deglaciation started at 14,000 yr BP, the heat low on the Indian subcontinent moved northward and brought the stronger southwest monsoon further north. At the time when maximum solar insolation appeared around 10,000 yr BP, although the global deglaciation was far from finished, regional deglaciation on the southern Himalayan slope reached a maximum. It is very likely both of the southwest monsoon and the northwesterlies were strengthened by the new strong heat low. However, as the monsoon system in this period was mainly controlled by the Indo-Pakistan area, the position of the southwest monsoon was still limited in the central and east Arabian Sea.

• early Holocene

It is not very clear in the west Gulf of Oman what happened to the southwest monsoon in early Holocene. It can be postulated, however, that the frontal of the southwest monsoon might have swept across the Indian sub-continent from south to north in this period. Vora et al. (1996) reported a 1300 km long shelf edge barrier reef in west India. The drowning of the reef is believed to be due to the Holocene transgression, but environmental changes, particularly fresh water supply and suspended sediments, also contributed significantly. On the Fifty Fathom Flat off Bombay, Halimeda bioherms were found to be growing until 8,300 yr BP, when climate changed and nutrient supply increased, due to the increased rainfall in this area at about 9,000 yr BP (Rao et al., 1994). It is believed that the southern reef was drowned generally at an earlier period (Vora et al., 1996).

• mid-Holocene and later

It is quite possible that the prevailing southwest monsoon at present had only started to dominate the north Arabian Sea from 6,000 yr BP, when the albedo on the Tibetan Plateau decreased drastically, hence shifted the position of the heat low. This change effectively bolstered the southwest monsoon, making it stronger and further northwest, in the meanwhile depressing the northwesterlies. This process seems still
5.4.2 Afro-Arabia and Indo-Arabia

on, i.e. the southwest monsoon is still moving westward, more slowly though, under the influence of the continuously emerging heat low in Makran and Persian Plateau at a later time. The present climate conditions were established at about 600 yr BP in the Himalayan lakes and 560 yr BP (6 cm) at coresite of 1734a, further confirming the close relationship between marine and land records linked through the southwest monsoon.

• oceanographic reflection: oxygen minimum zone

The palaeoenvironmental changes on land also have impact on the oceanography of the Arabian Sea. Apart from the upwelling system generated by the monsoons, there could be changes in redox conditions in seawater, or fluctuation of oxygen minimum zone at around 2,000 yr BP in the Gulf of Oman. This is mainly suggested by the brownish band at 22 cm down the core 1734a, where the indicative bimodality is just about to disappear. This band is probably caused by a thickening of the oxygen minimum zone induced by a stronger southwest monsoon, or a drastically reduced input of organic matter. Actually these two mechanisms are connected, for the production in this area is largely controlled by the upwelling driven by the southwest monsoon.

Palaeoenvironment in Afro-Arabia
• late Pleistocene to early Holocene

It has been suggested that the pluviometric evolution for the last 20,000 years in the northern Sahara is related, at least partly, to the variation of the Indian monsoon, unlike in the southern Sahara (Ragnon, 1987). In both the Sahara area and the Arabian Peninsula, high lake levels have been recorded before the mid-Holocene (Williams et al., 1993), and after that large scale aridity occurred. Sedimentary records from the Red Sea indicate a humid phase from 15,500 to 7,300 yr BP (Naqvi and Fairbanks, 1996), which might have been caused by the monsoonal changes, mainly in their directions. The cool water brought out by the upwelling may decrease the moisture input into the Arabian Peninsula, however, the more important factor should be the moisture-carrying winds. From the viewpoint of the northwesterlies, the decrease of its strength could make it less capable of bringing moisture from the
5.4.2 Afro-Arabia and Indo-Arabia

Mediterranean Sea, Black Sea and Caspian Sea area in summer to the Afro-Arabia. Moisture might also come from the Atlantic via the westerlies, because in the late-glacial period temperature was much lower than at present, e.g. around 10°C lower in summer and 20°C lower in winter in England (Atkinson et al., 1985, Coope, 1987), making the Atlantic a cold high relative to the heat low in Afro-Arabia. Another moisture supply in this period could be the Arabian Sea, where the turning northerly or even northeasterly winds from Arabia passed by. The palaeoclimatic conditions might not be the same in the whole region at a certain time, as indicated by studies on sedimentation in the Persian Gulf (Uchupi et al., 1996). They found the early Holocene is made up of a lower calcareous terrigenous unit deposited 18,000 to 12,000 years ago during a wet climate phase and an upper aragonitic-aeolian unit deposited 12,000 to 9000 years ago during a dry climate phase coeval with the Younger Dryas.

- mid-Holocene and later

A lot of palaeoenvironmental changes had taken place in mid-Holocene. One of the changes is that the very high monsoonal lake levels 9,000-6,000 years ago dropped to today's very low lake levels, encompassing most of the range of sensitivity of African lakes to orbital-scale changes in summer moisture balance (Street-Perrot and Harrison, 1984, Kutzbach and Street-Perrot, 1985). In the Persian Gulf, the youngest sequence, a late Holocene marl/carbonate unit, was deposited during the last 9000 years and reflects the more humid regime (Uchupi et al., 1996). In the Wahiba Sands, a relatively humid interval in the Holocene and finally an arid period of more rapid recent erosion are identified (Dutton, 1988). It is also noted that in Arabia climatic deterioration began about 6,000 years ago with the present hyper-arid climate being well established by about 3,000 years ago (Yan and Petit-Maire, 1994). These are in line with the weakening of a stronger northwesterlies ca. 6,000 yr BP, and possibly related to the merger of the southwest monsoon and the northwesterlies near Oman around 3,000 years ago. Further development of the monsoon system in the Afro-Arabia mainly relies on the spatial change, position and area, of the continental heat low, rather than simply the intensity of the previous heat low. In the recent Gulf sediment, a significant component of aeolian detritus is found deposited with the
5.4.2 Afro-Arabia and Indo-Arabia

calcareous and fluvial sediments by northwest winds known as the Shamals, which is still quite prevalent in Arabia (Uchupi et al., 1996). It is estimated that one third of the gulf sediments are aeolian, and the accumulation rate would be 1 mm per year (Khalaf and Al-Hashash, 1983).

• continental heat low and the climate mechanism

In the late Pleistocene, the south Asia might not serve as a significant low cell in summer, due to the low angle of the sun and the cold whether, and the north Africa could act as the main low cell in this region, owing to the concentrated solar insolation in the tropical area. This low cell is possibly the main reason for the strong yet swirling northerly and northeasterly winds in this region. Actually, even in winter time during glaciation the winds are believed to have existed in the Afro-Arabian region, as large ice-sheets cooled the North Atlantic sea surface and intensified the winter subtropical high over both the eastern Atlantic and west-central North Africa (Rind, 1987, DeMenocal et al., 1993). Since such winds had resulted in the wet climate phase in the Persian Gulf, and the weakening of such winds led to a dry climate phase (Uchupi et al., 1996), it is very likely this mechanism relating the northerly and northeasterly winds and climate is always effective in this region. This mechanism can be largely influenced by the heat low of the south Asia. As the south Asia low cell got strengthened at the beginning of deglaciation, geostropic wind would be formed, which divert the northerlies to its left, i.e. to eastward around the nearer low cell. When the cell got stronger in the late Pleistocene and early Holocene, it could not only change the direction of the northerlies to northwesterlies, but also produce an increasingly strong southwest monsoon, taking advantage of the high latitude of the Tropic of Cancer at around 10,000 yr BP. When the low cell extends to further north, i.e. deglaciation in Himalayas at ca. 6,000 yr BP, the southwest monsoon had been apparently enhanced. With the continental low expanded and moved westward, the southwest monsoon followed. While the south and southeast Asia still remains as a low cell to the northwesterlies, the two monsoons have to merge in the west Arabian Sea in the intertropical convergence zone, and the northwesterlies continues to blow across the southwest monsoon at a higher altitude.
5.4.3 Connections and Teleconnections

• two possible ways: atmosphere and ocean

Palaeoenvironmental changes in the Chinese and Arabian regions are actually within one integrated earth system, which extends as far as to the North Atlantic (e.g. McCabe and Clark, 1998, Schulz et al., 1998), and they are naturally connected and teleconnected in one way or another. The connections can be realised in two ways, the atmosphere and the ocean. In certain areas, human civilisation may also contribute to the connections.

Oceanic connections

• sea-level change

As the oceanic circulation cannot connect the two regions directly, the salinity and temperature of the seawater and current system are quite independent from each other. However, sea-level changes can affect the two regions simultaneously. Although the greatest contributor to the sea-level rise in the Holocene is the polar and high latitude continental ice-caps and ice-sheet, the mid latitude alpine glaciers around the world, including those on the Tibet Plateau, may also play a role, especially after the termination of global deglaciation at 8,000 yr BP, which may be responsible partly for the regional palaeoclimatic change.

• direct impact

The obvious impact is the Holocene transgression, which is important for the Bohai and Huanghai Seas and the Persian Gulf. When the shallow continental shelf was filled with water, the regional climate would be definitely affected. The broad continental shelf in China, including the Huanghai Sea and the Bohai Sea, are mostly shallower than 70 m, therefore the seawater could have advanced over 500 km west and over 1,000 km north during the Holocene transgression. This had certainly brought more moisture inland, as indicated in the humid period on the Loess Plateau from 8,500 yr BP (Sun et al., 1991). In the Arabia, the Persian Gulf is believed to have been filled with seawater at the beginning of the Holocene, contributing to the wet climate on the peninsula. The global sea-level reached its present height around
5.4.3 Connections and Teleconnections

6000 years ago (Fairbridge, 1961, Fairbanks, 1989), which is evident in both regions (IOCAS, 1985, Qin et al., 1989, Potts, 1990). However, although the sea surface expanded in the continental shelves and trimmed the land area in the transgression, it still depends on other climatic factors and the relationship with them to determine how the regional climate would change and to what extent the sea-level influence could impact the change.

- other impacts

Sea-level changes in Holocene were accompanied by a rise in seawater temperature in many parts of the ocean. This should increase the moisture availability to land on one hand, and change the albedo, possibly reduce it, on the other. The combined effect would help develop a mild climate, i.e. wetter summer and warmer winter as compared with the glacial time. Moreover, more sea area in mid-latitude might result in more clouds, also contributing to the regional climate. However, the effect of high sea-level might not be the main controlling factor in the whole climatic system, because it apparently failed to halt the aridification after the early mid-Holocene, both in the Chinese and Arabian regions.

Atmospheric connections

- a transcontinental role for the Tibetan Plateau

The Tibetan Plateau is sometimes called 'the third pole' of the earth or 'the roof of the world'. It determines many surficial processes, particularly the monsoon system over Eurasia, through which the China Seas and the Arabian Sea is connected. Actually the Tibetan Plateau serves as the same meteorological centre for the two regions on its opposite sides. To understand the palaeoenvironmental change over the Eurasia, one cannot miss the changes on the plateau.

- monsoons in China

The monsoons in China can be divided into three categories: the winter monsoon, the summer monsoon and the Tibet monsoon. The winter monsoon in China originates from the central Eurasia, the Siberia and the Mongolia, but it cannot pass through the Himalayas, therefore is limited to China. On the other hand, as part of the summer
monsoon, the southwest monsoon in China can blow in from the Indian Ocean, or more precisely the Bay of Bengal (Porter and An, 1995). Neither the northwest monsoon nor the Tibet monsoon can impose direct impact on this Indian monsoon in China. However, the connections are still there, as all the monsoons are mainly driven by the heat low inland, particularly on the Tibetan Plateau.

• deglaciation impact on both regions

It is still debatable whether the palaeoclimatic change in the Arabian region is of glacial pattern or monsoonal pattern (e.g. Ruddiman, 1997). In fact, palaeoclimatic change is associated with both of them, though more influence from one aspect may be shown in one place than the other. In the two regions on opposite sides of the Tibetan Plateau, it seems the change of snow-ice cover on the plateau has a great impact on palaeoenvironment, especially from the mid-Holocene. On the Chinese side, as the deglaciation proceeded on the plateau, flooding caused by melt water from glaciers and intensified precipitation would be prevalent over the coastal plains, particularly on the Great North China Plain. The reason for the overflowing flood is that there was possibly no Huanghe River in the glacial time due to the cold and arid climate inland (Zhao, 1995), and therefore no previous river course available. This deglaciation related period is known for the big flood in many parts of the world, though maybe at different times because of different processes. In the Middle East, it had been recorded in the Bible, and in China the flood was documented in the form of legends and the earliest fairy tales. On the other hand, this change had enhanced the southwest monsoon and depressed the north westerlies, and therefore brought lavish monsoonal rains to Indo-Pakistan, but aridity to most parts of the Arabia.

**Civilisation connections**

• significance

As human activities began to play a significant part in the Holocene, it is of help to discuss palaeoenvironmental changes due to anthropogenic influence. Whilst much attention is paid on the recent human activities (within c.a. 200 years), earlier human activities (within c.a. 3,000 years) also deserve in-depth study. The importance of the early trend lies on the fact that this is the first time the human activities could
probably play a distinctive part in the environmental change; moreover, the later activities would be simply added to the previous background, and make it more complicated when effort is made to distinguish the anthropogenic influence from the natural trend. This problem is now often raised when considering the effect of global warming on local environment. A puzzle in the Chinese region is whether a warmer climate can make arid or semi-arid areas, e.g. the Loess Plateau, more arid, since as we know a 'climatic optimum' some 7,000 years ago (Goossens and Berger, 1987) did have a higher temperature.

- environmental impact

The civilisation connection mainly concerns the exchange and expansion of the knowledge and technology required for civilisation development. This communication between civilisations can fasten the development of the civilisations and make the same technology available in a wider area at the same time, putting more pressure on the local environment at least. The Mesopotamia (Middle East) and the Indian civilisations are believed to have such communication in late mid-Holocene, and China had a similar contact with them in a later period. The Bronze Age and Iron Age are possibly the beginning of such a meaningful connection, which could certainly lead to possibly permanent deforestation. Agricultural development, whether they learnt from each other or not, usually started with deforestation as well. It is not quite clear, however, whether the climate change in both regions is due to human activities or due to natural processes. The effect of human activities on the palaeoenvironment has possibly never been experienced by the earth system and may be unique in the whole geological history, which deserves further careful study.
5.4.4 Discussion and Summary

Discussion

- precipitation and albedo

The glacial activities on the Tibetan Plateau was mainly controlled by precipitation rather than temperature. Therefore although the temperature had risen slightly in the early Holocene, the major effect of the increasing temperature and precipitation is only to make the glaciers more active and the snow-field expanding, increasing the overall albedo on the plateau. Moreover, to make the albedo generally greater does not require a persistent snow-cover year round, and a shorter snow or frost free interval in wetter climate with more snow-falls would be enough to reduce the strength of the southwest monsoon (Barnett et al., 1988, Barnett et al., 1989).

- elevation

Within the last 14,000 years the elevation of the plateau had only increased about 70 m as estimated from a high rate of 5 mm per year, so the palaeoclimate was little influenced by the increased elevation. In fact, the elevation increase can only make a difference of 0.35 °C in temperature, estimated from the gradient of -0.5 °C per 100 m, which is negligible as compared with an over 8 °C drop in glacial time. Moreover, this effect is even less influential when the overall temperature rose along with the elevation since the late Pleistocene, making the temperature on the plateau only a bit more stable.

- the Younger Dryas

The Younger Dryas is thought to be a wide-spread rapid cooling phenomenon around 11,000 yr BP. However, if the Younger Dryas really had a global influence, it might not bear the same cooling feature everywhere, because the total solar insolation the earth received at that time might not be significantly reduced. It is likely that the Younger Dryas would appear quite differently or even conversely in low latitude, where its initiator may lie. The Arabian Sea could be a determining factor to the Younger Dryas in three aspects. Firstly, the rapidly recovered upwelling in the late Pleistocene could absorb large amount of CO₂ from the atmosphere, leading to a
global cooling. Secondly, monsoonal change could disturb global atmospheric circulation (section 5.3) and result in more moisture to the cold alpine area to feed the glacier advance, which in turn deteriorate the climate further. And thirdly, the monsoonal change could divert oceanic current to re-arrange the paths of moisture supply globally.

- civilisation and monsoons

It has been noted that the earliest civilisations began in the Nile catchment in Northeast Africa (Egypt) and Tigris-Euphrates Mesopotamian Plain (Babylon), followed by the Indus River (India) and the Huanghe River (mainly on the Loess Plateau in China). This seems to be very much in line with the monsoonal changes and the consequent moisture supply inferred from this study. In the early Holocene and early mid-Holocene, the Arabian Sea and the Mediterranean Sea was still dominated by the northerly winds, turning to northeast as they travelled on, which brought monsoon rains to the Nile catchment to foster the Egyptian civilisation. In the meantime, the northerly and slightly northwesterly winds in Arabia brought moisture from the Mediterranean Sea, the Black Sea, the Caspian Sea and the newly-filled Persian Gulf to the Tigris-Euphrates plain to support the Babylonian civilisation. When the southwest monsoon began to take control of the Arabian Sea in mid-Holocene, it severed the lavish moisture supply to the north Africa and Arabia, but to India instead. In the meantime, driven by the same continental heat low on the Tibetan Plateau, the summer monsoon in China took the moisture from the newly-formed China marginal seas to the Huanghe catchment to sustain the Chinese civilisation. The monsoonal rains actually mean more than drinking water, but also a mild climate, thick forest, rich grassland, abundant food, sufficient energy and adequate building materials. Therefore the thriving of human civilisations may heavily rely on the moisture supplied by the monsoons in the Arabian and Chinese regions, and human civilisation might be very vulnerable to environmental changes.

- ancient upwelling

It is interesting to note that some of the largest oil fields are found in Arabia, where the present coastal upwelling prospers. This actually may not be a co-incidence. As
5.4.4 Discussion and Summary

long as the positions of the lands and seas are similar to what they are now, the Arabian Sea, located in the tropical/subtropical area subject to strong monsoons, will become an ideal place for massive biogenic production under many monsoons in different directions. As pointed out by Shimmield et al. (1995) after discussing the upwelling system around the world, a possible relationship may exist between the ancient upwelling system and oil rich basin development. A large oil-field is possibly under construction in the Arabian Sea for the many million years to come.

Summary

• general result

Through sedimentological and geochemical studies on the sediment cores from the Bohai Sea, Huanghai Sea and the Arabian Sea, together with various data from previous studies, the palaeoenvironments of the Chinese and Arabian regions are revealed and the characteristics, mechanisms, relationship with human activities and history of the palaeoenvironmental changes since the late Pleistocene have been extensively explored and discussed.

• mechanism about the palaeoenvironmental changes in the two regions

After the last global deglaciation set on firstly in high latitude around 14,000 yr BP, its influence extended to the mid-latitude, in particular on the alpine glaciers such as those on the southern side of the Himalayas. This created an increasingly strong heat low along Himalayas, which gradually outplayed the previous heat low centred in North Africa in the Afro-Arabian and Indo-Arabian region. The heat low change, originated from alpine albedo change, was fundamental to the Indian monsoon system, which served as a practical force to change the regional environment. As a result, the glacial northerly winds in the Arabian region, turning from northwesterly to northeasterly when travelling from mid-latitude (Middle East) to low latitude (North Africa), was weakened and diverted by the increasingly strong southwest monsoon. As the deglaciation on the Tibetan Plateau switched on, the trend continued in the Arabian region and a monsoonal change was initiated in the Chinese region. With the help of expanded heat low in south Asia and the Middle East, the southwest monsoon has successfully driven the northwesterlies out of most part of
the Arabian Sea, causing a series of palaeoclimatic and paleoceanological changes, including the precipitation pattern and wind-driven upwelling system. It is worth noting that the albedo change on the Tibetan Plateau was vital for the monsoon systems on both sides of it, though with different impacts. In China, it enhanced the summer monsoon and the Indian monsoon and generally increased the precipitation in central China, including the Loess Plateau; whilst in the region from Africa to India it altered the southwest monsoon and the northwesterlies and hence the precipitation distribution, transporting the moisture to the Indo-Pakistan, and leaving arid climate to the rest of this region. Before the human civilisations, palaeoenvironmental changes in the two regions were mainly controlled by two factors: the variations of solar insolation and the albedo on the Tibetan Plateau.

- history
The main monsoonal change on the two sides of the Tibetan Plateau started at different times. In the Chinese region, it seems the change started when the albedo on the Tibetan Plateau changed, i.e. ca. 6,000 yr BP, while in the Arabian region it was as early as the global deglaciation began at ca. 14,000 yr BP, though there were also distinct synchronous changes in the Arabian Sea around 6,000 yr BP. More recent palaeoenvironmental changes took place in both regions around 2,000 - 3,000 years ago, which are characterised by aridification in many parts of the regions, probably linked to human activities. The main history in the two regions can be listed in Table 5-6 with divisions for the Holocene.

<table>
<thead>
<tr>
<th>division</th>
<th>date (BP)</th>
<th>the Chinese region</th>
<th>the Arabian region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holocene</td>
<td>Late</td>
<td>2,500 a</td>
<td>Huanghe channel switching</td>
</tr>
<tr>
<td></td>
<td>intensive land erosion</td>
<td>intensified land erosion</td>
<td>aridification</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>5,500 a</td>
<td>increasing land erosion</td>
</tr>
<tr>
<td></td>
<td>early</td>
<td>8,500 a</td>
<td>deglaciation on Tibet</td>
</tr>
<tr>
<td></td>
<td>Early</td>
<td>11,000 a</td>
<td>transgression</td>
</tr>
<tr>
<td>Pleistocene</td>
<td>Late</td>
<td>shelf wetland (peat)</td>
<td>emergence of the southwest monsoon</td>
</tr>
</tbody>
</table>
5.5 General Summary

• brief summary
Through multi-disciplinary studies on sediment cores from the Bohai Sea, the Huanghai Sea and the Arabian Sea, this thesis identifies and characterises the sedimentation processes in the Chinese and the Arabian regions. Based on these and previous work, in particular terrestrial and historical records, palaeoenvironmental changes in the two regions are revealed, interpreted and correlated, and trans-continental palaeoenvironment has been reconstructed. The outcome of this thesis includes not only the results and conclusions (5.5.2), but also the framework and basic philosophy (5.5.1), which are essential for a sound research project. Future work is proposed in 5.5.3 as an end of this thesis.

5.5.1 Framework and Philosophy

Four dimensional framework

• four dimensions
The whole study is completed in a four dimensional framework,
1. time: providing a time scale for the sediments, making them time sequences.
2. space: fitting the sediments into particular geological settings in different environments and on different scales.
3. content: retrieving sedimentary records with a multi-disciplinary approach.
4. correlation: stressing mechanisms involved at different levels, integrating temporal and spatial variations in different aspects.

The four dimensions are equal and independent of each other in terms of research interest, but are inter-dependent when the whole issue is tackled. For instance, although mechanisms can be explored independently, data and information from the other three dimensions are certainly considered to confirm these mechanisms.

• birth of the four dimensions
This study starts with retrieving sedimentary records, i.e. measurements (chapter 2). The basic data firstly appear with no specific meanings, however, it is from these
data that the four dimensions are developed, with the initial help and limited information provided in chapter 1. Although the four dimensions are equal theoretically, the extent of dependence of one dimension on the other is different. One dimension can be more independent and more fundamental than the other, and should be developed in the first place. Time (chronology) is such a dimension and is therefore studied first, followed by space, content and correlation, which are actually the procedure of interpretation of the sedimentary records (chapters 3, 4 and 5).

**Practical procedure and research philosophy**

- **signifying the data**
  The first step from sedimentary records involves confirmation of the basic data and establishment of a reliable relationship between the data and reality. This is usually done theoretically, however, reliable interpretation of the particular sedimentary records still relies on a cross examination of the data. In chapters 3 and 4, four aspects of the procedure are applied, which should agree with each other in the end.
  1. **theory**: theoretical consideration and calculation and previous work.
  2. **model**: modelling based on principal laws and previous reliable data.
  3. **observation**: in-person observation and historical records.
  4. **measurement**: basic data and carefully applied calculation.

- **significance**: five levels
  The significance of sedimentary records can be reflected on five levels in terms of sources of influence and their scales (excluding human activities here).
  1. **in situ**: post-depositional processes and disturbance (bioturbation);
  2. **local**: hydrodynamic conditions and sedimentation processes;
  3. **regional**: land-sea correlation and land-sea-atmosphere interaction;
  4. **global**: trans-continental correlation and tele-connections;
  5. **external**: earth orbit forcing and solar insolation

- **interpretation of sedimentary records**
  Interpretation of the sedimentary records starts within one level, which is not necessarily the lowest level. This is because although there are strong inter-
relationships between the levels, it is found more feasible to firstly interpret various
indicators on one level and then extend to other levels. The level chosen to start in
this study is that on the local scale, which actually comprises the major part of the
sedimentary records, i.e. the major and most distinctive variance. On this level,
sedimentation processes are the profound subject of study. Any breakthrough on this
level will be able to lead naturally to reasonable interpretation on the other levels,
and that is actually why sedimentation processes are so important in this study. The
practical interpretation procedure can be summarised in six steps with examples:

1. identify the most explicit parameters in individual cores with clear significance,
e.g. particle size parameters and/or certain elements;
2. compare and cross-check a group of parameters of similar behaviour and reaffirm
their significance, e.g. element group relating to sedimentation processes;
3. examine other groups of parameters to identify all the major local processes, e.g.
processes influencing different stages of sedimentation procedure;
4. re-examine the data to determine the \emph{in situ} influence, e.g. bioturbation;
5. correlate with other cores and data sources (e.g. terrestrial records) to determine
regional influences, e.g. dust source related wind direction;
6. correlate and compare with various sources to assess global and external
influences and explore the mechanisms and links behind the sedimentary records
on all levels, e.g. orographic feature and its role in feedback mechanism.

• logic of interpretation

Due to the interdependent nature of the four dimensions, progress made on one
dimension can be beneficial to the other three. Limited progress will be made on the
four dimensions at one time, making sure they support each other. With more data
the four dimensions will grow fully-fledged after a few rounds of study. This
procedure is reflected in the somewhat complex inter-dependence in the discussions,
where evidence seems to come from conclusions of further studies. This kind of
confusion, if any, is mainly caused by the chapter arrangement, which has to have an
order of study and is more or less objective oriented, i.e. chronology first, and then
sedimentation processes followed by palaeoenvironment.
5.5.2 Results

- structured results

It is not quite possible to carry out blanket studies in every detail in this thesis, though effort has been made to cover as many aspects as possible. The results of this study are also structured according to the different levels or aspects of research, which can be displayed as general or (major) specific achievements or conclusions.

General achievements

- six points

1. Nine sediment cores have been sampled and/or subsampled for this study, viz. JX91-2A and JX91-3B from the Bohai Sea, JX91-7m and 7G from the Huanghai Sea and cores 1733, 1734(a), 1735, 1736 and 1739 from the Arabian Sea.

2. Measurements and description have been made on the nine cores concerning lithology, sedimentology (particle size analysis), magnetism (magnetic susceptibility, (S)IRM and ARM), geochemistry (XRF major and trace element analysis) and radiochemistry ($^{210}$Pb and $^{14}$C). A multi-disciplinary approach has been taken throughout the thesis.

3. Accumulation rates of the surface sediments have been determined for the Bohai Sea, the Huanghai Sea (the China Seas) and the Arabian Sea.

4. Chronostratigraphy and event stratigraphy have been established in the China Seas and the Arabian Sea using radiometric dating as well as core correlations relating to the Huanghe River channel switching and monsoonal changes respectively.

5. Sedimentation processes in the Chinese and Arabian regions have been characterised and compared, with a multi-disciplinary approach concerning the whole sedimentation procedure from sediment source, erosion, transport, deposition, reworking and redistribution.

6. Palaeoenvironments in the two regions since the late Pleistocene have been reconstructed and connected and the mechanisms behind these palaeoenvironmental changes have been explored.

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Specific achievements

• historical records

Historical records are widely used in this study, particularly those about the channel switching of the Huanghe River on the delta since 1855 and on the lower reach of the river since 2047 BC between the Bohai Sea and the Huanghai Sea.

• conceptual refinement

The concepts of chronostratigraphy and event stratigraphy are refined and compared, which lays a firm cornerstone for the analysis of palaeo-environmental changes, particularly the monsoonal variations in the Arabian Sea. In the China Seas, unlike in the Arabian Sea, the two are almost identical.

• wide correlation

Land-sea-atmosphere correlation is sought after to construct large scale palaeoenvironmental changes over a relatively long time-span, i.e. from late Pleistocene to present. In particular, the seifs in the Arabian deserts are seen to be quite indicative to the palaeomonsoon strength and direction which associated with the upwelling system in the Arabian Sea and the palaeoclimate in the Arabian region.

• thesis plan

Proper and clear chapter and section arrangements are made to go with the multidisciplinary approach and 4D structure in this study, and a short title, usually key words and/or a conclusive phrase, is added atop of every paragraph.

• technical improvements

1. A Huanghe sediment dispersion model is established to assess the accumulation rate in the Bohai Sea.
2. $^{210}$Pb models, especially the total excess $^{210}$Pb model, are explored for correction of the $^{210}$Pb data used to calculate accumulation rate.
3. 3D illustration of particle size distribution and 3D illustration of the PCA results are designed to give clearer view over the downcore trend and element grouping respectively.
4. Probability plot is drawn with computer after creation of a probability scale using error function.

5. Coriolis force is considered for its 3D effects in the Arabian Sea, relating to the efficiency of the monsoons driving the upwelling system.

6. JX91-7mG is welded together from JX91-7m and JX91-7G, as a result of comprehensive core correlation and observation.

**General conclusions**

- **general pattern of sedimentation processes**
  
  Sedimentation processes in the two regions are basically different. Fluvial and aeolian processes are two main sedimentation processes in the Chinese and Arabian regions respectively. In the China Seas, the sedimentation processes are mainly controlled by fluvial processes related to the Huanghe River while in the Arabian Sea it is mainly the aeolian processes, including those leading to the extraordinary cyclone deposits on the Murray Ridge and saltation population in near-shore cores.

- **the Huanghe River**
  
  The Huanghe River largely controls the sedimentation in the Bohai and Huanghai Seas by both its massive sediment load and the considerable water discharge and its associated hydrodynamic effect. The major lithological and stratigraphical changes in the sediments are determined by the river's well documented channel switching since over 4200 years ago. It is found in the late-Pleistocene that the Huanghe River drained into the Huanghai Sea area, though there might not be a single main course for the river; and from the beginning of the Holocene to early Holocene (8,500 yr BP) the river passed through the Bohai Sea area, and entered the Huanghai Sea again in the mid-Holocene.

- **monsoons**
  
  Monsoonal variations since the late Pleistocene in terms of both wind strength and wind direction are responsible for the lithological changes in the Arabian sediments directly, and biogeochemical changes indirectly through the wind-driven coastal upwelling system in the Arabian Sea. The now northwesterlies might have retained a
more northerly direction in the Arabian Sea in late Pleistocene and prevailed till the early Holocene, giving way to the increasingly stronger southwest monsoon only around 6,000 yr BP. While the southwest monsoon was migrating from India to Arabia, the northwesterlies retreated from most part of the Arabian Sea and is now largely limited on land.

• upwelling
The upwelling system in the Arabian Sea is determined by the Indian monsoons. Monsoonal direction seems to be more important than its strength in generating the upwelling. The favourite direction in the Gulf of Oman and northwest Arabian Sea is northwesterly, which was the wind direction in early Holocene around 9,000 yr BP when the maximum upwelling since the late Pleistocene was recorded.

• turbidity current and its deposits
Estuarine turbidity current can be formed around the Huanghe River delta in the Bohai Sea in a different way from that in deepwater and lakes, owing to the extremely turbid riverwater and highly diluted seawater in a relatively quiet depositional environment. This current seems to be unique in the Bohai Sea and unlikely in the Huanghai Sea, though mass flow would be an alternative. The estuarine turbidites are composed of two contrasting sediments featuring channelled (sands) and unchannelled (mud) deposits. Turbidites in the Arabian Sea are mainly caused by sediment failure and can be better revealed by their geochemical signatures.

• Tibetan Plateau
The Tibetan Plateau serves as the common heat low for the monsoonal systems on both sides of the plateau, and has determined the palaeoenvironmental changes at least since the late Pleistocene. Albedo on the plateau is determined mainly by the snow-field and alpine glaciers, which are not only influenced by temperature but also precipitation on the plateau. The actual deglaciation on the plateau might be delayed about 6,000 years due to its elevation and culminated at around 6,000 yr BP.
• main mechanisms
Palaeoclimate responds to external (earth orbit) forcing via complex feedback mechanisms, in which mid-latitude orographic features on the southern side of the Himalayas and the highly elevated Tibetan Plateau may play a significant role through the albedo which is determined mainly by alpine glaciers and snow-fields and their consequent ecological effect. The special environment in this area has postponed the regional deglaciation process, created the Indian monsoon system, strengthened the east Asian monsoon, changed the moisture supply and caused the wide-spread continental aridity.

• human activities and civilisation
Human activities also played an important yet interactive part in the palaeo-environmental change of the two regions since the mid-Holocene. The connection between human civilisations and natural environment is the moisture mainly supplied by the monsoons in all the Afro-Arabian, Indo-Arabian and Chinese regions. However, deforestation and over-grazing, supposed to sustain the civilisations under pressure from the increasing population and advancing technology, had finally led to wide-spread aridification and desertification in the last few thousand years, which in turn ruined, to a great extent, the civilisations themselves.

Specific conclusions
• accumulation rate
Accumulation rates in the China Seas are about an order of magnitude higher than those in the Arabian Sea, sustained by the massive sediment input from the Huanghe River. The accumulation rates in the Arabian Sea follow roughly an exponential law with the distance from the coast, which can be inferred from pure aeolian process.

• soil erosion
Huanghe estuarine sediment in the Bohai Sea can be linked to the recent soil erosion on the Loess Plateau through geochemical and palaeomagnetic indicators, viz. P, Ti, REE and magnetic susceptibility, which are relatively enriched or enhanced in soils rather than in loess.
5.5 General Summary

• disturbance
Physical disturbance is dominant in the shallow China Seas, while bioturbation is abundant in the Arabian Sea, which looks more intensive particularly in terms of bioturbation per weight.

5.5.3 Discussion and Future Work

• importance of framework
Although the significance of this thesis depends on discussions of sedimentation processes and palaeoenvironmental changes in the Chinese and Arabian regions, the correctness of the results is not the only thing important. The framework constructed in this thesis may be of more value in the long run when similar projects are to be launched. In this sense, a comprehensive and workable framework may be more important. Therefore the significance of this study should not be limited to findings of new facts and mechanisms, which actually should be viewed only as a case study, the philosophy and multi-disciplinary approach reflected in the framework for palaeoenvironmental reconstruction should also deserve due recognition.

• basic objectives of this study
Palaeoenvironmental study can not only tell us what happened in the past, but also help understand what is happening now and what will happen in the future. It is noted in this study that although the environmental mechanisms could be the same throughout the geological time, attention still needs to be paid to the boundary conditions to understand palaeoenvironment correctly. For instance, when the Tibetan Plateau was not high enough, even under the same orbital driving, the regional and global palaeoenvironment could not be the same as in the late Pleistocene. Therefore the particular results of this study may not be extrapolated to the far past, and this is probably why the palaeoenvironmental cycles could not be traced back to the early Quaternary. As for the practical application of palaeoenvironmental reconstruction, it should go in line with the social development. Today sustainable development becomes more and more appreciated and actually has
to be adopted world-wide, to which earth science may contribute; so the basic objectives of this study should be in line with the two themes of today’s earth science, resources and environment. While studies on sedimentation processes and palaeoenvironment, particularly the upwelling system, are potentially oil-related, they concern more about the environment and the mechanisms of environmental changes. For the recent environmental changes, however, human activities need to be paid special attention, and their interactive relationship with the environment deserves careful study, though it is more like a subject of environmental geology. Environment, resources and sustainable development of human society should be the most fundamental objectives of present geo-science studies, which I have tried to emphasise.

- future work

Comprehensive discussions have been made in this thesis, but it is still far from complete. The future work will comprise improvements mainly in two fields: the framework of research and content of study. Firstly, the four dimensions need to be further extended and more detailed inner-structure of the framework needs to be constructed. For instance, human activities should be woven into the system and other ‘invisible’ factors should be considered, i.e. the influence of geomagnetic field and solar activities on environment. Secondly, the content of study should be enriched even under the current framework. For instance, uniform systematic measurements should be carried out on every core, and better examples and data should be used at certain positions in the framework, e.g. the Brahmaputra River should be picked to better reflect the deglaciation on the Tibetan Plateau. Of course, technical and instrumental improvements are always important to upgrading research work, which can result in rich content of study to enable full implement of an improved framework. Although such kind of future work will possibly never be done for a PhD thesis, they should be considered for larger projects.
Appendix A

(Techniques)

A1. Coring techniques

A1.1 Mackereth type corer
This is a pneumatic corer designed by Mackereth (1958) originally for coring lake sediment. The operation involves mainly three steps: mooring, coring and recovering. Although this coring technique can cause little disturbance to sediment due to its adjustable quasi-steady movement of coring tube, soft top sediment may be lost when mooring and sandy bottom sediment may drop when recovering.

A1.2 (Piston) gravity corer
This kind of corer is widely used to take marine sediment. Heavy weights are put on the corer to drive the coring tube into sediment within seconds. The impact of the corer may damage the sediment top and change the inner structure of sediment.

A1.3 Box corer
This corer can take large amount of sediment with intact water/sediment surface and theoretically no disturbance, however, the cores are relatively short, mostly less than 50 cm.

A2. Subsampling techniques

A2.1 Liner subsampling
Usually several liners were applied to subsample a box core, which was practised on R/V Charles Darwin in Cruise 17 in the Arabian Sea. The liners are sealed at both ends and kept in a cool room set at 4 degree Celsius. Some sediments were later found to be oxidised, possibly due to the seal failure. To subsample the liner, a manual hydraulic pump or simply a rubber piston is used to push the sediment upwards. The extruded top was sliced at certain thickness, using a wire saw or a cheese cut and then sealed in air-tight plastic bag. Most samples were 2.0 cm thick,
some cores, e.g. 1734a, were subsampled at a 1.0 cm interval. All samples were stored in 4 °C cold room before use.

A2.2 Palaeomagnetic and geochemical samples

Palaeomagnetic samples were taken from the Mackereth cores, which are made of PVC. First cut the cores on board in half using electric saw, then press the plastic cubes (ca. 2x2x2 cm³) into the sediment side by side, making sure the box contains as much sediment as possible. Care should be taken not to squeeze the sediment. Geochemical samples were taken at an interval of 5 cm after its lithology was taken. For gravity cores, the corer needs to be laid down horizontally in order to extrude the sediment out of the stainless steel coring tube using a hydraulic piston. The sediment is then cut in half using a wire and subsampled at an interval of 10 cm. JX91-7G may have lost a considerable part of its top, as sands were seen flowing out from the tube during recovery. The sands were so fluid that they could not be subsampled, and the true depth could not be ascertained. All the samples are kept in air-tight bags and stored in cold room at 4 °C before being analysed. Samples for rock magnetic measurements are made from subsampled sediment in self-sealed bags. The same plastic cubes are used. When filling the cubes with sticky sediment, one must not squeeze the sediment, nor leave any bubbles in it, because the weight of the samples will determine the density of the sediment and its water content.

A3. X-ray photography

X-ray photograph for core 1734a was taken in the Scan-Ray X-Ray Laboratory in BGS (British Geological Survey) on 8 May 1995 by Mr. Graham Tulloch. The machine used in the Marine Geology and Operation Group is ScanRay AC 120 L. This is a fully potable X-ray cabinet with a Tungsten source. The whole procedure includes 1) warm-up, 2) photograph and 3) darkroom film developing.

The machine settings for core 1734a, which is in the category of f. sand/mud, are 85 kv, 3 mA and 3.5 minutes exposure time. Two orthogonal directions are oriented to X-ray. To take the X-ray photograph, the core was laid down horizontally in a mould
made of a mixture of resin and mud in order to compensate the exposure on the negative. There are two halves of mould. When combined, they form a rectangular block with a hole in the centre along the long axis. It is made so to eliminate the torture caused by different angles to the X-ray source. One side of the lower half is marked with lead dots with an interval of 1.0 cm and the name of core "1734". The "1" of "1734" in the first position is deliberately placed where a brown thin band is seen, but nothing appeared on the X-ray.

To developing the negative, put in solutions for 2 minutes each and then wash clean with running water. To get positives, set the contrast at 1.5 and exposure at 6 minutes in the departmental student darkroom. The machine can develop automatically within a minute. In this way the upper part is clear enough but too dark for the lower part of the core. Therefore for the lower part, exposure is set at 2 minutes.

A4. Particle size analysis (acetic acid treatment)

A Coulter LS100 laser particle size analyser was used for particle size analysis. Normal particle size measurement only requires sediment to be dispersed in water. For fresh unconsolidated sediment, extra sonicate time may not be quite necessary as the analyser has the built-in sonicate function before running (30 seconds is used). Normally less than 1 g sediment is enough for measurement.

Approximately 1 g of bulk sediment was placed in a beaker with 100 ml 20% acetic acid, and then set in warm bath for sonicating for 30 minutes with a glass cover, and left overnight for complete digestion. The sediment was washed with deionised distilled water to centrifuge tubes and centrifuged. Drain the clear liquid from the tubes, wash the sediment and centrifuged for three times.

For core 1739, the particle size analyses before and after the acetic acid treatment reveal completely different particle size distributions. As the acetic acid applied to dissolve forams is too weak for the lithogenic component in the sediment, this difference is therefore almost entirely caused by dissolving of the forams. It is often
noted that the mode of particle size distribution after acid treatment falls in the trough formed by the previous modes (poly-modal sediment), in particular for the top samples. This means the previous modes are purely formed by forams, and the detrital fraction is largely dwarfed by forams, unlike the matching modes in Fig. A-1.

The finer-grained forams seem to be non-existent earlier on in the sample of 36-38 cm, where the $^{14}$C dating is taken, as the finer fraction of the distribution matches with each other pretty well (Fig. A-1). This has provided a basis for estimating the foram contribution in terms of volume in the sediment. On the particular sample at 36-38 cm downcore, the volume of the forams is seen to be roughly 50% of the total sediment volume.

Fig. A-1 Particle size distributions of a sample at 37 cm in core 1739 before and after acetic acid treatment. NB the volume of the after-treatment sample is reduced to 52% to match the bulk sediment distribution before treatment, where the total difference in the fine range (0.4 -20 μm) of the two distributions is minimised.

Poly-modal particle size distribution is usually caused by more than two (inclusive) different transporting forces. For poly-modal sediment, the bulk sediment can be separated theoretically to a few normal distributions, each of which has one of the modes obviously seen in the bulk sediment particle size distribution. The characteristics of each independent fraction can be reflected by the individual normal
Appendix A

distributions. Please note this theoretical dissemblage of sediment is different from
the concept of 'population' used in probability plots, which is mainly based on
different transporting mechanisms.

A5. Magnetic measurements

A5.1 Magnetic susceptibility
Magnetic susceptibility is measured using a magnetic susceptibility meter (Model
MS2) made by Bartington Instruments Ltd, Oxford. The operation is simple: just
place the sample in the middle of the measuring cylinder after calibrating the reading
to zero and switch on. The meter is calibrated at 10cc and 10g, and can measure
susceptibility at two frequencies, which can be used to calculate frequency dependent
susceptibility using the formula,

\[ X_{fd}(\%) = \frac{X_L - X_H}{X_L} \times 100\% \]

where \( X_L \) is the susceptibility at low (1k Hz) frequency and \( X_H \) at high (10k Hz)
frequency. \( X_L \) is usually called magnetic susceptibility too.

A5.2 (S)IRM
Samples are first magnetised using a pulse magnetiser and then measured with a
Molspin magnetometer calibrated with a standard sample of 19.6 x 10^6 Am^2 (total
moment). The pulse magnetiser usually magnetises samples from about 10 mT up to
500 mT in about ten steps spread on logarithm scale (10, 20, 40, 60, 80, 100, 150,
200, 300, 500), and beyond that an electric magnet has to be applied to magnetise at
1T, which is regarded as the saturate magnetisation (SIRM). As IRM can slightly
decay with time, all the measurements have to be done in a systematic manner to
reduce error. As SIRM is hard to be fully demagnetised, (S)IRM is normally carried
out as the final magnetic measurement.

A5.3 ARM
Samples are implanted ARM using a demagnetiser (degausser) with a static magnetic
field of about 210 Oe (current 2.825A × instrument constant 74.6), and then
measured with a Molspin magnetometer calibrated with a 19.6 x 10^6 Am^2 standard.
Samples are normally demagnetised using the same demagnetiser without the static magnetic field. ARM is an ideal remanent magnetisation, but rather complicated in explanation as it is associated with both the concentration of magnetic minerals and their grain size.

A6. XRF major and trace element analysis

XRF major and trace elements are all measured on a x-ray spectrometer (Philips PW 1480) calibrated with international standards, however, to certain trace elements, e.g. uranium, unrealistic negative values are sometimes given mainly due to the low concentrations, though the relative variation downcore should be reliable. Major elements here include 10 elements: Si, Al, Fe, Ca, K, Na, Ti, Mg, Mn and P, and the 21 trace elements are Sc, Ba, V, La, Ce, Nd, Cr, Ni, Cu, Zn, Pb, Th, U, Rb, Sr, Y, Zr, Nb, Mo, I and Br. Major elements are measured in fused glass disc, while the trace elements are in pressed powder pellets. As preparation and production of samples are carefully done, following lab instructions, and more importantly in a systematic manner, the errors of XRF measurement, if of any significance, are limited largely to the average element concentrations in cores, but not the relative downcore variations. The error in the former is often found negligible as compared between different cores.

A7. $^{210}$Pb measurement: sample preparation
(based on Tim Brand’s instruction, 1994)

1) Weigh out accurately between 0.3 and 0.5 g of dry sediment powder and place into Teflon beaker.
2) Add 25 mls of digestive acid (1 perchloric acid : 10 concentrated nitric acid).
3) Add 50 (or 100) $\mu$L $^{208}$Po spike* to beaker
4) Reflux beakers with lids on for 36-48 hours on hot plate at 110 °C.
5) Remove lids and boil contents down to a small volume/mushy paste.
6) Add 20 mls of concentrated nitric acid and 10 mls of hydroflouric acid.
7) Reflux beakers with lids on for 36-48 hours on hot plate at 110 °C.
8) Remove lids and boil contents down to a paste or dryness.
9) Top up with 20 mls of concentrated hydrochloric acid.
10) Boil down to about half of the volume and take off hot plate.
11) Pour into labelled bottle and wash in with 10% hydrochloric acid.
12) Place 10 mls of 20% hydroxylamine hydrochloride into the bottles.
13) Adjust pH of solution in bottle to approx. 1.5 using ammonia solution.
14) Submerge labelled silver disc in the solution for about a week.
15) Recover the discs, rinse with deionised water and allow to dry.
16) Place in alpha detector.

The spike is made from standard $^\text{208}$Po sample diluting with 10% HCl. Silver discs waiting to be measured are kept in air-tight plastic bags. The whole procedure regularly achieves between 60 and 70% yield efficiency.

A8. $^{14}$C measurement: sample preparation

Five samples for $^{14}$C measurement are prepared (Table A-1). Effort was made to prepare samples from JX91-2A from the Bohai Sea and core 1735 from the Arabian Sea, but not enough CaCO$_3$ is present within an acceptable thickness of layer.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Core</th>
<th>Depth</th>
<th>Material</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1734a</td>
<td>25-28 cm</td>
<td>bulk sediment</td>
<td>Arabian Sea</td>
</tr>
<tr>
<td>2</td>
<td>1734a</td>
<td>32-35 cm</td>
<td>bulk sediment</td>
<td>Arabian Sea</td>
</tr>
<tr>
<td>3</td>
<td>1736</td>
<td>26-30 cm</td>
<td>bulk sediment</td>
<td>Arabian Sea</td>
</tr>
<tr>
<td>4</td>
<td>1739</td>
<td>36-38 cm</td>
<td>bulk sediment</td>
<td>Arabian Sea</td>
</tr>
<tr>
<td>5</td>
<td>JX91-7G</td>
<td>320 cm</td>
<td>bulk sediment + peat</td>
<td>Huanghai Sea</td>
</tr>
</tbody>
</table>

Samples 1-4 are sediments which should contain about 4 g of carbon each, calculated from CaCO$_3$ content using (Ca-0.28Al)x12/40. Sample 5 is a mixture of peat and sediment with exact carbon content unknown. The criteria for the above samples are
1) reasonably old (lower part of core);
2) high Ca concentration, which means thinner layer and therefore higher resolution;
3) at or near the event strata.
Appendix B

(Calculations and Programs)

B1. Salt-free correction

All the major and trace elements are corrected for salt, which remained in the sediment when fresh sediment was dried for measurements. This includes two steps, eliminating the responsible salt contribution to the raw element concentration and correcting for dilution effect.

B1.1 Salt contribution correction

Total salt (Ts) in a sample is:

\[ Ts = C_s \times Md = (w + Ts) \times S \]  \hspace{1cm} (B1-1)

where \( C_s \) is concentration of salt (%) in dry sediment, \( Md \) is the weight of dry sediment; \( w \) is total pure water in fresh sediment and \( S \) is salinity of seawater.

Md can be measured immediately out of the drying oven, and the pure water \( w \) can be calculated from wet sediment \( (M_w) \) and dried sediment \( (Md) \) using formula,

\[ w = M_w - Md \]  \hspace{1cm} (B1-2)

Therefore, from B1-1 the salt concentration \( C_s \) can be written as,

\[ C_s (%) = \frac{(w \times S)}{(Md \times (1 - S))} \times 100 \]  \hspace{1cm} (B1-3)

As water content \( C_w (%) \) is often expressed as pure water per weight of wet sediment, i.e.

\[ C_w (%) = \frac{w}{M_w} = \frac{w}{(w + Md)} \]  \hspace{1cm} (B1-4)

formula B1-3 can be rewritten as,

\[ \frac{C_w \times S}{1 - C_w} \times \frac{S}{1 - S} \times 100 \]  \hspace{1cm} (B1-5)

The elements need to be corrected are mainly Na, Mg, Ca, K, Sr, Ba, Rb, Mo, I and Br, based on element concentrations in seawater listed in Table A-2 (Bearman, 1989, and Weast, 1974).
Table A-2 Average concentration of principal ions present in seawater

<table>
<thead>
<tr>
<th>Element</th>
<th>Proportion by weight</th>
<th>Element</th>
<th>Proportion by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>10.556 %w</td>
<td>Sr</td>
<td>13 ppm</td>
</tr>
<tr>
<td>Mg</td>
<td>1.272 %w</td>
<td>Ba</td>
<td>0.05 ppm</td>
</tr>
<tr>
<td>Ca</td>
<td>0.400 %w</td>
<td>Rb</td>
<td>0.2 ppm</td>
</tr>
<tr>
<td>K</td>
<td>0.38 %w</td>
<td>Mo</td>
<td>0.01 ppm</td>
</tr>
<tr>
<td>Br</td>
<td>0.065 %w</td>
<td>I</td>
<td>0.06 ppm</td>
</tr>
</tbody>
</table>

The element correction ($C_{cor}$), which will be deducted from the raw element concentration, can be determined as in formula B1-6.

$$C_{cor} = (\frac{C_{ele}}{S}) \times C_s$$

$$C_{w} \left(1 - C_{w}\right) \left(1 - S\right)$$

where $C_{ele}$ is the element concentration in Table A-2.

It should be noted that salinity ($S$) varies from place to place. In the Bohai Sea, it is taken as 28 %w and in the Huanghai Sea 32 %w. Seawater in the Arabian Sea is regarded as standard with a salinity of 34.48 %w.

B1.2 Dilution effect correction

This correction is carried out on all the elements. It is mainly a correction for the dilution effect caused by the salt, usually quite small though. All elements need to multiply a factor $D$ to get corrected, which is established in the equations below,

$$C_{true} = D \times C_{raw} = D \times C_{cor}$$

$$C_{true} = \frac{C_{raw}}{1-C_s}$$

Therefore,

$$D = \frac{1}{1-C_s}$$

where $C_s$ is salt content determined in formula B1-5.

B2. Probability plot (program)

The key point to draw a probability plot is to create a probability scale, which can be well simulated by an error function. The program below can project the cumulative particle size data (volume in percentage) onto probability scale.
program pps2
  c Program to calculate Error Function and produce a probability scale to
c make the probability plot of the particle size data.
c
  integer n
  real erf(601), x(601), ps1(7200), ps2(7200), ps3(7200)
  character infile*80, outfile*80

  x(0)=-0.005
  do 10 i=1,601
    x(i)=0.005+x(i-1)
  x1=x(i)
  x2=x1*x1
  x3=x2*x1
  x4=x3*x1
  x5=x4*x1
  x6=x5*x1
  x7=1+0.0705230784*x1+0.0422820123*x2+0.0092705272*x3
  x8=0.0001520143*x4+0.0002765672*x5+0.0000430638*x6
  er(i)=1-(x7+x8)**(-16)
  continue

  print *, 'number of samples:'
  read (5,*), n
  print *, 'Enter the name of input file please:'
  read (5,'(a80)) infile
  print *, 'Enter the name of output file please:'
  read (5,'(a80)) outfile

  open (11, file=infile)
  open (12, file=outfile)

  do 19 j0=1,n
    do 20 j1=1,72
      j=(j0-1)*72+j1
      read (11,1) ps1(j)
      if (ps1(j).LT.0.01.OR.ps1(j).GT.99.99) goto 50
      ps2(j)=abs(1-ps1(j)/50)
    end if
    if (ps1(j).EQ.50) then
      ps3(j)=0
      goto 50
    end if
    do 30 k=1,601
      if (ps2(j).LE.erf(k)) goto 40
      continue
      30
    ps3(j)=(x(k)*(ps2(j)-erf(k-1))+(k-1)*(erf(k)-ps2(j)))/e
    if (ps1(j).LT.50) ps3(j)=-ps3(j)
  end do

  40 write (12,*), ps3(j)
  continue
  19 continue

A-10
Appendix B

B3. Principal component analysis (Minitab)

Principal component analysis (PCA) can be done using statistics package ‘Minitab’ now available in Microsoft Windows. Generally speaking, this analysis can give quantitative information about how consistent the data columns in a dataset are and how the data columns co-vary with each other. It is used in two ways in this study, 1) to correlate the element (major and trace) data down the length of cores and 2) to correlate the downcore samples (with depth) based on element variations.

Correlation between the elements can reveal the grouping of the elements and help analyse the pattern and origin of sediment, and the depth correlation can show the sediment types at different depths and even between different cores if used with data from more than one core, as in JX91-7m and 7G. To do the depth (stratigraphical) correlation, the dataset has to be normalised using the formula below, otherwise smaller absolute variations will get lost when used with greater ones.

\[ NE = \frac{(OE) - \text{min}(OE)}{(\text{max}(OE) - \text{min}(OE))} \times 100 \]  

(B3-1)

where [NE] is normalised element content, [OE] is original element content, min(OE) is the minimum in the [OE] dataset and max(OE) is the maximum in the [OE] dataset.

This formula can normalise every data between 0 and 100, making every dataset have the equal weight for PCA process. Moreover the whole data sheet needs to be transposed before put into 'Minitab' spread sheet. Normally only the first three principal components are used to examine the relationship between data columns.
**B4. Supporting level for \(^{210}\text{Pb}\)**

Suppose the \(^{238}\text{U}\) series in the sediment is in equilibrium, then the radioactivity of \(^{238}\text{U}\) should be equivalent to that of \(^{210}\text{Pb}\), and this is why we have the supporting level for \(^{210}\text{Pb}\). The system is supposed to be a ‘close’ one with no addition of \(\text{U}\) or \(\text{Pb}\) etc. and without \(^{226}\text{Ra}\) and particularly \(^{222}\text{Rn}\) loss (Ivanovich and Harmon, 1982).

Through XRF trace element measurement, we know the concentration of the uranium in the sediment can be determined. The isotope ratio of uranium is quite stable in nature and hence we know the concentration of \(^{238}\text{U}\) atoms in the unit of ppm [U]. Divided by the atomic weight of uranium, 238.029, and multiplied by the Avogadro constant \((L)\), 6.022\(\times\)10\(^{23}\), we have the total number of uranium nuclei. With a stable \(^{238}\text{U}\) isotope ratio of 99.275\%, we have the total number of \(^{238}\text{U}\) atoms in one gram of dry sediment:

\[
N = [\text{U}]\times L \times 99.275\% / 238.029 \tag{B4-1}
\]

Secular equilibrium implies that the activity at any particular decay in a series is the same, i.e. the activity of \(^{210}\text{Pb}\) is equal to that of \(^{238}\text{U}\). Hence we have,

\[
dN/dt = -xN = -N \times \text{Ln}(2) / (4.47 \times 10^9 \text{ yr}) \tag{B4-2}
\]

For activity in dpm:

\[
A = [\text{U}] \times 6.022 \times 10^{23} \times 0.693 \times 99.275\% / (238.029 \times 4.47 \times 365 \times 24 \times 60 \times 10^9) \text{ (dpm)}
\]

\[
= 7.409 \times 10^5 \times [\text{U}] \tag{B4-3}
\]

For \([\text{U}] \) of 1 ppm, the activity is 0.74 dpm/g.

**B5. Accumulation rate**

Radioactive activity \((A)\) can be generally expressed as an exponential equation (Ivanovich and Harmon, 1982) as below,
\[ A = A_0 \exp(-\lambda t) \]  \hspace{1cm} (B5-1)

where \( A_0 \) is the original activity and \( \lambda \) is the decay constant, which is determined by the half life \( (t_{1/2}) \) of radioactive element as,

\[ \lambda = \frac{\ln(2)}{t_{1/2}} \]  \hspace{1cm} (B5-2)

\(^{210}\)Pb is found to be ideal for dating because the half of \(^{210}\)Pb is 22.3 years, not too long or too short for most sedimentation processes. Moreover, the isolation of \(^{210}\)Pb is ascribed to its precursor \(^{222}\)Rn, a noble gas, which escapes from the earth's surface into the atmosphere where it decays to \(^{210}\)Pb through a series of short-lived intermediaries (Ivanovich and Harmon, 1982). This unsupported \(^{210}\)Pb is brought down from troposphere by precipitation and dry fallout at a constant rate at a given locality, which forms the basis for \(^{210}\)Pb dating.

Suppose the accumulation rate (R) is a constant at the top part of a sediment core, then the time (t) in formula B5-1 becomes,

\[ t = \frac{d}{R} \]  \hspace{1cm} (B5-3)

where \( d \) is the depth of sample.

Substituting B5-3 in B5-1, we have

\[ A = A_0 \exp(-\lambda d/R) \]  \hspace{1cm} (B5-4)

\[ \ln(A) = \ln(A_0) + (-\lambda d/R) \]

\[ R = \frac{\lambda d}{[\ln(A_0) - \ln(A)]} \]  \hspace{1cm} (B5-5)

In a downcore \(^{210}\)Pb profile, \([\ln(A_0) - \ln(A)]/d\) is the slope of the curve (s). So the accumulation rate can be obtained as,

\[ R = \frac{\lambda}{s} \]  \hspace{1cm} (B5-6)

The \(^{210}\)Pb activity should be only produced by the excess \(^{210}\)Pb, as seen from the inference, therefore a \(^{210}\)Pb supporting level, which forms the background of the activity profile, has to be determined and deducted before applying formula B5-6. The slope of the curve is usually taken from the data regression results.
B6. Correction for effect of different pellet thickness

There are two types of pellets for gamma counting of core 1736. One is 10g and the other is 15g. As they have the same diameter, the difference in weight only causes the difference in pellet thickness.

Suppose the 10g pellet is composed by two sub-pellets, each of which is 5g and half of the thickness, and 15g pellets three of the sub-pellets. The gamma ray produced from the lower sub-pellet will be directly detected by the gamma detector, and the upper one will penetrate the lower to be detected, and so forth. Suppose the outcome of gamma ray from the lower sub-pellet is \( G \) (cnts/s) and the adsorption parameter of the sub-pellet is \( k \) (0<\( k <1 \)), then for the 10g pellet (G10) we have:

\[
G_{10} = G + kG \\
\]
and for the 15g pellets (G15):

\[
G_{15} = G + kG + k^2G \\
\]

If no sample is prepared with both a 10g and a 15g pellets, a possible solution to the equations can be found in the supporting level, where 15g pellet will show a slightly stronger activity than the 10g pellet, which is solely due to the mass difference. If the 10g supporting level is determined as \( G'_{10} \) and the 15g is measured as \( G'_{15} \), then

\[
G'_{10} = G + kG \\
\]
and

\[
G'_{15} = G + kG + k^2G \\
\]

From (B6-1'), we have, \( G = G'_{10}/(k+1) \). Substitute in (B6-2'), we get,

\[
G'_{15} = G'_{10} (1 + k + k^2)/(k+1) \\
\]
i.e.

\[
k^2 + (1 - G'_{15}/G'_{10})k + (1 - G'_{15}/G'_{10}) = 0 \\
\]

Let \( r = 1 - \frac{G'15}{G'10} \) (-1/2 < r < 0), we have

\[
 k = \frac{-r + \sqrt{r^2 - 4r}}{2} \quad \text{(B6-4)}
\]

This parameter can be used in the whole core, if the lithology does not change very much.

So an equivalent activity of a 10g pellet for any 15g one is

\[
 G'10 = (1 + k) \frac{G = G15}{(k+1)/(k^2+k+1)} \quad \text{(B6-5)}
\]

If \( k=0 \), then \( G'10 = G15 \)

If \( k=1 \), then \( G'10 = \frac{2}{3} G15 \)

In core 1736, as the support level is already very clear at 23 cm (2.85 dpm/g), the pellet at 25 cm should have shown the same result if it were a 15g one, so \( G'10 = 2.8575 \) dpm/g and \( G'15 = 3.142 \) dpm/g, and \( k=0.37 \).

**B7. Conversion of gamma counting data to alpha counting data**

The conversion is basically a problem of calibration. To find the link between the two data formats, a set of samples need to be run on both machines, which are not necessarily standard ones. A few samples of JX91-3B were measured on both of the gamma counter and the alpha counter. Samples at 0, 5 and 20 cm down the length of JX91-3B are taken for the calibration. The results are as in Table A-3 and depicted in Fig. A-2.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>gamma counting (cts/s)</th>
<th>alpha counting (dpm/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0118</td>
<td>2.792642</td>
</tr>
<tr>
<td>5</td>
<td>0.01127</td>
<td>2.72656</td>
</tr>
<tr>
<td>20</td>
<td>0.01024</td>
<td>2.434879</td>
</tr>
</tbody>
</table>
Fig. A-2 Conversion between gamma and alpha counter data based on samples from JX91-3B.

The calibration line can be determined by regression on the three points, which shows good linear correlation ($R^2 = 0.97$):

$$A \text{ (dpm/g)} = 236.6811G \text{ (cts/s)} + 0.023411 \quad (B7-1)$$

where $G$ is the gamma counting and $A$ is the equivalent alpha counting. This formula is used to convert the gamma counting data to alpha data format in core 1736.

It is worth noting that the same accumulation rate can be practically worked out using either $A$ (dpm/g) or $G$ (cts/s), for the constant 0.023411 is negligible as compared with the normal $A$ values (two orders smaller in magnitude) and the ratio of 236.6811 does not count when logarithm is taken in the operation of subtraction (ref. to Appendix B7).

**B8. Coriolis force: 3D effect**

It is often thought the Coriolis force is only acting on moving object on a ‘horizontal’ plane. In fact, the Coriolis force has a 3D effect on moving object from the viewpoint of the earth (Fig. A-3). The Coriolis force is accurately expressed as

$$F_c = 2m \mathbf{u} \times \omega \quad (B8-1)$$

where $\mathbf{u}$ is the velocity vector and $\omega$ is the rotational vector of the earth. In a local coordinates, $\mathbf{u}$ and $\omega$ can be expressed as
\[ u = u_1 \hat{i} + u_2 \hat{j} + u_3 \hat{k} \]
\[ \omega = \omega_1 \hat{i} + \omega_2 \hat{j} + \omega_3 \hat{k} \quad (B8-2) \]

where \( \hat{i}, \hat{j} \) and \( \hat{k} \) are unit vectors indicating east, north and upward respectively. As \( u \) is restrained on the horizontal plane, \( u_3 = 0 \), and as \( \omega \) points north and upward in northern hemisphere, \( \omega_1 = 0 \). Suppose the latitude of origin of the local co-ordinates is \( \phi \) and the angle between \( u \) and \( j \) is \( \theta \), i.e. \( \theta \) degree east to north, then we have:

\[ u_1 = u \sin \theta, \quad u_2 = u \cos \theta \]
\[ \omega_2 = \omega \cos \phi, \quad \omega_3 = \omega \sin \phi \]

\[ u = u \sin \theta \hat{i} + u \cos \theta \hat{j} \]
\[ \omega = \omega \cos \phi \hat{j} + \omega \sin \phi \hat{k} \quad (B8-3) \]

The Coriolis force is then has the form of:

\[ F_c = 2\omega (\cos \theta \sin \phi \hat{i} - \sin \theta \sin \phi \hat{j} + \sin \theta \cos \phi \hat{k}) \quad (B8-4) \]

Usually, only the horizontal component of the force is stressed, which is

\[ F_{ch} = 2\omega (\cos \theta \sin \phi \hat{i} - \sin \theta \sin \phi \hat{j}) = 2\omega \sin \phi (\cos \theta \hat{i} - \sin \theta \hat{j}) \quad (B8-5) \]

\( F_{ch} \) has an magnitude of \( 2u \omega \sin \phi \), as written in most text books, and a direction perpendicular to \( u \), as we can see \( (\sin \theta \hat{i} + \cos \theta \hat{j}) \cdot (\cos \theta \hat{i} - \sin \theta \hat{j}) = 0 \).

The upward force \( F_{cu} = 2\omega \sin \theta \cos \phi \hat{k} \) should also be noticed. When two winds meet together at a particular latitude, the wind direction, \( \theta \), seems important for the vertical movement of the wind. Ocean current follows the same law. N.B. when the current moving at an angle \( \theta > 180^\circ \), \( F_{cu} \) will point downward, i.e. no upwelling.
Appendix C
(Mathematical Models)

C1. Sediment dispersion model

C1.1 Sediment transported by water current
The particles should be deposited at a rate proportional to the density in the current if
the particles can be locked up immediately after deposition. However, the deposited
particles can rejoin the current or move along the surface of the water/sediment
interface (saltation and traction). This determines in most cases in fluvial processes a
simple mathematical description of deposition will not be available, different from
that in aeolian deposition at sea (C1.2).

Direct deposition process will theoretically result in a rapid decrease in intensity from
sediment source, but as there are saltation and traction, which can bring in previously
deposited particles, the actual decrease will not be that rapid. A realistic model
should be a compromise of the two processes. Mathematically a linear decrease
model and a 1/x model for sediment dispersion are both between an exponential
decrease and constant dispersion, but considering the high proportion of saltation
population in the bulk sediment (ref. to Figs. 4.1-2, 4.2-4), I will use the linear
dispersion model rather than the 1/x model for the Huanghe estuarine sediment
dispersion in the Bohai Sea. The establishment of model in the Bohai Sea is
discussed in section 3.1.

The average annual sediment discharge to the Huanghe River Delta is about 1.2
billion tons in the long run, but only a quarter of it is dispersed out of the rivermouth
area in the Bohai Sea (Pang and Si, 1979). As the average wet density of the Bohai
Sea sediment is 1.8 t/m^3, so the volume of the annual sediment input (V) is 1/6 km^3.
So we have,

\[ V = \int_{170}^{70} (\pi r/2)k(170-r) \, dr = (k\pi/2)(8.5r^2 - r^3/3) \bigg|_{170}^{70} = 1/6 \, (\text{km}^3) \]  (C1-1)
where $\pi r/2$ is the length of a quarter of a circle and $k(170-r)$ is the accumulation rate at distance $r$ ($70<r<170$). The integration is the total volume of sediment dispersed in the Bohai Sea. Therefore, $k = 2.05 \times 10^{-7}$.

Let the distance from the delta $x$ (km) = $r-70$, the accumulation rate $s$ will be,

$$s = k(170-r) \text{ (km/a)} = 2.05 \times 10^{-7} (100-x) \text{ (km/a)}$$

$$= 0.0205x(100-x) \text{ (cm/a)} \quad \text{(C1-2)}$$

At the coresite of JX91-3B, $x=30$ km, so the accumulation rate

$s = 1.4 \text{ (cm/a)}$

At the coresite of JX91-2A, $x=70$ km, the accumulation rate

$s = 0.6 \text{ (cm/a)}$

C1.2 Sediment transported by wind

As particles transported by wind and deposited in water cannot bounce back to the air, nor move along at a speed comparable to the wind, the relationship between density of the particles and the dropout is simple: they should be proportional.

Within a windfield where the transporting force is stable and unique, the distribution of particle size will represent only this single force and has the form of a normal (Gaussian) distribution. As long as the wind strength remains the same, which is very likely at open sea, the particle size distribution will not change much, although the mode will move to the finer end as heavy and large particles drop out preferentially at air/sea interface.

Suppose the concentration of particles in a wind near sea surface is $C$ (g·m$^{-2}$), the rate of dropout is $r$ (g·m$^{-3}$), in a stable windfield over a sea, the relationship between the
concentration of particles over a distance of $u$ (km) from source area can be expressed as,

$$r = -\frac{\Delta C}{\Delta u}$$
$$r \propto C$$

$$\frac{dC}{du} = -r = -kC$$  \hspace{1cm} (C1-3)

where $k$ is a constant

$$\ln (C) = -ku + \ln (C_0)$$
$$C = C_0 \exp [-ku]$$

$$r = kC_0 \exp[-ku] = r_0 \exp(-ku)$$  \hspace{1cm} (C1-4)

This means the accumulation rate of aeolian dust is exponentially decreasing with the distance from the source. The characteristics of the exponential function is that it decrease very rapidly at the beginning and remain fairly constant in the long run.

As the accumulation rates at core 1735 has the best date control and core 1733 present the smallest accumulation rate in the nearshore area, these two cores are used to determine the two parameters, $r_0$ and $k$ in formula C1-4. The formula thus becomes:

$$r \text{ (cm/ka)} = 265 \exp(-0.105*u)$$  \hspace{1cm} (C1-5)

However, it seems the accumulation rates between the two cores are rather great, another parameter is therefore added to the equation to simulate the curve (Fig. 4.3-2) with concise parameters. It is the ambient accumulation rate in the Arabian Sea, 3.3 cm/ka, obtained from core 1739. The formula has finally had the form:

$$r = 400 * \exp (-0.15 *u) + 3.3$$  \hspace{1cm} (C1-6)
Actually the particles in the sea can be carried away by water current, but there are two main reasons making it negligible for consideration.

1) speed. The speed of horizontal movement is rather small as compared with the wind speed, so it is negligible. On the other hand, the falling speed is greater than the current speed (Hsu, 1989).

2) relation. If all the particles experience the same process in the region, then the uncertainty of particle deposition becomes a systematic error, i.e. there will be practically no difference as considering the particles do not move laterally at all.

C2. $^{210}$Pb correction model

C2.1 Bioturbation

1. Sediment mixing

How bioturbation, among other disturbance to sediment, affects radiochronological results, e.g. $^{210}$Pb dating, is not well known. Here theoretical approach is applied to figure out the possible influence of the bioturbation on sediment based on mathematical models. Sketch of a thorough mixing model is depicted in Fig. A-4.

2. Mixing zone

Mixing zone is where the bioturbation is occurring, and/or physical mixing is effective. Sediment is mixed up within the zone and it can definitely affect the dating results, increasing the accumulation rate if measured only in this zone. In this simple mixing model, the activity of all the sediment within the zone is the same.

3. Stable section

The word 'stable' here is only relative to the mixing zone. The stable section means the part of core under the mixing zone, which had been mixed early on and radiochemical activities can take place undisturbed. Suppose a stable unit cell in the sediment is the result of constant bioturbation, which always mixes completely $l$ units of sediment in the upper part of the core. The depth of the unit is greater than $l$, so it is under the mixing zone and free of bioturbation. It contains components from
Appendix C

infinite original units underneath and \( l \)-1 original units upward due to bioturbation. These original units are numbered \( 1, 2, 3, \ldots, m \).

![Diagram showing original and mixed sediment with time](image)

Fig. A-4 Sketch of a thorough mixing model with a mixing depth of 3 units.

As the mixing zone consists of \( l \) units, the component from the first original unit is \( 1/l \). The second component occupies \( 1/l \) of the rest of unit \( 1-1/l \), so it should be \( 1/l \) (1-

1/l). The third component is therefore \( 1/l \) of the rest of unit apart from the first and
the second components, and can be expressed as \(1/l [1-1/l -1/l (1-1/l)] = 1/l (1-1/l)^2\).
It can be derived that the \(m\) component is \(1/l (1-1/l)^{m-1}\), which is actually a
generalised formula for the volume of components within the unit.

In fact we have the volume of the unit,

\[
V = \sum_{m=1}^{\infty} \frac{1}{(1/l)^{m-1} = (1/l)} = 1 \frac{1}{1- (1-1/l)}
\]

Suppose the original activity of the unit is \(A_0\), which obeys the decay law \(A = A_0 e^{-\lambda \Delta t}\), and the accumulation rate remains the same, then the time span between any two
original adjacent units, \(\Delta t\), will be the same and the activity of the unit after
bioturbation is

\[
A_0' = \sum_{m=1}^{\infty} \frac{(1/l) \sum_{m=1}^{\infty} e^{-\lambda(m-1)\Delta t}}{1- (1-1/l) e^{-\lambda\Delta t}}
\]

so, \(A_0' = \frac{A_0}{l e^{\lambda \Delta t} - (l-1)}\) \hspace{1cm} (C2-2)

This is to say in the stable section the activity of the unit depends on how thick the
mixing zone \(l\) is and the time span, \(\Delta t\), i.e. the accumulation rate. It is obvious from
formula (C2-2) that if \(l\) (\(l>1\)) is a constant and \(\Delta t\) changes, or \(\Delta t\) remains the same and
\(l\) varies, \(A_0'\) is always greater than \(A_0\), just as predicted from the effect of
bioturbation. Actually, if we let \(z=e^{xy}+x\) +1, where \(x=1, y=\lambda \Delta t, x>1, y>0\), then,
\(\partial z/\partial x = ye^{xy}+y+1\), if \(x=1, y=0\), then \(\partial z/\partial x = 0\), and \(\partial z/\partial x\) increases with \(x\) and \(y\), so
\(\partial z/\partial x > 0\), therefore, \(z>0\), i.e. the factor \(e^{\lambda \Delta t} / [l e^{\lambda \Delta t} - (l-1)] > 1\)
This effect tends to average the $^{210}\text{Pb}$ distribution along the column, thus leads to a higher accumulation rate if calculated across the boundary of the mixing zone and the stable section.

Select a series of points with an interval of $l$ in the stable section, 0, 1, 2, 3, ..., $n$, ..., and suppose the activity of the first point is $A_0' = A_0 e^{\lambda \Delta t} / [l e^{\lambda \Delta t} - (l-1)]$ (from C2-2). According to formula C2-1, it is not difficult to get the activity at the second point,

$$A_1' = \sum_{m=1}^{\infty} \frac{1}{l} (1-1/l)^{m-1} A_0 e^{\lambda (m-1)\Delta t}$$

$$= A_0 \frac{e^{\lambda (l-1)\Delta t}}{l e^{\lambda \Delta t} - (l-1)}$$

(C2-3)

$$...,$$

and the activity at $n$ is,

$$A_n' = A_0 \frac{e^{\lambda (l-n)\Delta t}}{l e^{\lambda \Delta t} - (l-1)} = A_0' e^{\lambda n \Delta t}$$

(C2-4)

In comparison, the original activity should be $A_n = A_0 e^{\lambda n \Delta t}$, therefore the decay ratio is the same, i.e. both the original and the bio-disturbed accumulation rate is the same, though the amplitudes of the activity with and without bioturbation are different. The ratio of the amplitudes is

$$R = \frac{A_n'}{A_n} = e^{\lambda l \Delta t} / [l e^{\lambda \Delta t} - (l-1)]$$

(C2-5)

$$n = 0, 1, 2, 3, ..., which is dependent on the length of the mixing zone.

If the accumulation rate is calculated using data from the stable zone, the result should be reliable according to this model, but the activities there can be exaggerated as a result of sediment mixing either biologically or physically.
4. Discussion

The accumulation rate is not a direct result from the $^{210}$Pb measurement. The activity is expressed in dpm/g, so the ratio can only reflect the mass input rate. If the accumulation rate has to be worked out, sediment density should be multiplied to give volume activity in dpm/cm$^3$. Only volume activity, not mass activity, can be used in calculation of accumulation rate in the common sense. However, as sediment density is usually roughly the same in mixed sediment or constantly accumulated sediment, which is actually a presumption for $^{210}$Pb dating, the dpm/g based accumulation rate is acceptable and should be the same as the dpm/cm$^3$ based one.

C2.2 Total excess $^{210}$Pb method

The basic idea behind this method is that the total excess $^{210}$Pb in the whole sediment profile should be a constant (at equilibrium) regardless of the downcore $^{210}$Pb distribution, if

1) the site has been receiving continuous deposition for over 100 years,
2) the characteristics of particulate (scavenger of $^{210}$Pb) remain the same during that time, and
3) $^{210}$Pb distribution in water mass remains the same during that time.

The first condition guarantees an equilibrium in sediment, though not necessary in practice. The second and third conditions can be less strict if relevant total excess $^{210}$Pb in two adjacent cores are considered. It only requires the properties of sediment and distribution of $^{210}$Pb change simultaneously.

For the purpose of comparison of accumulation rates of two nearby cores, such like cores 1735 and 1736 in the Gulf of Oman, the three conditions listed above need to be examined to see whether the total excess $^{210}$Pb between the two cores is comparable. It usually has the ground to compare if the cores are within a small area.

Total excess $^{210}$Pb in sediment profile is determined by (1) the $^{210}$Pb available to the system and (2) the presence and effectiveness of the scavengers. The distribution of
$^{210}\text{Pb}$ is usually assumed uniform in seawater column. In two simple situations, the relationship between total excess $^{210}\text{Pb}$ in two cores can be found directly.

1) If $^{210}\text{Pb}$ in seawater column is scavenged at the same rate in different water depths by the same amount of scavengers (particulates), the total excess of $^{210}\text{Pb}$ should be proportional to the water depth;

2) If the water depths are the same, the total excess $^{210}\text{Pb}$ will be proportional to the scavengers available, i.e. the accumulation rate, provided the properties of sediment are the same, which means the higher accumulation rate is, the more total excess $^{210}\text{Pb}$ can be kept in the sediment profile.

Therefore the relationship between total excess $^{210}\text{Pb}$ ($T$), waterdepth ($d$) and accumulation rate ($r$) can be expressed as:

$$T = k \cdot rd$$  \hspace{1cm} (C2-6)

where $k$ is a constant in certain area, but maybe different from area to area.

In different cores from the same area, we have

$$\frac{T_1}{T_2} = \frac{r_1 \cdot d_1}{r_2 \cdot d_2}$$

$$\frac{r_1}{r_2} = \frac{(T_1 \cdot d_2)}{(T_2 \cdot d_1)}$$  \hspace{1cm} (C2-7)

$T_1$, $T_2$ can be calculated from the $^{210}\text{Pb}$ profile and $d_1$ and $d_2$ are the known waterdepths at the coresites. This formula can give a rough idea how accumulation rates of two nearby cores are related with each other within certain area, despite bioturbation and other disturbance to the sediment.
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infinite *original* units underneath and $l-1$ *original* units upward due to bioturbation. These original units are numbered 1, 2, 3, ..., $m$.

As the mixing zone consists of $l$ units, the component from the first original unit is $1/l$. The second component occupies $1/l$ of the rest of unit $1-1/l$, so it should be $1/l (1-1/l)$. The third component is therefore $1/l$ of the rest of unit apart from the first and
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Recent Soil Erosion on the Loess Plateau through Geochemical and Palaeomagnetic Studies on the Huanghe Estuarine Sediment in the Bohai Sea, China

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Abstract

An estuarine sediment core, JX91-3B, was recovered about 30 km off the Huanghe River delta in the Bohai Sea. Multidisciplinary studies, including geochemistry and palaeomagnetism, have been carried out on the core. Principal component analysis (PCA) of XRF major and trace elements has revealed four groups of elements relating to two main processes involved in the sedimentation. Palaeomagnetic analysis supports the idea that in situ depositional environment in the Bohai Sea and sediment supply from the Huanghe River are the two controlling factors. Lithogenic elements, represented by Si and Al, frequency-dependent susceptibility $\chi_{fd}$ (%) and particle size distribution are controlled by the former, while magnetic susceptibility, phosphorus, REEs and titanium are determined by the later. On the Loess Plateau biogeochemical elements, such as P and Mo, are generally enriched and magnetic susceptibility is enhanced in topsoil in contrast to loess, therefore topsoil erosion, once occurs, can produce a distinct signal in the sediment. As topsoil on the plateau is normally protected by vegetation, topsoil erosion, unlike loess erosion, is less likely to occur except during heavy rainstorms. A comparison is made between the magnetic susceptibility and the hydraulic records of the Huanghe River over the past 60 years, which shows a sound coincidence of magnetic susceptibility spikes in flooding years. This confirms magnetic susceptibility, P, REEs and Ti in the Huanghe estuarine sediment are good indicators of soil erosion on the Loess Plateau, and consequently reveals a longer yet unknown history of topsoil erosion on the plateau.

Keyword: soil erosion, estuarine sediment, geochemistry, magnetic susceptibility, Huanghe River, Loess Plateau, Bohai Sea

INTRODUCTION

The Huanghe (Yellow) River traverses the vast Loess Plateau in North China and transports an average of 1.2 billion tons of sediment annually to the Bohai Sea [9, 15, 20]. As about 90% of the sediment is from the Loess Plateau [20], the Huanghe River has practically served as a strong land-sea connection which makes it possible to study soil erosion on the Loess Plateau by examining Huanghe estuarine sediment in the Bohai Sea. Sedimentary records of recent soil erosion on the plateau could be preserved straightway in the rapidly accumulated estuarine sediment [5, 9], however, as sedimentation processes in the Bohai Sea would inevitably impose their impact on the sediment, it will be crucial to identify as many indicators as possible in the sediment regarding all the main processes so that the two sets of records can be separated and recovered.
To tackle this problem effectively, detailed multi-disciplinary studies, together with statistical analysis, are essential. While palaeomagnetic studies on the Chinese loess have been so successful concerning palaeoclimate and magnetostratigraphy [8, 10, 11, 26], much less work of this kind has been done in the Bohai Sea [9]; on the other hand, more systematic geochemical work has been carried out at the sea than on the plateau [25, 27, 31]. Besides these difficulties caused by incomplete data sets, another problem for making a direct land-sea correlation was the lack of a high resolution chronostratigraphy for the estuarine sediment, which is recently solved by Chen and Shimmield [5] using historical records of channel switchings on the Huanghe River delta and $^{210}$Pb dating. This paper will focus on geochemical and palaeomagnetic studies, which prove to be two most successful analytical methods, on the Huanghe estuarine sediment concerning the soil erosion on the Loess Plateau.

**Geological setting and core description**

The Bohai Sea is a semi-isolated inlet in northeast China with an average water depth of 18 m [9]. The rather quiet depositional environment in the sea helps the Huanghe River develop a huge modern delta, which is still growing at 23 km$^2$/a [16]. The Huanghe sediment dominates most part of the sea and the sediment around the delta is almost exclusively from the Huanghe River. Because of the enormous sediment input from the river, the accumulation rate in the estuarine area is pretty high [9], ensuring the sedimentation record a high resolution.

A sediment core, JX91-3B, was recovered during cruise JX91 using a pneumatic Mackereth type corer [12] at about 30 km off the Huanghe River delta within the Huanghe estuarine area (Fig. 1). Fig. 2 shows the lithology profile of the core. The normal Huanghe sediment is fine-grained mud, hardly coarser than 20 µm [9], which is seen to comprise the main part of the core. It is extraordinary to find three sandy layers interspersed in the mud with means exceeding 60 µm (ref. to Fig. 4), as the typical mode of loess only falls in the range of 20 - 40 µm [18]. In fact, the sandy layers were generated under a much stronger hydraulic condition when the river discharged towards the coresite where the fine-grained fraction of the original Huanghe sediment could not get deposited [5]. The three sandy layers are found to be formed during 1897-1904, 1929-1934 and 1934-1953 AD respectively, and the shell layers were associated with initial flushing at the beginning of channel switching [5, 16].
GEOCHEMICAL AND PALAEOMAGNETIC ANALYSES

Geochemistry

Not all the XRF major and trace elements of JX91-313 vary in a same pattern down the length of core (ref. to Fig. 5). In order to analyse these multivariate data, the widely used principal component analysis (PCA), is recommended [17], which has already proved to be successful on geochemical analysis of marine sediments [e.g. 22]. PCA is a data reduction technique used to identify a small set of variables that account for a large proportion of the total variance in the original variables.

Table 1 shows the PCA results for JX91-313. As the third component pc3 contributes less than 5% to the total variance, the first three components, pc1, pc2 and pc3, combined to account for over 80% of the total variance, are thought to have enclosed all the major controlling processes present. Here each principal component is regarded as one particular process, and each value for an element shows the extent of its impact on this elements. Negative value simply indicates an opposite impact on the element. Therefore an element that possesses the greatest value on one component but smallest on the other two should best represent that particular process; while those with modest values may be influenced more or less by other process(es). Fig. 3 illustrates the PCA results in 3D diagram and in biplots, for all the principal components are orthogonal. Four elements, namely Si, Al, P and Sr, are identified as representatives of their groups relating to three independent processes.

Figure 2. Lithology profile of JX91-313. Note three homogeneous sandy layers are interspersed in muddy sediment and the upper two are separated by a thin mud layer. Two obvious shell layers locate at the bottoms of two sandy layers.

The major rock-forming minerals in loess are quartz (SiO2) and feldspar (up to 90%), especially in the coarser fractions [2]. It can be therefore expected that Si content will be higher in sand but lower in mud. In Fig. 4, which shows the four element representatives in comparison with particle size data, Si does vary very much in line with the mean of particle size distribution, indicating the Si group (also including Na and Zr) is controlled by lithology and hence the in situ depositional environment. It is quite understandable that the Al group, including the majority of the rest elements and representing finer fractions of the Huanghe sediment, varies opposite to the Si group.
Figure 3. PCA results of XRF major and trace elements for JX91-3B, (a) a 3D presentation, (b) pc3 vs. pc2, (c) pc3 vs. pc1 and (d) pc2 vs. pc1. Distribution of these elements is determined by three processes quantified in pc1, pc2 and pc3. Two of the components, pc1 and pc3, are related, but pc2 is independent. Si, Al, P and Sr are four representatives of four groups of elements controlled by these processes.
As for Sr, its association with Ca in shells is well known [31], but because of the high content of calcium carbonate in Huanghe sediment [9], Ca failed to turn up in this group. Nevertheless, Sr has already been confirmed to be almost exclusively of shell origin in the Bohai Sea sediment [31], which can also be found in Figs. 2 and 4. It is highly suggested these shells were washed to the coresite by initial flushing of the riverwater via tidal flat at the very beginning of a new channel switching that later formed the sandy layers [5]. The Sr spike at 205 cm down core is boosted by shells too, actually many tiny shell fragments, which were not quite distinguishable to naked eyes. So the Sr group is also related to depositional environment, or more accurately, the change in depositional environment.

It is interesting to note that unlike the Si, Al and Sr groups, the P group shows nothing comparable to the lithology and hence in situ depositional environment (Fig. 4). As the second largest process (pc2), accounting for nearly 20% of the total variance (Table 1), the P group controlling process is not at all negligible. Since the P group receives little influence from the prevailing sedimentation processes, nor is it likely to be affected by minor processes even collectively in the Bohai Sea, it must have been associated with the original sediment supply from the Huanghe River.

**Palaeomagnetism**

Magnetic susceptibility (S.I.) and frequency-dependent susceptibility $\chi_{fd}(\%)$ are two commonly used palaeomagnetic parameters for loess study [e.g. 7, 13, 14, 32]. Generally speaking, magnetic susceptibility reflects the overall concentration of magnetic minerals, while the frequency-dependent susceptibility targets the ferromagnetic grain size distribution, the ultra-fine fraction in particular [23, 24, 28, 32].

Fig. 4 shows clearly that the magnetic susceptibility agrees with P pretty well, though in more detail due to a smaller sampling interval (~ 2.37 cm) for palaeomagnetic samples.
Figure 4. Profile of representative elements, Si (%), Al (%), P (%), and Sr (ppm), magnetic susceptibility X (S.I.) and its frequency dependence Xfd (%), and mean (μm) of particle size distribution for JX91-3B. It can be seen that Si, Al, Xfd and mean are associated with lithology, while Sr is related to shell layers and P and X are in good agreement but independent of the others. The three sandy layers indicated by hatched area are dated by Chen and Shimmield [5].
Nevertheless, $\chi_{fd}$ follows the pattern of Al and opposite to that of Si and particle size mean, indicating the grain size of magnetic minerals is in line with the bulk sediment. It is noticed that while $\chi_{fd}$ fluctuates very little within the rather homogeneous layers, the susceptibility varies significantly. This means the magnetic susceptibility variation in the sediment is not resulted from grain size change of magnetic minerals, but simply the effect of their variable input with grain sizes relevant to the bulk sediment. Apparently sedimentation processes have effectively controlled the magnetic minerals in terms of grain size, but failed to influence the magnetic susceptibility, which is actually a matter of mineral quantities pre-set by sediment supply.

It has been recognised, from both geochemical and palaeomagnetic studies, the sedimentation process in the Bohai Sea is the foremost one of the two main processes controlling the estuarine sediment. Meanwhile, all the evidence shows the other main process is associated with the sediment supply from the Huanghe River, which is directly linked to soil erosion on the Loess Plateau.

**INDICATORS OF SOILS**

Soil erosion on the Loess Plateau has two aspects: one is topsoil erosion concerning surficial soils, such as farmland and contemporary soils which are normally covered with vegetation; the other is loess erosion relating to pristine loess, which may also include fossil soils (palaeosols) interbedded in loess profiles. Change in relative proportion of these two erosions is the true determinant to the compositional variation in the Huanghe sediment. Soils, in contrast to loess, is believed to form under more humid and warmer conditions, and as a result of pedogenesis, its geochemical and magnetic properties become rather different from those of loess [4, 10, 11, 14, 25]. As suggested from the above analyses, it is possible to identify the various indicators of soils on the plateau.

**Geochemical indicators**

Phosphorus, the representative element in P group, is a typical biochemical element essential to plants. It gets enriched in topsoil through various mechanisms. Once released from weathered phosphate, P is easily precipitated with poorly crystalline forms of Fe and Al, which is rich in soils, and accumulates in soils [21]. In the meanwhile P in loess, as compared with topsoil, suffers more from leaching and frequent mechanical and chemical erosion owing to lack of protection from vegetation. Organic P, largely held by biota, accounts for a considerable proportion of total P in soil in the long term [21], which can not be matched by the P content in loess. Moreover, P can be enriched absolutely in soils due to the great deal of phosphorus added to the farmland as traditional (mainly organic) fertilisers in the early days and synthetic fertiliser after the 50's. Another biochemical element in P group, molybdenum, is a constituent of several enzymes, including nitrogenase [21]. Mo is thus essential for the biological activities [6], and apparently should present a higher content in soils than in loess.

The other elements in P group are mainly rare earth elements (REEs) and those connected with them. The REEs in this study include La, Ce and Nd, but as yttrium and thorium are frequently found in association with the lanthanide elements, they are often regarded as REEs [6]. As titanium is usually found to coexist with REEs in heavy minerals [31], it may
also be included in REEs in the following discussion. The main connection of REEs with soils is found in the ores containing REEs, mostly phosphates [6], which tend to undergo rapid weathering involving chemical as well as biological processes in soils. While the phosphorus is taken up by biota, the REEs would be likely attracted by organic matter, iron oxide minerals and clay minerals, and retain in soils. The enrichment of these elements in soils is achieved to a large extent by contrast of the depletion of elements in loess, especially at the top part of profile.

**Magnetic susceptibility**

It has long been noticed that magnetic susceptibility is enhanced in contemporary soils as well as in palaeosols [25]. This phenomenon is well known as magnetic enhancement [28]. Throughout the Loess Plateau, a higher iron-oxide content and a much stronger magnetic susceptibility signal in farm soils and contemporary soils have been confirmed [1, 25]. It is generally agreed that a higher detrital fraction of total magnetic minerals is present in soils, and that the pedogenetic and biogenetic fraction plays an important part in the enhancement as well [7, 13]. In addition, the traditional Chinese farming on the plateau also contributes to the magnetic enhancement in farm soils by burning the remains of crops after harvest, which can convert non-magnetic iron-bearing minerals to ferrimagnetic minerals, which is known as the burning effect [28].

Both the P group elements and magnetic susceptibility have presented a closer relationship with soils rather than loess and demonstrated certain enrichment or enhancement in soils. As a matter of fact, as a group these elements and minerals also maintain close connections among themselves. It is well known that iron-oxides, the main bearers of magnetic susceptibility, can absorb P very effectively; and that Ti often associates with Fe in their solid solution, ferrimagnetic titanomagnetites. In soils, iron oxide minerals, such as iron oxyhydroxide, are acting as hosts for many cations released from phosphate weathering, including REEs, because hydroxide radicals (-OH) are often negatively charged [21]. Organic matter contains organic P and also attracts many other elements, such as REEs. After all, it is biogeochemical processes in soils that make the soils so different from loess geochemically and magnetically, and that is how the P group elements and magnetic susceptibility are made indicators of soils.

**TOPSOIL EROSION ON THE LOESS PLATEAU**

As shown in Fig. 5, the Loess Plateau geographically consists of two types of land, the vegetation-covered soils and the barren loess. The typical landform of the plateau, erosion gully including various rills and gullies, is carved by water erosion, although loess landforms of gravitational erosion and wind erosion may also be present. Being the main form of water erosion, the gully erosion overwhelms on the plateau, while other water erosions, such as sheetwash, are generally dwarfed [20, 26].

**Topsoil erosion**

Because most soils on the plateau are found in somewhat flat area, often on the top of yuan, liang and mao [20] where the slope gradient is relatively small, the topsoil erosion can be provoked mainly by sheetwash, which is much less erosive than the gully erosion in a slope system [30]. On the other hand, the loess, without protection from vegetation but with
greater porous space and looser intergrain contact, is much more vulnerable to water erosion, mainly in the form of gully erosion and pipe erosion [26, 30].

Topsoil erosion is less likely to occur than loess erosion during modest rainfall owing to the protection from the vegetation and the small slope, however, when the rain intensity exceeds a threshold and overland flow is generated as excess rainfall over infiltration and as a result of soil saturation, it can also take place on a large scale. The water flow carries elements in suspension as well as in solution. The later is viewed as a more important erosion procedure to the elements either soluble or, more commonly, in occluded form, such as phosphorous. This solution and suspended matter with higher content of soil-related elements and minerals will definitely produce a strong signal in the total sediment eroded from the plateau, and will be eventually recorded in the Huanghe estuarine sediment in the Bohai Sea.

Huanghe hydraulic records and topsoil erosion indicators
Although the relationship between topsoil erosion and sediment records has been decided in principle, it needs to be confirmed that other processes do not interfere the relationship too much and the topsoil records are well preserved. In order to test the validity of the relation, a comparison between the magnetic susceptibility, a typical indicator of soils, and the hydraulic records of the Huanghe River [19, 29] is made (Fig. 6). The magnetic susceptibility is selected as a representative of the soil indicators simply because its profile has a higher resolution to present the record in more detail. As the overall accumulation rate at the coresite is over 1 cm/yr [5], the magnetic susceptibility should be able to show every recent topsoil erosion event. The time-scale for the magnetic susceptibility profile in Fig. 6 is modified slightly between the fixed dates at the lithological boundaries by bringing the susceptibility peaks into phase with flooding years with consideration of the actual situations described by Pang and Si [16].

A pretty good agreement is seen between the magnetic susceptibility and the hydraulic records, despite that the relative magnitudes of water discharge, sediment load and magnetic susceptibility are not perfectly matched. This merely reflects the complexity involved in the relationship among the three as regarding to the actual precipitation procedure, e.g. short but heavy rainstorm would be possible to bring about relatively more topsoil erosion than a long but modest rainfall. This agreement confirms that magnetic
susceptibility is an indicator of topsoil erosion induced by flooding on the plateau and the estuarine sediment can preserve records of soil erosion on the Loess Plateau. Obviously, just as magnetic susceptibility, the P group elements are also indicators of topsoil erosion on the plateau, though some of them may be subject to other influences and not be so typical.

Figure 6. Comparison between hydraulic records of the Huanghe River over the past 60 years [19, 29] and magnetic susceptibility in the top part of JX91-3B. N.B. there is a gap between 1938-1947 AD when the levee of the river was deliberately breached at Huayuankou during W.W.II and no Huanghe sediment was supplied to the Bohai Sea during that period.

DISCUSSIONS AND CONCLUSION

Firstly, the PCA grouping of elements is mainly based on the most significant three processes, however, other processes, though not revealed, may also play a role in the distribution of elements in Fig. 3 and may result in different groups especially to some sensitive elements. Moreover, some elements may be prone to be influenced by more than one processes simultaneously, or have several different origins and in different forms. That is why some elements are found scattered and away from the three axes in Fig. 3. The P group, for instance, includes elements (REEs mainly) that are not only determined by sediment supply, i.e. topsoil erosion on the plateau, but also controlled by other processes,
such as coprecipitation of REEs with P at estuary [3]. Therefore, only magnetic susceptibility, phosphorous and titanium are regarded here as trusty indicators of topsoil erosion in the Huanghe sediment in the Bohai Sea.

Secondly, although sediment supply seems to be independent from sedimentation processes, all the sediment is deposited through these processes anyway. A good example is the magnetic susceptibility. The original grain size distribution of magnetic minerals is different in soils and loess as a result of pedogenesis and bacterium activities [7, 32], so the susceptibility spike in sediment should demonstrate a higher fraction of ultrafine-grained magnetic minerals as expected, but did not. All the sediment has actually been reworked by the sedimentation processes before deposited at the coresite. It is only because of an absolute increase of magnetic mineral input in the Huanghe sediment that the topsoil erosion signals have survived the reworking of sedimentation processes.

At last, it should be pointed out that the relationships among the elements and minerals as discussed previously should not be over-extended. Even at the central part of the Bohai Sea, they may not be valid any more, since the depositional environment and biogeochemical conditions have changed from the Huanghe estuary. Moreover, in the whole Huanghe River catchment, erosion of other areas covered by vegetation, but not exactly on the Loess Plateau, may also contribute to some extent to the topsoil erosion signals in the estuarine sediment records in the Bohai Sea.

Geochemistry and palaeomagnetism have been jointly applied to study Huanghe estuarine sediment in the Bohai Sea, providing a new insight into the relationship between the Huanghe estuarine sediment records and the soil erosion on the Loess Plateau. With the help of principal component analysis of the XRF major and trace elements, together with detailed magnetic susceptibility measurements, two kinds of main processes controlling the sediment have been revealed. The dominant one is sedimentation processes in the Bohai Sea and the other is soil erosion processes on the Loess Plateau. Relationships between soils on the plateau and magnetic susceptibility and the P group elements are established, making them indicators of topsoil erosion. Soil erosion on the plateau is discussed and the variation of sediment supply owing to different erosions is linked with precipitation on the plateau. A comparison made between magnetic susceptibility and Huanghe hydraulic records over the past 60 years confirms the relationship between the topsoil erosion and estuarine sediment records as indicated by magnetic susceptibility, phosphorous, titanium and REEs.

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