SEDIMENTOLOGICAL EVOLUTION OF THE EMINE & KAMCHIA BASINS, EASTERN BULGARIA

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“Pobiti Kamani”: Dikilitash Formation (Lower Eocene) Nummulitic sand-columns near Beloslav, NE Bulgaria
ABSTRACT

Mountain belts are inherently asymmetric, defined by the sense of plate subduction. The resultant orogen can be divided into peripheral and retro-arc wedges with the retro-wedge overlying the overthrust plate. Modelling suggests that retro-wedges and their neighbouring foreland basins have patterns of sedimentary architecture and sediment sourcing distinct from that of peripheral foreland basins. This study is a sedimentological and petrographical investigation into the evolution of the retro-arc wedge and foreland basin of the Hellenide/Balkan system from the Late Cretaceous to Mid-Miocene. This system is analogous in tectonic setting to the small retro-foreland basins of the Apennines and Pyrenees.

The east-west trending Balkans were the collisional product of the late Mesozoic/early Cenozoic Alpine Orogeny. The depocentres studied here were situated on the overthrust plate of the Eurasian-Anatolian subduction zone, north of the orogenic deformation front, the Stara Planina Frontal Thrust, and south of the stable craton, the Moesian Platform. Present day coastal exposures in Eastern Bulgaria, oriented perpendicular to the strike of the orogenic system, preserve an excellent onshore record of the transition from a tectonically inactive basin subordinate to a major back arc basin (the Late Cretaceous to End Palaeocene Emine Basin) to compressional underfilled and subsequently overfilled foreland basin (the Lower Eocene to mid-Miocene Kamchia Basin).

Late Cretaceous sediment filling of the trough-like Emine Basin was in the form of deep-water turbidites (Lower Emine Formation) transported west-to-east and sourced from Cretaceous granitic basement approximately 250 km west of modern outcrops. Turbiditic deposition continued through the Palaeocene (Upper Emine Formation) but the southern basin margin began to experience compression during this time and sporadic influx of submarine fans (Kozichino Formation) sourced from the arc/incipient thrust wedge to the south of the depocentre mixed with the along-strike transported turbidites. Deposition into the Emine Basin continued to be turbiditic during the Lower Eocene (Atanas and Gebesh Formations) but there are signs of stronger basin instability and shedding of sediment off both the northern (platform)
and southern (orogenic) margins from high energy deposits (Bardarevo and Meshilika Formations). The Mid-Miocene Illyrian Unconformity is a period of major tectonic compression and uplift creating structural features such as the Irakli and Obzor Synclines and mass flows sourced from recycled arc volcanics (Obzor Formation) are documented from this period. Mid and Upper Eocene deposition persisted to be easterly-transported turbidites (Dolen Chiflick Formation) but the depocentre migrated north into a shallower and geographically more restricted basin, the Kamchia Basin. The dominant control on sedimentation became increasingly eustatic rather than tectonic. By the Oligocene, sedimentation was uniformly low energy and shallow water (Ruslar Formation). The Mid-Miocene Galata Formation displays high energy, directed flow in a very narrow channel-like basin into the early Black Sea which had, by this period, begun to open through east-west extension from plate reconfiguration and orogenic collapse.
DECLARATION

This thesis has been composed entirely by myself and represents my own work. This work has not been submitted for any other degree or professional qualification. Photos used in figures were taken by the author unless otherwise stated. Likewise, figure sources are clearly declared unless original to this work or of unknown origin.

Hannah Louise Suttill
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CHAPTER 1

INTRODUCTION & RATIONALE

1.1 INTRODUCTION

Foreland basins form adjacent to mountain belts and fall into two main types – peripheral-foreland basins and retro-arc foreland basins (Allen & Allen, 2005). Despite the recognition of the geodynamic difference between these two types of basins in the 1970s by workers such as Dickinson (1974), the progress of research into the stratigraphy and structure of retro-arc foreland basins in European mountain belts has always languished behind that of peripheral-foreland basins. This state has largely arisen due to the ease of access to well-exposed modern and ancient field examples of the inherently larger pro-foreland basins and extensive hydrocarbon exploration in what have proved to be more prospective regions e.g. the Apennines, the North Slope of Alaska and the North American Seaway amongst others. In addition to the bias associated with their tectonic setting, ground-truthed studies of small curvilinear mountain belts have often been regionally focused on the Alps or Apennines.

The Balkans are a relatively narrow system comprising the retro-wedge and foreland basin to the doubly-vergent Hellenide-Balkan orogen (figure 1.1) (Boccaletti et al., 1974; Sinclair et al., 1997). This research uses exposures in eastern Bulgaria, as a case study into the patterns of sediment sourcing and delivery in the retro-arc foreland basins of a small curvilinear mountain belt. An overview of the literature illustrates its consistency with this classification of the tectonic setting and although there have been extensive stratigraphic studies in Bulgaria, there is limited geological interpretation in the literature with regard to this tectonic setting and studies in analogous settings. No studies currently exist that incorporate provenance information from clastic petrography to improve our understanding of sediment sourcing and tectono-stratigraphic relationships during development of Balkan
basins. This research thus attempts to address this major gap in knowledge and the results represent a significant development in our understanding of sediment routing during development and filling of the Emine and Kamchia basins in the eastern Balkans from the Cretaceous to the Miocene.

The extensive data available for this particular location ensures the success of this opportunity for a detailed case study into the interpretation of the sedimentological evolution of the Balkan retro-wedge/foreland basin. Offshore hydrocarbon exploration data from the western Black Sea has been provided by Melrose Resources plc., co-sponsors of this project, and onshore field data has been obtained through nine weeks of field work in Eastern Bulgaria. Significant work, predominantly by Bulgarian geologists, has been done on biostratigraphical dating of the Cretaceous to Recent sediments. This study is using sedimentary provenance in particular to help determine and characterise the sedimentary evolution of the Balkans.
Figure 1.1 Tectono-stratigraphic isopic zones of Bulgaria, Greece and Turkey. The Vardar Zone marks the oceanic suture along which NE subduction began in the Late Jurassic. Inset showing approximate tectonic settings during Tertiary. Modified from Boccaletti et al. (1974).
1.2 OVERVIEW OF RETRO-ARC AND RETRO-FORELAND BASINS

Foreland basins are elongate regions of sediment accumulation that develop as a result of flexure on continental crust sandwiched between a contractional orogenic (fold-and-thrust) belt and autochthonous craton in convergent settings (Allen et al., 1986). They form by the combined processes of subduction and topographic loading causing downward flexure of the lithosphere during development of the orogenic belt (figure 1.2). The typical lithospheric signature of a foreland basin is a negative free air gravity anomaly (at sea) or a negative Bouguer anomaly (on land) due to flexure of the lithosphere (Allen & Allen, 2005). Peripheral-foreland basins form on subducting plates beyond the frontal thrust of the orogen whilst retro-arc foreland basins develop on the overriding plate in the hinterland of fold-and-thrust belts (Johnson & Beaumont, 1995) (figure 1.2). To clarify foreland basin classifications in this tectonic situation, in ocean-continent (Andean-type) settings, the basin on the upper plate is termed the retro-arc foreland basin whilst in a continent-continent setting (Himalayan or Alpine-type), the basin on the upper plate is the retro-foreland basin. The Balkan Mountain chain is thought to represent an example of this latter group of sedimentary basins.

As orogenic wedges propagate over a foreland plate in a doubly-vergent collisional zone, the locus of deformation migrates and a deflection in the foreland plate attributable to the flexural loading is developed progressively ahead of the fold-and-thrust belt (Willett et al., 1993). This forms distinct sediment depocentres laterally along the plate, and these are recognised as being distinctive of foreland basins. Subsidence in pro-foreland basins is due to the combined effects of flexural loading by the thrust belt/sediment loads (supra-lithospheric loading) and subduction loads (sublithospheric loading). In retro-foreland systems, flexural loading is the key subsidence mechanism (Catuneanu, 2004) but in large convergent margins, additional far-field subsidence is induced by “viscous coupling” between subducted slabs and mantle-wedge material beneath the outboard part of the overlying continent (DeCelles & Giles, 1996). The latter effect was termed “dynamic loading” (also known as dynamic topography) by Gurnis (1992). Although orogenic loading is the
defining characteristic of foreland basin systems, the differences between styles of subsidence in pro- and retro-foreland basin systems remain profound (figure 1.2). Most established models of foreland basins involve a rate of subducting plate movement and thus simulate pro-foreland basins (Sinclair et al., 1991). At present, the implications for structural development and thus sedimentary history and architecture in the retro-wedge/foreland basin system developing on non-subducting, i.e. static, retro-lithospheric plate have not been explored although the implications are starting to be recognised through modelling work e.g. Naylor & Sinclair (2005).

The combined forces responsible for deflecting the continental plate are extremely variable due to complexities in the crust and mantle within collision zones, the implication being that orogenic wedge loads and sedimentary basin-fills have to be modelled as spatially distributed loads. Unlike oceanic crust, no simple relationship exists between flexural rigidity and age of crust in the continental crust, more likely is that flexure is related to:

- differences in geothermal gradient caused by variations in crustal radiogenic heat production;
- decoupling between a strong upper crust and strong underlying mantle lithosphere during bending;
- plastic yielding at high curvatures;
- viscoelastic relaxation (Allen & Allen, 2005).

The orogenic wedge itself is considered as a dynamic system with critical slopes within which gravitational and deviatoric forces continually attempt to achieve steady state (Davis et al., 1983). External perturbations such as changes in convergence rate impact heavily upon rates of contraction or extension of the wedge. These changes inherently affect erosion rates in the mountain belt, resulting in increased or decreased sediment supply to the foreland basin whilst changes in loading induce deflection of the overriding plate. The tectonically-induced subsidence in foreland basins is always variable, normally increasing towards the orogen and results in the foreland basin wedge-shaped geometry. The character of
each individual foreland basin provides insight into the evolution of the orogenic belt itself.
Figure 1.2 Generic model of pro- (peripheral) and retro-arc foreland basin systems detailing tectonic setting and controls on accommodation (modified from Catuneanu, 2004). Note the asymmetry of the tectonic load with a wide pro-foreland side and shorter but steeper retro-foreland side. Dynamic loading is an effect noted on in the largest systems e.g. the Andean basins & the Karoo Basin in South Africa.
1.3 **CONTROLS ON SEDIMENT SUPPLY IN FORELAND BASINS**

The sedimentary fill of foreland basins reflects the controlling mechanisms on basin formation and it inherently reflects the evolution of the fold-thrust belt to which the basin is genetically linked. The primary control on the composition of sediments is parent rock mineralogy. Secondary controls include the climate and physiography of the source area from which the sediment is derived (Weltje & von Eynatten, 2004; Jordan *et al.*, 1988). The objective of a provenance study is to trace and interpret the movement of sediment from initial parent rock to the final burial location by identifying source areas through compositional and textural information about the sediments themselves (Pettijohn *et al.*, 1987).

This is the first study to undertake quantitative petrographical provenance analysis of the sediments documenting the evolution of the Emine (back-arc) Basin to Kamchia (retro-foreland) Basin in Bulgaria. Published studies of the provenance of sediments in retro-foreland basins worldwide are far less numerous than studies of peripheral-foreland basins. McCann & Saintot (2003) emphasise the difficulty in making a distinction between the sedimentary records of peripheral- and retro-foreland basins. This may be for reasons such as multiple accretion events, changes in subduction polarity and changes in the angle of convergence which may lead to features such as strike-slip displacement of basin and source areas or superposition of basins with different tectonic styles (Miall, 1995). Hybrid basins with indistinct original tectonic settings are very likely in areas of extreme deformation. The Emine and Kamchia basins, however, do not display overly complicated overprints of tectonic deformation aside from what is expected in a foreland basin setting with subsequent orogenic collapse.
Asymmetry of a doubly vergent mountain system is a key control on sediment provenance as the thrust belt supplies the greatest amount of sediment, especially when a basin is overfilled. In underfilled basins, where accommodation space is being created faster relative to sedimentation rate and thus water depth is increasing (Catuneanu, 2004), locations proximal to the orogenic belt will be filled more completely than those on the distal side. Additionally in an underfilled basin, a proportion of sedimentation may be received through axial drainage from along-strike.

Sediment supply pathways constitute another control as material may be supplied from single or multiple point sources, depending on drainage patterns in the thrust belt. Rivers draining mountain systems can pass through a marginal thrust belt along major antecedent valleys, such as the Po draining the Southern Alps (Garcia-Castellanos, 2002). In such a system, sediment supply varies greatly along-strike compared to the situation where small rivers are directly draining only the thrust belt. Periodic re-organisation of the mountain drainage networks also lead to large shifts in sediment supply and the resultant complex stratigraphy should not be confused with the stratigraphic manifestation of episodic tectonic activity or sea-level change (Damanti, 1989; Milana, 1991). The drainage system also exerts a strong control on whether basins are under- or overfilled. Tectonic subsidence is usually a result of thin-skinned thrust belt activity at the margin of the orogen, although rivers are commonly delivering sediment from the mountain interior (Damanti, 1989; Schmitt & Stedtmann, 1990). As such, certain individual rivers may have drained sufficiently large regions to overfill the basin or, on the flip side, a river may have only drained a small area of the thrust belt and will not carry enough sediment to fill the basin. The contribution of along-strike sediment transport in advance of the migrating frontal thrust acts to smooth variations in sediment transport from the orogen and minimises volumetric irregularities in individual depocentres. Busby (1995) suggests that the composition of the “average” foreland basin sandstone lies in the recycled orogen field of Dickinson and Suczek (1979). This represents a sandstone rich in quartz, with very little feldspar but abundant lithic fragments, especially sedimentary and metasedimentary but also locally volcanic (e.g. Lawton,
1986; DeCelles & Hertel, 1989; Johnsson, 1990). Alternatively the metamorphic and igneous interior of an orogen may constitute the dominant component of the sediment where major rivers systems cut across the thrust belt (Mack & Jerzykiewicz, 1989; Schmitt & Steidtmann, 1990).

1.3.1 PROVENANCE STUDIES IN ANALOGOUS RETRO-FORELAND SETTINGS

1.3.1.1 Apennines, Italy

Significant provenance work has been done on the Italian Apennines to improve the investigation methodology of looking at sediment sourcing and relating this to the development of composite orogenic belts. Modern sands from the Apennines are derived from diverse source rocks, including pelagic cherty limestone and carbonate platform sediments from the Apulian palaeomargin (undissected continental block provenance), foredeep turbidites accreted along the eastern margin of the orogenic (clastic wedge provenance) and volcanic or locally plutonic arc rocks outcropping along the eastern retro-side (magmatic arc provenance) (Garzanti et al., 2007). Because westward Apenninic subduction started in the late Paleogene alongside eastward Alpine subduction (Doglioni et al., 1998), the Apenninic orogen is topped by the proto-Alpine subduction complex, including remnant-ocean turbidites and accreted ophiolites, and incorporates boudinaged greenschist-facies to amphibolite-facies remnants of the Alpine axial belt. Because of limited tectonic uplift, erosional unroofing is restricted and the spatial distribution of detrital signatures is predominantly controlled by geological recycling (Garzanti et al., 2002) (figure 1.3). To unravel the sourcing of Apenninic sediments, Garzanti et al. (2007) discriminated between detritus sources using sediments found within thrust belts and this emphasised five distinct orogenic domains (magmatic arc, ophiolites, axial belt, foreland uplift and continental block, and clastic wedge) (figure 1.4). This classification was established using Gazzi-Dickinson point-counting on river and beach sands derived from single homogeneous thin-skinned orogenic domains around Italy.
**Figure 1.3** Drainage pattern in an idealised Apennine foreland basin. The thrust belt to the southwest verges northeast and represents crustal shortening associated with northeastward overriding of Adriatic (Apulian) foreland, a spur of the African plate. To the northeast, this foreland is underlain by slightly older Alpine chain (redrawn from Miall, 1995; Ricci-Lucci, 1986).
Figure 1.4 From Garzanti et al. (2007): Detrital modes of modern sands from the Apenninic thin-skinned orogen. Shown are river and beach samples derived from one single geological domain or subdomain. Also shown are field for the 10 largest rivers on each side of the orogen. All of these carry recycled detritus of clastic wedge provenance, associated with lithic sedimentary detritus of undissected continental block provenance (Adriatic rivers draining to pro side of the orogen) or with feldspatholithic to arkosic detritus of magmatic arc provenance (Thyrrenian rivers draining the retro side of the orogen). Detritus from remnants of the Alpine subduction complex and axial belt are locally dominant (Northern Apennines and Calabria, respectively). Petrographic parameters, symbols, provenance fields and confidence regions around the mean. Scale = 250 µ; all photos crossed polars.
1.3.1.2 Andean Foreland Basins, South America

The Andes are a very large composite series of orogenic episodes. South of the equator, the Andes are flanked on the eastern side by a series of Miocene to Recent retro(-arc) thrust wedges and foreland basins from which samples have been taken to investigate sediment sourcing and routing (Jordan et al., 1983; Jordan, 1995). The Andean orogen stretches through a vast range of climatic conditions and variation in collisional styles, thus the fill of the foreland basins varies considerably. The weathering of Andean sands and potential for destruction of unstable grains is significant so only the proximal parts of the foreland basins retain a primary compositional character (Johnsson, 1990). It is worth noting that scale and geometry of the broadly linear Andean system contrasts considerably with the small, curvilinear Balkan system. Part of this project aims to explore the differences in sediment routing and provenance which may result from different scales and shapes of basins in similar underlying retro-arc tectonic settings and the Andes are at the opposite extreme to the Balkans in terms of system size. The significant number of sediment provenance studies that have been done in various different Andean retro-foreland basins give the opportunity to compare modern and older sand provenances and present excellent control on the assessment of source areas.

In the broadest sense, Andean foreland basins display a mixed provenance from the Cenozoic volcanic chain of the Andes, Palaeozoic and Mesozoic sedimentary, volcanic and plutonic rocks, and reworked older foreland basin deposits (Jordan, 1995). In modern sands of the northern half of the Andes, compositions fall into recycled-orogen domains on the ternary diagrams of Dickinson & Suczek (1979), however, compositions of detritus from the Andes show a marked asymmetry. Volcano-plutonic detritus is dominant along the west (pro-side) of the cordillera, whereas quartzolithic to quartzose detritus with abundant metamorphic lithics dominate the east (retro-side) (Potter, 1994). Sediments in the Peru-Chile Trench range from undissected-arc provenance adjacent to areas of active volcanism, to transitional-arc and dissected-arc provenances where the batholithic roots of the inactive arc massif have been uplifted and widely exposed along the Corillera
Oriental (Garzanti et al., 2007; Yerino & Maynard, 1984; Thornburg & Kulm, 1987). Sediments shed by metamorphic to granitoid basement rocks and Palaeozoic to Mesozoic strata of the Cordillera Oriental and Subandean thrust belt display continental block provenance and are invariably mixed with subordinate volcano-plutonic detritus from the arc massif (DeCelles & Hertel, 1989). A couple of specific studies within different parts of the larger Andean system will now be discussed.

**Bermejo Basin, Southern Andes**

Volcanic rocks from the Late Cenozoic contribute significantly to the composition of river sands in the southern Andes, in the Rio Colorado, and these sediments plot in the magmatic-arc field. Blasi and Manassero (1990) explain these sands are sourced from a drainage area with volcanic geology. Sandstones in the south of the Andes (in the Bermejo Basin, figure 1.5) older than ~16 Ma show sediments from the High Andes west of the thrust belt (Palaeozoic volcanic and plutonic rocks forming volcanoclastic sandstones). Sandstones younger than ~16 Ma contain clasts eroded from the thrust belt when tectonic activity resumed after a quiescent phase between 19 and 15 Ma (Jordan, 1995). As the thrust belt and orogen developed topographically, by 10 Ma, there was sufficient topography on the range to trigger a change in drainage pattern – minor rivers with Andean interior sources were funnelled into a couple of major antecedent rivers cutting the thrust belt and supplying fan sediments (Damanti, 1989; cited in Busby, 1995) rather than numerous small streams feeding river facies material into the basin. During its history, the Bermejo Basin narrowed from an initial width of 220 km and the basin axis was between 100 and 160 km away from the contemporaneous thrust front.
Figure 1.5 Simplified geologic map showing principal tectonic elements associated with the Bermejo basin in western Argentina. The Frontal Cordillera is the ‘High Andes’ at this latitude, composed primarily of igneous and sedimentary rocks of Palaeozoic and Mesozoic age. The stippled area represents Neogene strata of the eastern Precordillera (Beer & Jordan, 1989).
Fildani & Hessler (2005) look at the stratigraphic configuration of the Rocas Verdes (back-arc) and Magallanes (foreland) basins over the transitional period from passive margin extension through the onset of Andean contraction and formation of the retro-foreland basin (location map shown in figure 1.6 and reconstruction in figure 1.7). As the amount of subsequent deformation in this basin is relatively minimal, the Magallanes Basin is akin to the Balkan system in that the tectonics documenting the extensional to contractional transition are well preserved and allow study of this critical period. The turbiditic Punta Barrosa Formation (Upper Cretaceous) is considered the first deep-water sequence of the Magallanes Basin, a period during which the retro-arc thrust belt of this system was initiated. Dott et al. (1982) suggested the primary source for this formation was a calc-alkaline, magmatic arc terrane. Compositionally, the Punta Barrosa Formation is rich in clay matrix (15-27%) and framework grains include angular quartz and commonly altered plagioclase as well as large, round clasts of chert. Lithic grains were noted to derive mostly from volcanic (70% andesitic and 30% felsic) and metamorphic rocks, rarely from plutonic rocks. Metamorphic rocks make up 5-15% of the framework grains and comprise quartz with white mica and commonly polycrystalline strained rocks. Metamorphic clasts are more dominant further up the formation. The mean composition of sandstones plot in the recycled orogen field (80% of samples, 20% plot in arc-related fields) but an arc signal is shown in the Qm-F-Lt diagram (figure 1.8).

Fildani & Hessler (2005) incorporate palaeocurrent data to show sourcing of the Punta Barrosa Formation was from the Andean belt north, west and northwest of the Magallanes Basin. This region comprises four potential terranes; (1) pre-Upper Jurassic metamorphic basement complexes, (2) the unconformably overlying volcanic Tobifera Formation, (3) the Sarmiento complex and (4) late Mesozoic intrusive arc rocks of the Patagonian Batholith. The volcanioclastic content of the sandstones decreased through time, potentially due to exhumation and erosion of crystalline basement in the source area. The multi-source feeding of the formation is
in contrast with the earlier Zapata Formation of the extensional basin phase which shows increasing arc-influence up section. This study is an excellent example of using the basin sediment provenance to explain tectono-stratigraphy. Although not in a directly comparable system in terms of system size, these Andean examples demonstrate the effectiveness of petrographical provenance study in unravelling tectonic histories of complicated basins. They also serve to provide comparisons for the results from this study which will be discussed in Chapters 3 & 4.

Figure 1.6 Simplified geologic map of the southern Andes (Fildani et al., 2008). Magallanes Basin structure contours (in metres) delineate the top of the Jurassic volcanic rocks.
Figure 1.7 Model of the evolution of the Magallanes retro-foreland basin, Patagonian Andes (Fildani & Hessler, 2005).
Figure 1.8 Normalised ternary plots of sandstone point-count data for Punta Barrosa Formation (Magallanes Basin, deposited during initiation of the retro-arc fold-and-thrust belt). (A) Ternary Qt-F-L (B) Qm-F-Lt (compositional fields from Dickinson, 1985). Open triangles represent arithmetic mean of data, black polygon represents one standard deviation (Fildani & Hessler, 2005).
1.4 **Overview of the Geology of the Balkan Region**

The Balkans in Eastern Bulgaria represent the retro-arc foreland basin to the Hellenide peripheral foreland basin. It is geographically a relatively narrow system with excellent exposure and subsurface data coverage which provide the impetus for its use here as a case study into the dynamic sedimentological evolution of a retro-arc foreland basin. Growth of the Balkans began around 90 million years ago when two micro-plates, the Rhodopian and Moesian fragments, sandwiched between the African & Eurasian plates, began to collide (Foose & Manheim, 1975; Burchfield, 1980). This initiated a north-dipping subduction zone, north of which there was extension in the crust which formed back-arc sedimentary basins receiving sediment from the volcanic arc to the south and west (Boccaletti et al., 1974). Approximately 60-70 million years ago, the Balkans began to experience compression as the mountain belt grew & thrust faults propagated north due to the increasing load. This resulted first in the development of a retro-arc foreland basin (oceanic-continental crust collision) followed by a retro-foreland basin (continental-continental crust collision) once all oceanic crust was consumed (recognised by the formation of the Vardar suture zone). To the south a larger thrust wedge & foreland basin system, the Hellenides, was developing on the pro-arc side. Since these events, there has been extension and orogenic collapse of the system due to subduction rollback as the arc-trench has migrated south (Dercourt, 1970; Boccaletti et al., 1974), evident from igneous activity.

The Hellenide thrust-wedge and foreland basin to the south of the Vardar oceanic suture zone forms the much wider pro-side of the orogen and classic peripheral foreland basin systems (approximately four-times the width of the Balkans) on the Aegean plate which underwent north-east directed subduction. The position of the Balkans on the overthrust plate of the subduction zone is emphasised by patterns of magmatism that record discontinuous southward migration, *i.e.* subduction rollback, of the arc-trench system since the Mesozoic (Boccaletti et al., 1974). The Srednogorie Zone to the south of the Balkan thrust wedge consists of submarine calc-alkaline output followed by basaltic trachyandesites, characteristic of island-arc
systems (Boccaletti et al., 1974). These Cretaceous volcanic rocks are interpreted as having formed in the back-arc basin of the subduction zone due to descent of the north-dipping subducting slab.

In addition to the igneous geological record, structural and sedimentary evidence confirm the retro-wedge/foreland basin setting of the Balkans. Thrusts, for instance, in the Balkan wedge are seen to verge towards the north whilst the major overthrusts on the Hellenide side of the system also migrated in sequence towards the para-authochtonous (Pre-Apulia) foreland (Underhill, 1989) and verge with an opposite sense i.e. towards the present-day south-west. The clastic fill of the foreland basin in advance of the northwards-verging thrusts associated with the Balkans, the “Kamchia Depression”, thins progressively northwards towards the foreland (Moesian Platform) with classic foreland basin wedge geometry. This is clearly evident from both field exposures and on seismic sections. A transition from deep-water extensional basin to sand-rich/debris flow-dominated retro-foreland basin, migrating across the foreland plate is evident in the Cretaceous to Lower Eocene succession (Stoykova & Juranov, 2005) (figure 1.9). Boccaletti et al. (1974) cite the lack of significant overthrusting and the absence of ophiolites and radiolarites as features of the Balkans characterising its retro-arc tectonic setting. Such features are, however, not consistently always absent in retro-wedge/foreland basins, for example, as in the Magallanes Basin in the Patagonian Andes (Fildani & Hessler, 2005).
Figure 1.9 Model showing orogenic loading of a previously stretched continental margin during the early stages of convergence. The first orogenic loads are emplaced on a weaker lithosphere at considerable water depths (modified from Quinlan & Beaumont, 1984; Sinclair & Allen, 1992).
1.5 **PROJECT AIMS**

The major questions this research project set out to address were:

1. What was the history of sediment delivery into basins on the retro-arc side of the Balkan mountain chain from the Cretaceous through to the Middle Miocene?

2. What characterised the provenance and hence petrology of the Emine and Kamchia Basins and what does this imply for the palaeogeographic evolution of the system?

3. Is it possible to predict periods of flushing of high (hydrocarbon) reservoir quality clastic sediments into the deeper basin where hydrocarbon exploration activity in the Black Sea is currently focused?

4. Do the basins of the Balkans show similar patterns of sediment filling to other examples of retro-arc basins associated with small mountain belts?

The study attempts to do this through the integration of key sedimentary field and petrographic observations of samples from strategic localities which typify the key tectono-stratigraphic units identified within the retro-arc foreland basin succession.

1.6 **PROJECT METHODOLOGY**

The new dataset this study provides and utilises has been gathered from 9 weeks of fieldwork in Eastern Bulgaria during two seasons (spring 2006 and late summer 2007). Fieldwork included reconnaissance of the stratigraphic units of the basin sequences, outcrop sedimentology, fine-scale sedimentary logging, sample collection for petrographical analysis, palaeocurrent measurement and structural measurements. Samples obtained from field study were thin-sectioned for petrographic description and point-counting for provenance analysis. Offshore data provided by Melrose
Resources plc. was used for reference including well logs, core samples and core and outcrop thin-sections.

1.7 **Thesis Organisation**

This introductory chapter is followed by Chapter 2 which comprises a review by formation of the field sedimentology and existing literature on the regional stratigraphy of Eastern Bulgaria with a mention on structural styles observed in the field. In Chapter 3 the petrographical and provenance part of the thesis is presented with interpretation and implications for sedimentological models of system evolution. Field evidence and petrography are synthesized in Chapter 4 and palaeoenvironmental models for the Balkan foreland system are proposed. Chapter 5 concludes the study and briefly discusses the wider implications of this study in terms of the regional context and comparison with analogues. Recommendations for further work are also suggested in the final chapter. Appendices consist of sedimentary logs and petrographical databases.
CHAPTER 2

REVIEW OF THE STRATIGRAPHY OF THE THRUSTED MARGIN OF THE EMINÉ AND KAMCHIA BASINS

Much has been written on the Cretaceous to Miocene sediments of the Eastern Balkans by Bulgarian authors, unfortunately a lot of which remains untranslated from Bulgarian. The most useful published papers describing features of the stratigraphy include those by Doglioni et al. (1996), Vangelov & Sinnyovsky (2001) and Sinclair et al. (1997). Melrose Resources, the sponsors of this project, have been key in providing much unpublished in-house material such as field trip reports by Peck & Sinclair (2005). Key outcrops in Eastern Bulgaria occur along the north-south trending Black Sea coastline between Varna and Cape Emine (figures 2.1 & 2.2) and these sections provide much of the field data for the Cretaceous and Tertiary sequences. Additional inland outcrops such as Kozichino and Bardarevo are also integral to describing the regional geology.

This chapter describes each of the sedimentary units found along the northern margin of the Balkans by summarising any historical changes to formation nomenclature in the literature, type localities, lower and upper boundaries (and formation thickness) then describing the features of the lithologies (typical and variations) as seen in the field. Detailed petrography and sediment provenance analysis performed on each of the formations discussed in this chapter is documented in chapter 3. Included also is a literature review of the Cretaceous volcanic formations underlying the oldest sedimentary formation and interpretations of palaeoenvironments and sedimentary processes of each of the units obtained from the existing literature. The information in this chapter is integrated with the new findings of this study in chapter 4 to establish models of palaeo-depositional settings.
Figure 2.1 Chronostratigraphy of the onshore geology of Eastern Bulgaria (Peck & Sinclair, 2005 [Melrose Resources in-house report]).
Figure 2.2 Outline of Cretaceous to Miocene formations (Quaternary omitted) and major structures along the East Bulgarian coast between Cape Emine and Cape Galata (superimposed over a DEM-derived contour map).
Figure 2.3 A) Structural cross-section from the coastal exposures between Cape Emine and Varna. B) Structural reconstruction to the upper Eocene of the cross section using a line-length technique and using the Maastrichtian/Palaeocene boundary to link parts of the section (Sinclair et al., 1997)
2.1 CRETACEOUS & PALEogene VOlCANIC ACTIVITY IN BULGARIA

2.1.1 Srednogorie Cretaceous Volcanics

The Srednogorie Zone (Bonchev, 1930) represents the southern tectonic zone of the Balkan system (figure 1.1) and comprises Late Cretaceous volcanic and sedimentary formations and Palaeocene igneous intrusions. An understanding of the composition and setting of this region is important as many of the subsequent sedimentary formations deposited within the Balkan foreland basin received sediments shed from this volcanic zone.

The Srednogorie region contains two types of magmatism; older (Turonian to Senonian) calc-alkaline volcanic products (Gočev, 1970) and overlying younger alkaline rocks (Stanisheva & Vassilev, 1966). The older calc-alkaline rocks, widespread over the entire region, consist mainly of pyroclasts (tuffs, tuffites, agglomerates & volcanic breccias) and only about 20% lavas (Boccaletti et al., 1974). This episode of volcanism was submarine and its products are interbedded with marl and turbiditic deposits. Andesite is the main rock type but andesitic-basaltic and dacite-rhyodacitic volcanics are reported in the Panagyurishté and Burgas regions (Chipchakova, 1970; Stanisheva & Vassileva, 1971). Gočev (1970) reports the formation reaching a maximum of 2,000 m thickness in the Burgas region.

The later, alkaline volcanic formation is seen in the east of the Srednogorie region (Stanisheva & Vassileva, 1966) and consists of two magmatic episodes (Boccaletti et al., 1974). The first of these, in the central southern part of the Srednogorie Zone, comprises basic and ultrabasic rocks including trachybasalts, olivine basalts, leucite basanites and picrites. The second, more widespread, unit is dominated by trachyandesites with minor absarokites, limburgites and trachybasalts (Stanisheva & Vassileva, 1971). The alkaline formation as a whole shows alkali contents averaging 8-10% with the K₂O/Na₂O ratio >1, K₂O content ranging from 3-12% and TiO₂ content lower than 1% in basic and ultrabasic volcanics (Boccaletti et al., 1974).
Overall, the magmatism of the Srednogorie Zone bears a strong chemical and compositional resemblance to shonshonitic products which typically occur during late stage island-arc evolution. The interbedding with marine turbiditic sediments and marls is also characteristic of island-arc systems (Boccaletti et al., 1974).

After cessation of volcanic activity, Zagorchev (1998) asserts that the Srednogorie Zone itself was folded and uplifted in the Late Cretaceous and acted as the drainage divide between the two Palaeocene-Middle Eocene turbiditic basins – the Kamchia Basin to the north, and the East Rhodope-West Thrace Depression to the south. Zagorchev recognised the intense difficulty of making direct provenance correlations of potential source rocks to deposits owing to a lack of integrated field geology, petrography and geochemical studies of the volcanic and plutonic rocks in the region.

**Dragonovo Formation**

The stratigraphically lowest representative of the Emine Formation occurs in field exposures near the village of Tankovo (Sinnyovsky, 1988), where the lower levels of the Emine Formation grade gradually from volcanic rocks of the Cretaceous Dragonovo Formation [located at UPS/UTM GR 0552849, 4727792] (figure 2.4). These oldest outcrops of the Emine Formation are of Upper Campanian age (Sinnyovsky & Sultanov, 1994). At the Tankovo locality, boulder beds entraining large igneous cobbles are seen interleaved with thin, marl or fine sand rhythmic bedding (figure 2.5). The volcanics of the Draganovo Formation, part of the Srednogorie Volcanic Zone, are most probably potassic alkaline rocks although further south, other groups of the Srednogorie Zone are calcalkaline (Banks, 1997). Banushev & Tarawneh (2004) analysed Draganovo Formation volcanics (in the form of clasts within pyroclastic deposits and other volcanic fragments and ash tuffs) from the Dobrinovo area, approximately 40 km to the west of Tankovo. The volcanics consist of clinopyroxene, olivine, pseudoleucite, K-feldspar, analcime, plagioclase, biotite, apatite, magnetite and titanomagnetite. These represent alkaline basalts of the shonshonitic series (within-plate ocean-island basalts) (Banushev & Tarawneh, 2004) and as such are most likely to be part of the later alkaline series of Srednogorie
Zone volcanics. This low pressure/fast crystallisation signature is common to other basalts in the region such as the “St Spas Bakadjik” basaltoids (Banushev, 2004).

2.1.2 Paleogene Volcanics in the Rhodope

Paleogene volcanic activity in the Rhodope Mountains is restricted to a broad arc in the massif (Harkovska et al., 1989). Biostratigraphy and geochronological studies from the Perelik volcanic massif and the eastern Rhodope show maximum activity to have been close to the Priabonian-Oligocene boundary, continuing through the Early Oligocene and occasional late basic dykes were formed during the Late Oligocene (Pecskay et al., 1994; Lilov et al., 1987). Data from volcanics close to the Vadarc zone suggest two phases of volcanism, the earlier Priabonian-Early Oligocene and the later of Chattian-Acquitanian age (e.g. Stojanov & Serafimovski, 1990), much akin to the pattern found in parts of the Greek Rhodope. Volcanic activity youngs towards the west and south, allegedly due to the presence of other late Oligocene and Neogene volcanic arcs (Zagorchev, 1998). Evidence for ages of intrusive rocks in the Rhodope is unfortunately scarcer than that available for extrusives, especially because of resetting of radiogeochronological mineral clocks by intense Paleogene tectonothermal events (Zagorchev, 1991). To aid dating, some examples of contact metamorphism in Paleogene sediments are recognised e.g. around the Xanthi pluton (Dimitrov, 1957) and some plutons in the Eastern Bulgarian Rhodopes (Mavroudchiev et al., 1993). Magma sources for Paleogene plutons are of both “normal” crustal source in the north (granites with high initial isotopic Sr ratio) and of deeper, depleted crust or upper mantle origin in the south (gabbro and mozonites with low initial isotopic Sr ratio) (Zagorchev, 1998). This evidence is consistent with a volcano-plutonic Priabonian-Early Oligocene association resulting from subduction-volcanic arc processes, collision or orogenic collapse.
Figure 2.4 Lower Emine Formation interbeds incorporating reworked Dragonovo Formation near Tankovo village [UPS/UTM GR 0552849, 4727792]

Figure 2.5 Dragonovo Formation boulder beds at base of Lower Emine near Tankovo village [UPS/UTM GR 0552849, 4727792]
2.2 Upper & Lower Emine Formations

The Emine “Flysch” Formation is a thick, widespread unit in Eastern Bulgaria reaching an estimated thickness of over 1670 m (Sinnyovsky, 2004). Whilst this study considers the formation to span the Campanian to Palaeocene, earlier studies such as Sinclair et al. (1997) and Vangelov & Sinnyovsky (2001), have included sediments up to Middle Eocene age (the locally termed “Dvoynitsa Group/Series”) within the Emine “Group”. However, this study recognises the importance of major unconformity at the end of the Palaeocene which marks the end of Emine Formation thinly-bedded turbidite-style of deposition and as such, the Emine Formation is used here to describe only Cretaceous to Palaeocene sediments, the end Tertiary boundary marking the divide between Upper and Lower Emine Formations. §2.1 discusses the underlying volcanics of the Srednogorie Zone, including those of the Dragonovo Formation which is found interbedded with the lowermost Emine Formation (figure 2.4).

This formation outcrops in two major synclines (the Irakli or “Banya” Syncline and the Obzor Syncline as located on figure 2.2) which are well exposed on the north-to-south trending Black Sea coastline between Byala in the north and Cape Emine to the south. The Emine Formation was first fully studied as a distinct stratigraphic unit by Gochev (1932) and later studies have commonly focused on the micropalaeontology in great detail which has resulted in high-resolution dating of the formation, particularly of the Palaeocene Upper Emine Formation (e.g. Sinnyovsky, 2004; Campion, 1993; Juranov, 1994). Use of calcareous nannofossils zones has enabled an accurate estimate of the thickness of the formation to be generated as other methods of measurement would be misleading as the entire sequence is overprinted by extreme folding and thrusting/back-thrusting associated with later compression. Sinnyovsky (2004) estimated the Cretaceous, Lower Emine, to be 820 m and the Palaeocene, Upper Emine, was determined to be ≥850 m, uncertainty associated with that measurement being due to an incomplete uppermost nannoplankton (NP) 9 zone. Sinnyovsky’s estimates of total formation thickness are significantly lower than
those of Vangelov et al. (1996) and Sinclair et al. (1997) as these authors suggest estimates based on apparent thicknesses.

2.2.1 LOWER EMINE FORMATION

Synonymy

Lower part of the Emine “Flysch” Formation (Gochev, 1932).

Type Locality

North of Cape Emine (UPS/UTM GR 0573695, 4728213), within the Mesozoic units of the Irakli Syncline. Juranov & Pimpirev (1989) describe the type sections of the Upper Cretaceous and Palaeocene Emine Formation.

Lower and Upper Boundaries

As discussed, the lower boundary of the Lower Emine Formation is seen at Tankovo (figures 2.4 & 2.5) where volcanioclastic turbidite deposits and boulder beds containing large, rounded, reworked volcanic clasts are seen in close proximity to pillow lavas of Cretaceous volcanics (Dragonovo Formation of the Burgas Group). The upper boundary of the unit within the Irakli Syncline exposures on the coast is dated by microfossil assemblages at the top of the Cretaceous but sedimentologically is expressed as continuous deposition into the Palaeocene Upper Emine Formation. Elsewhere, such as at Kozichino village, sharp unconformities representing erosion during end Cretaceous times are clearly observed where sands overlie the contact. Sinnyovsky (2004) estimated the Lower Emine Formation to be 820 m thick.
Lithological Description

The deformed Campanian to end Maastrichtian Lower Emine Formation outcrops along the coastline north of Cape Emine (figures 2.2 & 2.6). Logs 6.1 and 6.2 (Appendix I) detail small-scale 3 to 4 metre-long sections of the lowermost Emine Formation taken close to the stratigraphically lowest exposures at Cape Emine. At the base, the formation displays regular interbeds that together form 1-1.5 m thick units of fining-upwards cycles of 0.15-0.2 m thick, medium- to coarse-grained sandstones fining gradually up or abruptly where underlying siltstones/shales. The basal sandstone beds of each set of fining-up units possess sharp planar bases and commonly gradual undulose top surfaces. The thicker sandstones often display soft sediment deformation in the form of dewatering structures, slumped laminae or merely undulose laminae (figure 2.7). Intra-bed, soft sediment deformation-related extensional faults and small scale faults are also observed e.g. bed 13 of log 6.1. Larger, metre-scale intraformational back thrusts are reported throughout the Emine Formation e.g. at UPS/UTM GR [0548690, 4737766], and these are discussed more in §2.13 with regard to their role in accommodating deformation during folding of the Iracli Syncline.

Thin ripple horizons are occasionally present with foresets showing palaeocurrent direction towards the ESE. Flute and tool marks on basal surfaces also show consistent flow directions to the south-east (figure 2.8). This palaeoflow direction for the Lower Emine is consistent with that recorded by Sinclair et al. (1997). Assemblages of trace fossils are common on the base of the thicker sand beds and include *Chondrites*, *Zoophycos*, *Cruziana* and others characteristic of stressed deep-water facies (figure 2.9). Campion (1993) suggests that based on the rich and diverse microplankton assemblage, the Lower Emine Formation has a fully open marine setting. Compositionally, the Lower Emine Formation is reported by Sinclair et al. (1997) and other authors to be carbonate-rich, consisting of fine- to medium-grained peloidal and bioclastic wackestones interbedded with grey and cream micritic mudstones.
Figure 2.6 Typical back-thrust and deformed Lower Emine Formation at Cape Emine (locality 6.6). North is on the right of this photo and the vergence of folding is directed to the south.
Figure 2.7 Examples of intra-bed deformation within the Lower Emine Formation in the southern limb of the Iralki syncline (a & b show small-scale soft sediment deformation formed during deposition, c & d show south-vergent intra-bed thrusts).
Figure 2.8 Flute and tool marks with ESE palaeocurrent direction at locality 6.1

Figure 2.9 Trace fossil *Zoophycos* (typical deepwater, below storm wave base environment indicator) in Lower Emine Formation (locality 6.10)
Figure 2.10 Restored palaeocurrents obtained from the Lower Emine Formation during field work showing dominant ESE-directed flow. Measurements taken primarily from flute marks and ripples.
2.2.2 Upper Emine Formation

Synonymy

Upper part of the Emine “Flysch” Formation of Gochev (1932).

Type Locality

The Upper Emine Formation is best exposed within the core of the Irakli Syncline, just north of the entrance to the beach at UTM/UPS GR [0572744, 4733694] (figure 2.11).

Lower and Upper Boundaries

The lower boundary of the Palaeocene Upper Emine Formation with the Cretaceous Lower Emine Formation is conformable, dated by biostratigraphy (calcareous nannofossils and planktonic foraminifera [Globotruncanidae, Heterohelicidae, and “Gloigerinidae”]) (Peybernès et al., 2004). Continuous deposition across the K-T boundary is also documented in the platform sediments of the Byala Formation to the north (Stoykova & Ivanov, 1992; Ivanov & Stoykova, 1994). The upper boundary of the formation is marked by the End Palaeocene Unconformity. Juranov (1994) reported the absence of any planktonic foraminifera of Upper Palaeocene age and concluded deposition of the Upper Emine must have ended in the Middle Palaeocene. Doglioni et al. (1996) assert that the Kozichino Formation (c.f. §2.3) is the westerly, more proximal unit, time-equivalent of the Upper Emine Formation and a foraminiferal study by Valchev (2006) identified the K-T boundary approximately 20 m below the contact between typical Emine Formation and Kozichino Formation near Kozichino village.
Lithological Description

The Upper Emine Formation (Lower to Upper Palaeocene, Nannoplankton zones 1-9, (figure 2.12) as seen in the core of the Irakli syncline and particularly well exposed to the north of the syncline axis, is, in terms of broad depositional process, little different to the Lower Emine Formation. Many authors have, however, identified a transition from carbonate-dominated to clastic-dominated sedimentation (Sinclair et al., 1997; Vangelov & Sinnyovsky, 2001). There is certainly more variability in depositional style in the Palaeocene Emine Formation as manifest in bedding features but overall decimetre- to metre-scale fining-up beds or abrupt interbeds of coarse- or medium-grained sandstone and fine-grained silts/clays dominate, typical of turbidite sequences (figure 2.11). The Palaeocene-Eocene boundary marking the top of the Emine Formation is defined by Campion (1993) based on microfaunal assemblages.

Sediments of the Upper Emine Formation consist of thin-bedded, fine-grained sandstone (beds 10 to 25 cm thick) with mudstone alternations (5 to 10 cm thick) in fining-up packages based with thicker sandstone with ripples at the top and evidence of bioturbation at the base. Amalgamated beds are relatively common, as are small muddy/silty sedimentary (?)rip-up clasts within sandstones, both features which may be ascribed to high energy, rapidly moving flows. Occasional beds suggest chaotic flow or extreme soft sediment deformation. Logs 7.1, 7.2, 8.1 and 8.1 (Appendix I; figure 2.13) document detailed sections of the Upper Emine Formation. Palaeocurrent measurements from ripples, flutes and tool marks show flow within this unit to be more easterly than the southeast-directed flow of the Lower Emine (figure 2.10). Doglioni et al. (1996) also confirm a N110° directed palaeoflow direction.

Sinclair et al. (1997) report diverse trace fossil assemblages in the Upper Emine Formation, containing Chondrites, Rhizocorallium, Zoophycos, Cruziana, Palaeodictyon and numerous other small traces. Fresh exposure of the Upper Emine Formation in the river valley on the junction with the road to Kozichino village (UPS/UTM GR 0548690, 4737766) display extensively grazed top surfaces to sand
beds with abrupt bed boundaries and marly interbeds as well as *Cruziana* and abundant vertical burrows. Sinclair *et al.* (1997) also reported glauconite pellet-lined burrows although these were not observed in this study. Doglioni *et al.* (1996) describe *Helminthaidea labyrinctica* (small, “meandering” feeding trails [Heer, 1865; Aceñolaza & Tortello, 2003]) to be common along with less common *Paleodctyon* and *Lorenzinia* (bathyal feeding traces of the *Nereites* ichnofacies). Campion (1993) reports that microfaunal abundances become increasingly sparse up the Emine Formation from the Lower to Upper units and foraminiferal assemblages of very small sized individuals indicate highly stressed conditions at the very top of the formation. Overall microfauna show the Emine Formation in its entirety has a lower bathyal to abyssal water depth.

**Review of Tectono-sedimentary Interpretations from Published Literature**

At varying times, the Emine succession (deposited in the “Emine Basin”) has been interpreted as having been deposited in a back-arc basin (Bocaletti *et al.*, 1974) or piggy-back (Doglioni *et al.*, 1996) basin with clastic and volcaniclastic sedimentation. The facies of the Lower and Upper Emine Formations were studied in detail by Vangelov & Sinnyovsky (2001), who interpret the formation of the unit in a back-arc basin with increasingly clastic sedimentation in line with the observation that the Lower Emine unit is more carbonate-dominated. Ten different facies within the Emine Formation were described by these authors, all of deep-water clastic flows, ranging from sandy/carbonate debrites to muddy contourites. Sinclair *et al.* (1997) also suggest a deep-water setting with clastic deposition by episodic turbidity currents for the Emine sediments. They also describe potential migration of lobe-type sand accumulations on the basin plain or sandstone flux variations into the deeper basin based on variations in the sandstone/mudstone ratio although this appears to be a qualitative assertion.

The Upper Emine Formation was deposited when there was a high flux of tectonically-controlled clastic sedimentation from the thrust wedge into the basin implying active faulting inducing shedding of sediment. This established a multiple-
source sand-rich turbidite system in the basin axis as documented by the facies analysis of Vangelov & Sinnyovsky, 2001. The only observed upper and middle fan lithologies with distributary channels forming part of the feeder system are reported to the west near the town of Sliven, approximately 110 km due west of Cape Emine (c.f. §2.3). Vangelov & Sinnyovsky (2001) describe sediments representing muddy contourites, muddy debris flows and slumps deposited from the SSW. They also noted a change in depositional style south of Golitsa village as the muddy slumps and debris flows become concentrated in the lower parts (?Lower Emine) of sections and contourites and turbidites prevail in the upper sections (?Upper Emine) with transport towards the SSE.

The lateral transition that must be present between the Emine Formation and the time-equivalent Byala Formation (c.f. §2.2.2.1) to the north is hard to ascertain due to basin shortening and younger sediment cover. The Byala Formation represents the northern margin of the Emine Basin at this time as the margin was structurally controlled by east-west striking, pre-existing normal faults downthrowing to the south. Robinson (2004) notes that there is evidence for a major sequence boundary at the end of the Maastrichtian, in common with many other European basins, and as such, the erosion associated with the end Cretaceous boundary is unlikely to be related to any local structural feature affecting just the Balkan foreland. It is most probable that the basin was still forming the passive, southern margin of the Western Black Sea on the Moesian Platform. The End Palaeocene unconformity is interpreted to be of tectonic origin by Stoykova & Juranov (2005).
2.2.2.1 Byala Formation

The Upper Campanian to Upper Eocene 800 m thick Byala Formation (often divided into Upper and Lower but here considered as a whole, figure 2.1 for chronostratigraphic context) consists of a thrusted (north-vergent, steeply dipping structures) interbedded sequence of dm-scale beds of grey micrites, limestones and marls (the latter often possessing a tectonised fabric) occurring on Byala beach immediately south of the frontal thrust. Significant shortening is taken up via inter-bed slip as well as thrusting. The lithology is interpreted to represent deposition in a shelfal/outer-shelfal setting with background micrite deposition interrupted by sporadic input of fine clastics (Sinclair et al., 1997). There is evidence of extensive bioturbation, body fossils (echinoids) and trace fossils (recognised by Sinclair et al. (1997) as echinoid-grazing traces). Occasional thin organic-rich black shale horizons are present underlying lap-out terminations of marls.
Figure 2.11 Typical Upper Emine Formation on the south limb of the Iralki syncline (locality 7.1, Log 7.1 c.f. figure 2.13).
Figure 2.12 Biozones of the Emine Formation in the Emona (southern limb of the Irakli Syncline) locality of Peybernes et al., 2004.
Figure 2.13 Locations of logs (Appendix I) within the Emine Formation
2.3 KOZICHINO FORMATION

**Synonymy**

The Kozichino Formation is often referred to as the Kozichino Series of the “Dvoynitsa Formation/Group” (Juranov & Pimpirev, 1989). It was referred to as part of the Emine Formation by Vangelov (2001) and other authors although prior to this, Doglioni *et al.* had recognised it as a separate “Palaeocene Sandstone-Clay- Flysch” unit in their 1996 paper.

**Type Locality**

The only major outcrops of the Kozichino Formation surround the village of Kozichino itself (studied sections are located at ‘Kozichino North’ [UTM 0547179, 4743540] & ‘Kozichino South’ [UTM 0546760, 4742391]) (figure 2.2).

**Lower and Upper Boundaries**

The abrupt unconformable contact at the base of this formation with the underlying Upper Emine (basal Danian [NP1] according to Sinnyovsky, 1996) can be seen clearly at Kozichino South (figure 2.14). Vangelov & Sinnyovsky (2001) place the top Emine Formation underlying the Kozichino Formation within the *Micula prinsii* zone, approximately 15 m below the Cretaceous-Tertiary boundary as described from type localities in Bulgaria (*c.f.* Valchev, 2006). Stoykova & Juranov (2005) date the ‘Kozichino South’ locality as lowermost Danian (NP1) to Selandian (NP5). The ‘Kozichino North’ locality is stratigraphically higher (the contact with the underlying Emine Formation cannot be seen) but the succession is also given a date of Danian/Selandian (NP1 to NP5) (Sinnyovsky, 1996; Stoykova & Juranov, 2005).

The interfingering of the Emine and Upper Palaeocene-age formations is well recognised as the coastal exposures of Upper Emine can be traced into Upper Palaeocene (NP zones 7-9; Sinnyovsky & Sultanov, 1994). The stratigraphic range
of the Kozichino Formation is lowermost Danian to Selandian (Stoykova & Juranov, 2005) and is estimated to be greater than 400 m thick.

**Lithological Description**

Sedimentary logs 30.1 and 31.1 cover the entire ‘Kozichino South’ section and the lower 36 m of ‘Kozichino North’ respectively (Appendix I). The lower exposed section (‘Kozichino South’, log 30.1) consists of medium sandstone to pebble conglomerates in thick, laterally variable or discontinuous beds (figure 2.15). The conglomerates are approximately 0.5-1.0 m thick, commonly clast-supported, poorly sorted and are polymictic, containing clasts of rounded micrites, siltstone, quartz and micaceous sandstone up to 100 by 80 mm in size. There are sharp, erosive contacts between all beds. Isolated micritic beds become increasingly common, approximately 27 m from the basal contact with the Emine Formation (bed 11 on log 30.1; Appendix I). Lenses of very coarse to granular clastic material are commonly found in troughs and often form ‘basal lags’ fining up into medium to coarse sand beds up to approximately 1 m thick. Poor preservation of silty/very fine-grained lithologies is likely as the outcrop is well weathered and located in a river valley so the dominance of medium grained sands and coarser is possibly an artefact of this modern weathering history rather than depositional (17 m out of the 82 m documented on log 30.1 were not exposed). Stoykova & Juranov (2005) report reworked clasts of Upper Cretaceous limestones (possibly of Byala Formation) and marls within the clastic sediments. The same authors also identified rare calcareous nannofossils and agglutinated foraminifera in the limestones present.

The ‘Kozichino North’ locality (log 31.1, Appendix 1) is a continuous exposure in a river valley to the north of Kozichino village behind the church (figure 2.16). Log 31.1 shows the lowermost 36 m of the outcrop. Sedimentation styles are similar to the ‘Kozichino South’ locality, dominated by thick bedded and massive, medium- to coarse-grained sandstones, granular conglomerates and poorly exposed siltstones. Sedimentation gets finer and increasingly dominated by siltstones and shales further up the section. Palaeocurrents are extremely variable and although a direction of
flow from the west is most commonly implied, individual measurements range between flow towards the NE and flow towards the SW and can be attributed to multi-directional flows (figure 2.17).

**Review of Tectono-sedimentary Interpretations from Published Literature**

Previous studies have interpreted the variable facies found in the Kozichino Formation to be indicative of high density debris flows/coarse turbidites formed under sustained high energy submarine discharge. Vangelov *et al.* (1996) interpret the facies of the Kozichino as middle fan environment given the association of coarse-grained siliciclastic and calcareous turbidites interbedded with fine-grained muddy turbidites. Flow patterns suggest sourcing from the west along the axis of an elongate trough in front of the thrust wedge and although up the sections (especially in Kozichino North) palaeocurrents become increasingly variable, they remain dominantly sourced from the SW. This pattern may be related to local thrusting events or material sourced from unstable local slopes during active basin deformation. Progradation of the unit to the north and northeast is recorded by Vangelov & Sinnyovsky (2001) and is attributed to deposition during active basin deformation.

Vangelov & Sinnyovsky (2001) observed clast-supported, subangular to subrounded mudstones, sandstones, limestones, quartzite and volcanic clasts in a medium-grained to gravely matrix. The random orientation and poor sorting of the clasts, along with inverse to normal grading and planar fabric led to their interpretation as clast-supported sandy debrites laid down by debris flows. This interpretation is supported by field observations presented here. The Kozichino sediments show mixed styles of sandy debrite deposition, are laterally discontinuous and beds vary in thickness. Such variability in a deposit, making it impossible to recognise separate single fans, channel/levee associations, slump events etc. may be typical of multiple-source feeding of the fan system or the development of multiple lobes. Olistostromes are reported in both the ‘Kozichino South’ and the ‘Kozichino North’ sections (Stoykova & Juranov, 2005; Vangelov 1996) although were not observed
during the fieldwork of this study although there is a suspicion that these “olistostromes” were actually concretions as the latter are a conspicuous part of the Kozichino outcrop (figure 2.16).

Vangelov & Sinnyovsky (2001) suggest the deposit was fed by a braided alluvial system or from sediment failure and slumps on a coastal plain with a narrow shelf supplying a large volume of sediment. Carbonate-rich layers may have been fed via sand-poor parts of the shelf or by sediment bypass. They also suggest rounded clasts of Emine Formation material present within the Kozichino Formation can be used to infer the presence of feeder canyons incising into and cannibalising the basin slopes and reworking Emine Formation down into the deepest parts of the basin.
**Figure 2.14** Abrupt erosive contact between underlying Lower Emine and overlying Kozichino Formations at “Kozichino North” locality. The actual Cretaceous-Tertiary contact has been dated by Valchev (2006) to be ~10 m below this lithological contact within the Emine Formation.

**Figure 2.15** Granular sandstone/pebble conglomerate overlying medium grained sandstone bed at “Kozichino South”
Figure 2.16 Discontinuous outcrop at “Kozichino North” locality looking south. The concretions which may have been interpreted as olistostromes by other authors are seen in the outcrop at the front of the photo.

Figure 2.17 Planar cross-bedded sandstones used as flow indicators showing flow towards the SE.
2.4 **Bardarevo Formation**

*Synonymy*

Bulgarian literature commonly groups all regional Lower Eocene units into the “Dvoynitsa Formation/Group” e.g. Juranov & Pimpirev (1989). Figure 2.1 showing the East Balkan chronostratigraphy, illustrates how the Bardarevo Formation is thought to fit into the “Dvyonitsa Group”.

*Type Locality*

The studied sections of Bardarevo Formation outcrop to the west of Bardarevo Village [UPS/UTM GR 0547975, 4753344] (figure 2.2). The formation is absent along the Black Sea coast. Outcrops of the formation are generally poorly exposed.

*Lower and Upper Boundaries*

Stoykova & Juranov (2005) state that the formation overlies Upper Cretaceous (Turonian) sediments, unconformably separated by the end Palaeocene event. The Bardarevo sediments are conformably overlain by further coarse sandstones units of the Lower Eocene (Atanas Formation) although exposures of this contact are limited to one stream section, located at UPS/UTM reference [0547975, 4753344]. The Bardarevo Formation is estimated to be greater than 150 m thick and covers a period of time spanning the Upper Palaeocene to the base of the Lower Eocene (above the End Palaeocene Unconformity).

*Lithological Description*

The Bardarevo Formation consists of coarse, unsorted siliciclastic gravels and conglomerates in a very muddy matrix which has been largely eroded away in a river bed. Large (metre-scale), chaotically distributed micrites/marl blocks (figure 2.18), with tectonised fabrics, are common clasts within this unit. Other clasts present
included limestones, siltstones, micrites and quartzites. Clasts range in roundness from angular to well-rounded. Stoykova & Juranov (2005) suggest the blocks may be sourced from Upper Cretaceous rocks along with Triassic dolomites and Jurassic quartzites. The same authors also report normal and reverse bedding and that the density of clasts lessens up-section and large clasts become far rarer although the muddy/silty matrix remains consistent. This was hard to corroborate in the field due to the very low quality of exposure.

Review of Tectono-sedimentary Interpretations from Published Literature

The large-scale, chaotic and heterogeneous nature of the clast content of the Bardarevo Formation and the setting of blocks in a fine-grained muddy matrix, infers that this unit is likely to represent a debris flow, potentially derived directly from the thrust wedge. Palaeocurrents are hard to confirm given the disordered nature of the sediments. There is very limited discussion of this unit in the literature probably on account of the poor outcrop quality and limited geographical extent.
Figure 2.18 Example of tectonised micritic block within Bardarevo Formation (locality 17.1, west of Bardarevo Village). A hammer handle can be seen in the bottom left corner of this photo for scale
2.5 **Atanas Formation**

**Synonymy**

Bulgarian literature commonly groups all regional Lower Eocene units into the “Dvoynitsa Formation/Group” *e.g.* Juranov & Pimpirev (1989). The Atanas Formation is termed the Atanas Sandstone by Sinclair *et al.* (1997) and others although this group also includes the Gebesh Formation (first considered separately by Doglioni *et al.*, 1996). Doglioni *et al.* (1996) use the term “Lower-Middle Eocene Coarse Flysch” to describe the Atanas Formation. Figure 2.1 puts the Atanas Formation into its chronostratigraphic framework.

**Type Locality**

Extensive outcrops are present on the Black Sea coast between Mona Petra Cape (UTM/UPS GR 0573294, 4737257) and St Atanas Cape (“Shelborun Place”) (UTM/UPS GR 0573425, 4745068) just south of Byala where the formation is incorporated into the Obzor Syncline (figure 2.2).

**Lower and Upper Boundaries**

The Atanas Formation is a Lower Eocene unit seen to be directly underlying the Gebesh Formation within the Obzor Syncline as exposed in Byala Harbour. The coastal section is approximately 50-60 m thick but in total the maximum thickness of the unit may be up to 450 m (Doglioni *et al.*, 1996). Elsewhere, the Atanas Formation stratigraphically overlies the Byala Formation *e.g.* directly behind Byala village, or the Bardarevo Formation as exposed west of Bardarevo village.
Lithological Description

The Atanas Formation is incorporated into the Obzor Syncline and shows thickening within the overturned southern limb of the structure. The formation comprises thickly-beded, coarse arenitic sandstones, often laterally continuous for up to ~10 m and amalgamated, with abundant rounded concretions and intraformational gravelly/conglomeratic lenses (figure 2.19). The lowest part of the Atanas Formation consists of grey-green and red clays (the latter coloured such due to weathering [Sinclair et al., 1997]) and overlies the uppermost, marly Byala Formation in Byala Harbour. The transition from muds to fully clastic lithologies is rapid, occurring over just ~10 m of vertical stratigraphy. In isolated exposures, transitions between silts/shales to thick massive coarse sandstones can be clearly seen (figure 2.20). In discrete beds with erosive contacts, monomictic rip-up clasts of silt of increasing size but decreasing density are entrained into increasingly coarse sandy matrix directly underneath the granular base of a massive, metre-thick, coarse sandstone bed typical of the Atanas facies.

Once into the Atanas Formation proper, approximately 15 m laterally east along the section from the Gebesh contact, normally-graded bedding and large-scale cross-beds can be seen within the 1-4 m thick sand beds with sharp bed bases. Facies present within the formation are impressively consistent and individual beds are laterally continuous with commonly amalgamated beds and other evidence for high energy erosive contacts between sandstones such as conglomeratic/granular bed bases, flute marks and sheared clasts. Bed bases can be undulose and Sinclair et al. (1997) recognised these undulations as having developed regularly with low angles (2-10°) and large wavelengths (1-10 m). Beds 1 to 2 m thick typically grade normally from massive coarse sands, sometimes with silty clasts, into planar-laminated medium sands (sometimes with concretions picking out horizons or occasional ripple horizons) then into finer, muddy lithologies. Sinclair et al. (1997) note the light coloured mudstones as being of calcareous composition and containing abundant Chondrites bioturbation and other larger burrows. Ripple horizons (e.g.
UPS/UTM GR 0573649, 4745029) provide palaeocurrent directions indicating a predominantly south or south-easterly flow direction.

Doglioni et al. (1996) noted traction structures, water escape structures and clay clasts within the upper parts of turbidite sequences (beds b to d of classic Bouma cycles). At UPS/UTM GR [0573560, 4745041] the deformed marly base to a 1.5 m thick coarse sand bed was noted to possess soft sediment deformation attributable to rapid deposition of the overlying sandstone which contained matrix-supported shale clasts in a granular quartz-rich matrix (figure 2.21). The base of some sandstone beds are conglomeratic (granular to pebble grade clasts) and channelised and cut directly down where underlain by sands rather than finer lithologies. A particular feature of the Atanas Formation, noted by all authors describing the unit, are the large, regularly distributed, spherically-weathering concretions common in the middle of the exposure (figure 2.19). Stoykova & Juranov (2005) attribute the presence of these concretions to variations in carbonate content or the presence of 10-50 cm sized clasts of clayey limestone which were also observed during fieldwork for this research (locality 34.2).

There were no macrofossils recorded in the Atanas Formation, probably on account of its coarse-grained nature and by inference, high energy of deposition. Juranov (1983) states that the mudstones of the lowermost Atanas Formation/uppermost Gebesh Formation contain a planktonic assemblage with a 99.9% plankton-to-benthon foraminiferal ratio (Sinclair et al., 1997). The same mudstone section is dated by Campion (1993) as late Palaeocene to early Eocene on the basis of its sparse foraminiferal assemblages. The very limited microfossil record attests to a bathyal or deep water with highly stressed bottom-water conditions in this lower part of the Atanas Formation.
The sand-rich Atanas Formation is commonly considered to represent sandy turbidite and debrites flows from the west into the deeper basin proximal to the main basin axis. The main depocentre of the basin had migrated northwards with respect to the Palaeocene basin by this time due to advancement of the thrust belt (Doglioni et al., 1996). The lower portion of the sequence, where background muds are relatively dominant, probably represents low density turbiditic deposition but up section, where sands become dominant, coarser and thicker, it is likely that high-density flows deposited under steady flow conditions were responsible for forming such thick, consistent sand beds (Sinclair et al., 1997; Kneller & Branney, 1995). Some sandstones of the Atanas Formation may represent high energy erosive mass flow deposits where there are rip-up clasts of intraformational silts and sandstones. The observation of traction carpets by Doglioni et al. (1996) can be interpreted as reflecting the formation of inertia layers recording fluctuating flow conditions under sustained flow (Sinclair et al., 1997; Hiscott, 1994).

Marine seismic lines studied by Sinclair et al. (1997) show the occurrence of a marked mound overlying the base Tertiary unconformity, which is interpreted as a possible basin-floor fan, and suggests that there are equivalents of the Atanas Sandstones offshore (figure 2.22).
Figure 2.19 Thick laterally continuous beds of Atanas Sandstone with regular elongate concretions (locality 15.1, Cape Atanas) and disturbance by apparent reverse faulting although offset is difficult to establish due to the featureless nature of the formation. Yellow A5 field notebook for scale.
Figure 2.20 Location of log 15.2 (field log below) at Cape Atanas showing abrupt transitions between monomictic siltstone conglomerates and thick beds of overlying medium grained sandstone.
Figure 2.21 Soft sediment deformation of fine siltstone beds overlain by a conglomeratic unit (Cape Atanas, locality 15.7)
Figure 2.22 From Sinclair et al. (1997) a) Offshore line 12 showing location of well IV/91-1 b) Depth-converted section of line 12 (with 1.8 vertical exaggeration). The highlighted “Lower Eocene fans” (in pink) are suggested to be offshore equivalents of the onshore Atanas Sandstone.
## 2.6 Meshilika Formation

### Synonymy

Bulgarian literature commonly groups all the regional Lower Eocene units into the “Dvoynitsa Formation/Group” e.g. Juranov & Pimpirev (1989). Figure 2.1 displays the position of the Meshilika Formation within this group on a regional chronostratigraphy.

### Type Locality

This formation is exposed on the coast at “Meshilika Place” (UPS/UTM GR 0572856, 4738794) south of the village of Obzor (figure 2.2).

### Lower and Upper Boundaries

The Meshilika Formation stratigraphically overlies the Atanas Formation as exposed in the Obzor Syncline (figure 2.23). Stoykova & Juranov (2005) date the formation as Ypresian (Lower Eocene) on account of the calcareous nannofossil and foraminifera content although there is significant reworking of blocks within the unit. The unit is estimated to be greater than 300 m thick and is seen to interfinger with and rework clasts from the time-equivalent Gebesh Formation to the south.

### Lithological Description

The Meshilika Formation is a very heterogeneous unit with large blocks (>10 m scale) of mixed lithology set within a muddy matrix. Much of the outcrop along the coast is badly eroded and the apparently chaotic nature of deposition makes systematic description difficult but the following represents some of the observations made.
The base of the succession contains:

- *Nummulite*-rich, 15 cm thick isolated beds of very coarse to granular well cemented sandstone with basalt clasts in irregular layers (figure 2.24). This facies is seen to regularly fine up into marly clast-ridden, finer sand overlain by fine- to medium-grained planar bedded sandstones with occasional silty trough laminae (UPS/UTM GR 0572811, 4739038).

- An apparent intraformational angular unconformity (UPS/UTM GR 0572725, 4739346) between two 30 cm thick micaceous and *Nummulite*-rich sandstone beds. The overlying bed contains sandstone lenses with truncated basal contacts, with ripple cross-laminae and silt rip-up clasts up to 10 cm in length attesting to a high energy event causing formation of the structure (figure 2.25).

- Large (metre-scale) slumped blocks of massive fine (mica-rich) sandstone in a muddy matrix (UPS/UTM GR 0572715, 4739392).

- Potentially deformed and thrustted, purple and green-grey marls (potentially possessing tectonised fabric/cleavage) with occasional loose sandstone fragments or very discontinuous sandstone beds.

**Review of Tectono-sedimentary Interpretations from Published Literature**

The nature of the outcrop suggests that there is likely to be low energy siltstone/mud background sedimentation that has been heavily eroded by present day coastal processes, interspersed with high energy flow and turbidite deposits which are variable in distribution and character. Stoykova & Juranov (2005) note that the upper part of the succession contains abundant shallow-marine macrofauna (including *Nummulitids*, gastropods, echinoids, corals and bivalves), all of which are considered in the large part to have been reworked during deposition.

From the coastal exposures, Stoykova & Juranov (2005) infer two environmental interpretations – the lower part of the unit being of middle-fan environment and the upper part being of base slope/inner-fan environment given the relative increase in
large, chaotically-deposited blocks in the deposit. The clasts in the Meshilika Formation are thought to be derived from the Byala Formation, Gebesh Formation and volcanic debris, all of which were probably sourced directly from the thrust wedge or remnant arc although the high carbonate clast content may be indicative of widespread instability on both margins as the basin narrows.

Figure 2.23 Meshilika Formation exposed in 20 m high cliff south of Obzor (UPS/UTM 0572715, 4739392) (locality 11.4). The slightly rounded blocks seen are metre-scale clasts set in a finer grained matrix within this heterolithic unit.
Figure 2.24 Nummulite-rich pebbly sandstone beds of the Meshilika Formation at “Meshilika Place” (locality 11.2) overlain by finely bedded, better sorted sands. These sediments are likely to be contained within a reworked clast.
Figure 2.25 Apparent angular unconformity between two 30 cm thick sandstone beds within the Meshilika Formation, north of Meshilika Place (locality 11.3) probably attributable to reworking of large clasts. Field sketch below.
2.7 **Gebesh Formation**

**Synonymy**

Bulgarian literature commonly groups all regional Lower Eocene units into the “Dvoynitsa Formation/Group” *e.g.* Juranov & Pimpirev (1989). Doglioni *et al.* (1996) first recognised the Gebesh Formation as a separate unit although the authors dated it as Middle Eocene. Figure 2.1 shows the Gebesh in its chronostratigraphic location.

**Type Locality**

The Gebesh Formation outcrops north of Obzor beach (near “Camping Luna”), south of Byala harbour in the core of the Obzor Syncline (figure 2.2) although the northern limb is better exposed due to modern alluvial deposits obscuring outcrops to the south on Obzor beach (UPS/UTM GR 0572092, 4743655).

**Lower and Upper Boundaries**

The Gebesh Formation is seen to directly overlie Atanas Formation in the type locality. The upper boundary of the unit is unexposed as it occupies the core of the Obzor Syncline but is likely to be erosive/unconformable given the presence of the Mid-Eocene Illyrian Unconformity. The formation is estimated to be greater than 250 m thick. Doglioni *et al.* (1996) estimate the thickness to be approximately 500 m.

**Lithological Description**

The Gebesh Formation consists of regular 10 to 25 cm thick interbeds of fine, often micaceous, rippled and bioturbated, sandstones and silts or marls in cycles of approximately 1 m thick (each containing approximately 6 to 12 fining-up cycles of sandstone to silts/marls) (figure 2.26). Where individual fining-up sequences
progress through fine sand to shale (3-6 cm thick) to marl (1-4 cm thick), contacts are gradational but where fine sand fines directly into marl/micrite (beds <2 cm thick, commonly with planar cross lamination) contacts are sharp. All sandstone beds are between 2 and 7 cm thick, possess sharp basal contacts, occasionally contain silty laminae and are poorly consolidated. Rare sandstone beds are up to 12 cm thick but this might not be depositional but rather a result of thickening by soft sedimentary deformation and slumping. Bed contacts within the unit are consistently planar and laterally extensive. In the stratigraphically lower portion of the type locality, the sand-to-marl fining-up cycles become thicker and shales become increasingly homogeneous and produce hackly-weathering scree. Individual sand and shale beds are commonly up to 20 cm thick in this section and bed boundaries become increasingly obscured.

Log 12.1 in Appendix I is a 20 m section through typical Gebesh facies. Slight variation in the nature of sand to marl interbeds can be seen in terms of bedding features and bed contacts as well as in the frequency of cycles but overall the formation is consistently made up of thin, finely bedded units. Structurally, the Gebesh Formation is folded into a succession of tight, upright synclines and anticlines on the northern limb of the Obzor Syncline (figure 2.27). It is suspected that these folds, which possess a common NW-SE fold axis, are the result of north-vergent blind thrusting (c.f. §2.13). Both normal and reverse small-scale faulting is present. Any palaeocurrent indicators would be extremely tenuous given the degree of deformation although Doglioni et al. (1996) suggest palaeoflow is approximately towards the east (N100°), again invoking sediment transport along an east-west trending basin axis.

*Review of Tectono-sedimentary Interpretations from Published Literature*

The classic fining-up sediment sequences of the Gebesh Formation are interpreted as low density turbidites (compared to the high density Atanas turbidites) deposited in deep water as sheet sands given the lateral continuity of each bed. Sinclair *et al.* (1997) suggest the turbidites become increasingly dilute up sequence whereas
Doglioni et al. (1996) intimate that there is a coarsening-upwards pattern with marls and clays with carbonate concretions at the base which up the section grade into silty and very fine sandstones. There are approximately equal proportions of very fine sandstone and shale.

*Figure 2.26 Typical dm-scale sand:shale interbeds of the Gebesh Formation (locality 12.2)*
Figure 2.27 Tight limbed anticlinal folding within Gebesh Formation north of Obzor (locality 12.10)
2.8 OBZOR CONGLOMERATE FORMATION

Synonymy

No other names can be found for the Obzor Conglomerate Formation although it is not widely discussed in the older, Bulgarian literature.

Type Locality

The Obzor Conglomerate Formation is poorly exposed but can be seen to form a discrete topographic high to the west of the coastal village of Obzor (figure 2.2). The Obzor Conglomerate is known only from this one locality but other “Dvoynitsa Conglomerates” such as that at the Chudnite Skali inland exposure (UPS/UTM GR 0523580, 4755939) may actually be of mid-Eocene age (pers. comm.; K. Stoykova, 2006) based on the nannofossil assemblages. Obzor-age conglomerates intercalated with middle Eocene, upper bathyal mudstones, are also recorded from well IV/91-1 offshore (Sinclair et al., 1997). The Obzor Formation as identified in wells and outcrop may not be a continuously mappable unit but in fact a local member; however, in this regional study, the outcrops at Obzor are of depositional significance due to their distinct composition and facies.

Lower and Upper Boundaries

Individual cliff faces are up to 20 m high but the total thickness of the unit is unknown. The unit is thought to unconformably overlie the Lower Eocene Gebesh Formation and would probably have been overlain itself by the Middle to Upper Eocene Dolen Chiflick Formation but no contacts with any other formations are visible. Vangelov (1996), however, does describe the unit as having a thickness of 165 m with erosive upper and lower boundaries, the lower boundary eroding down into the Gebesh Formation. Sinclair et al. (1997) were unable to find any boundary contacts but concluded it must overlie the Lower Eocene sequence. Stoykova &
Juranov (2005) give an age of Middle and/or Upper Eocene but this is from stratigraphic inference rather than biostratigraphy.

**Lithological Description**

Vangelov et al. (1996) describe the Obzor Formation as comprising thickly-bedded conglomerates, sandstone and siltstones with reworked shallow marine and continental macrofossils, including bivalves and gastropods (dated as Middle to probable Upper Eocene). Sinclair et al. (1997) note the poorly sorted natured of the formation and that clast sizes range from an average 10-20 cm up to a maximum of 40 cm. The matrix is described as a dark grey, poorly sorted, argillaceous medium-grained sandstone and the conglomerate is clast-supported, with vague low-angle cross-bedding picked out by rough sorting of different sized clasts (figure 2.28). The clasts are rounded and consist of basic igneous material (thought to be compositionally the same as the Srednogorie Zone calc-alkaline volcancics) and some cream-coloured micrite. B-axis imbrication of the clasts is also noted in the same paper to show flow to the south/southeast.

Three sandstone samples of Obzor Formation age from well R79 (Shorpilovsky) (1145 m [R79-12], 1258 m [R79-13] and 1442 m [R79-14]), which is located approximately 3 km south-east of Obzor, were point-counted as part of this study for provenance comparison. These details are recorded in chapter 3.

**Review of Tectono-sedimentary Interpretations from Published Literature**

Unfortunately, due to the restricted exposures of the Obzor Formation, interpretation of depositional settings and environments is a difficult task. Vangelov et al. (1996) infer a very generalised depositional setting of sedimentation in shallow marine and continental environments. Sinclair et al. (1997) suggest the clast-supported conglomerate, cross-bedding and aforementioned imbrication mean that sediment was transported as bed-load under a sustained flow, probably derived from the Srednogorie Zone to the south, which must have been emergent at the time. As also
invoked herein, the same authors also link this deposit to early thrust activity on the southern margin of the basin.

*Figure 2.28* Typical unsorted conglomeratic Obzor Formation containing rounded clasts of various igneous and sedimentary origins with rough alignment of clast b-axes (locality 38.2, Obzor Hill)
2.9 **Dolen Chiflick Formation**

*Synonymy*

Pollak (1933) (cited in Stoykova & Juranov, 2005) termed this unit the Dolen Chiflick Member of the Avren Formation.

*Type Locality*

There is no type locality in existing literature for the Dolen Chiflick Formation but the most comprehensive exposures studied in this work were located at Velichikovo and Chairdere.

*Lower and Upper Boundaries*

The formation is dated by nannofloral and microfaunal associations to the Bartonian and Priabonian (Upper Eocene) (Stoykova & Juranov, 2005). It is reported to have a transgressive lower boundary with the Lower Cretaceous (noted along the Armera River) and a tectonic contact with the “Dvoynitsa Formation” (*i.e.* Lower Eocene clastic units) between Krivini and Dolen Chiflick village. Laterally there is a sharp lithological change from the Avren Formation to the north and also a sharp lithological change with the overlying Ruslar Formation.

*Lithological Description*

Stoykova & Juranov (2005) describe the Dolen Chiflick Formation as being dominated by clayey sands with alternating sandy marls but also comprising silty marls, sandy limestones and calcareous gravels. The well exposed Dolen Chiflick section at Chairdere Reservoir (UPS/UTM GR 0555978, 4757571) comprises sandstones, marls and siltstones. Most of the section exposed here consists of fine, marly silts with only rare interbeds of very fine sandstone about 30 cm thick at the base and the top of the outcrop. These rocks are reported by Stoykova & Juranov
(2005) to be exceptionally rich in foraminifera and calcareous nannofossils as well as macrofossils (bivalves) and the formation here is apparently lithologically similar to cored sections from wells in the Lower Kamchia Depression.

Another section of possible Dolen Chiflick Formation at Velichikovo is unconfirmed by biostratigraphical dating but probably a locality mentioned by Doglioni et al. (1996) which is described as comprising marls with very thin sandstone laminae and beds of bioturbated fossiliferous sandstone. The exposures are found in a railway cutting to the east of the village of Velichikovo (UPS/UTM GR 0535739, 4766145). These 50 m thick cliff sections are a combination of metre-scale silty slope and indurated sandstone beds approximately 1 m thick with sharp contacts in between. There are two distinct types of sand beds with descriptions from this study as following:

1. Blue-grey sands with quartz pebbles and very well cemented although thinly bedded (three amalgamated beds approximate to 40 cm total thickness) and often interbedded with grey, micaceous, platy-weathering silts. These beds are occasionally shelly.

2. Yellow bioclastic and bioturbated (figure 2.29) sandstones with dm-scale silt clasts and common glauconite. These beds in particular show soft-sediment thrusting and intra-bed thickening towards the east (figure 2.30) with occasional large marly rip-up clasts at the base of sheared layers and noticeable deformation of underlying silts.

Both types of sand beds are sharp-based, laterally extensive, massive, coarse grained (but often fine up slightly) and poorly sorted but the contrast in composition may suggest two contrasting feeding sources from the west for the yellow bioclastic sands and possibly from the south for the blue-grey sands. Palaeocurrents are presented in figure 2.32. This hypothesis will be discussed further in the following synthesis chapters.

Review of Tectono-sedimentary Interpretations from Published Literature
There is little discussion of the Dolen Chiflick Formation in the literature. Doglioni et al. (1996) interpret the formation as being turbiditic from well data but in exposures, perhaps because of its highly localised occurrence, it appears to be pink clays with pelagic microfossils or bioclastic sandstone and siltstone interbeds like those at Velichikovo.

*Figure 2.29* Heavily bioturbated sandstones on fallen block at Velichikovo showing feeding burrows of up to 2 cm diameter.
Figure 2.30 Outcrop of thrusted (?) Dolen Chiflick sandstone at Velichikovo (thrust plane in shadow, sense of vergence left to right on photo towards east). The bed is overlying bedded and deformed silts and probably represents soft-sediment deformation given the lack of evidence for sharp fracturing.

Figure 2.31 Geometry of beds at Velichikovo outcrop (cliff section approximately 40 m high) with contrast between bluey-yellow beds at fore-front of photo and yellow beds higher in cliff.
Figure 2.32 Corrected palaeocurrent data from cross-beds in the Dolen Chiflick Formation at Velichikovo locality. Dominant flow is seen towards the SW although a certain degree of bimodality is suggested.
2.10 **ARNAUTLER FORMATION**

*Synonymy*

The name adopted for this unit comes from the old name of the village of Rudnik in the Varna area (Stoykova & Juranov, 2005). It is often incorrectly quoted in Bulgaria literature as being the Momino Formation *e.g.* Aladjova-Hrischeva (1991).

*Type Locality*

A type locality for the Arnautler could not be found in the literature but the extensive exposure at Goren Chiflick (UTM/UPS GR 0551001, 4762525) is a good example of the classic bioclastic sandstones of this formation.

*Lower and Upper Boundaries*

The Arnautler Formation overlies the Avren Formation but the upper boundary of the formation is obscured. Ajdanliksky & Vangelov (2004) describe both boundaries as being sharp lithological contrasts. The unit may be overlain by Oligocene Ruslar Formation but there is thought to be an unconformity separating the Eocene and Oligocene. The age given for the formation (Bartonian, Upper Eocene) by Stoykova & Juranov (2005) is based on its stratigraphic position with the Avren Formation. Ajdanliksky & Vangelov (2004) estimate the unit thickness to be between 30 and 50 m.

*Lithological Description*

Stoykova & Juranov (2005) describe the Arnautler Formation as consisting of sandy limestones and calcareous sandstones with abundant skeletal debris in a limey-sandy matrix and marls. The limestones present are firm, rusty yellow coloured and medium bedded whilst the sandstones are fine to coarse-grained, well to poorly cemented and also contain abundant skeletal fragments and reportedly some green
spots indicating a glauconitic content. Ajdanliksky & Vangelov (2004) state that the bioclastic content of the limestones and sandstones is mainly *Nummulites*. They also indicate that there is significant lateral variation of the unit and much interfingering of lithologies including interbedding of bioclastic limestones and sandstones with marls.

The Goren Chiflick section (locality 37.1) studied during fieldwork represents a well-exposed, 20 m high cliff section of well-bedded, quartz-rich, bioclastic-rich, coarse yellow sandstone characteristic of the Arnautler Formation. The lithology is generally very porous although the degree of cementation does vary between beds with an apparent link to sorting. There are planar cross-beds and soft sediment deformation (figure 2.33) as well as thin rippled laminae of fine silty sandstone (possibly mud drapes, often ripped up into overlying coarser sandstone) (figure 2.34). Load and flame structures were also noted up to 30 by 10 cm in size along with abundant dewatered bedding. Further up in the cliff section, “honeycomb” weathering indicating the dissolution of calcite cement is common and sands are extremely friable where uncemented. Burrows are present on the base of some beds, approximately 15 mm in diameter although these were hard to pick out in cross-section. The entire cliff section appears to become increasingly fine upwards and although no abrupt lithology changes can be seen the coarse bioclastic sands represent quite a facies contrast, possibly indicative of channel fill.

*Review of Tectono-sedimentary Interpretations from Published Literature*

No discussion of the tectonic setting of the Arnautler Formation could be found in existing English-language literature. Doglioni *et al.* (1996) mentions the Momino Formation, which is a possible synonym of the Arnautler Formation, although it is stated as being of Oligocene age (since disputed by more recent biostratigraphic work *e.g.* Stoykova & Juranov, 2005). In this interpretation of the arenitic and bioclastic sandstones, a tidal environment is inferred from the presence of abundant echinoids and *Nummulites*. The variable cross-bedding observed in the field may also support a tidal depositional environment. Upper Eocene sedimentation is
mentioned by Bokov et al. (1979) to have been of deep sea facies into an underfilled basin setting, in sharp contrast to the unconformably overlying Oligocene sedimentation although no further details are given and this interpretation does not tally with observations made about the Arnautler depositional facies which suggest tidally influenced, possibly shelfal facies deposited within the fair weather wave base.
Figure 2.33 Deformed bedding in Arnautler Formation at Goren Chiflick (locality 37.1) showing disturbance due to either dewatering or slope movement.

Figure 2.34 Cross-bedded bioclastic Arnautler sands interbedded with finer siltier planar layers with variable cross-set directions at Goren Chiflick
2.11 RUSLAR FORMATION

Synonymy

First described by Gochev (1934) (cited in Stoykova & Juranov, 2005).

Type Locality

The top of the Ruslar Formation is exposed at Karadere (also known as Black Cape) (UTM/UPS GR 0573159, 4752282) just north of Galata village (figure 2.35), overlain by a sharp, erosional contact with the Galata Formation.

Lower and Upper Boundaries

The upper part of the Ruslar Formation at the Karadere locality is assigned to the Lower Oligocene (Rupelian, Nannoplankton Zone 21) by Stoykova & Juranov (2005) based on the data obtained from calcareous nannofauna assemblages by K. Stoykova. Aladjova-Hrisceva (1991) does, however, report the base of the Ruslar Formation on the Frangen Plateau (in the Beloslav region) to be of Upper Eocene age (based on foraminiferal data) but the rest of the formation is Oligocene in age. The Ruslar Formation is in fact the only Oligocene unit within the Balkan foreland basin sequence (Ajdanliksky & Vangelov, 2004). The lower boundary is a sharp or erosional contact with the Avren and Arnautler Formations within the Kamchia Basin region. Doglioni et al. (1996) note that the lower contact is unexposed in the field but appears to onlap the Dolen Chiflick Formation on seismic. Further north on the platform, widespread Ruslar Formation unconformably overlies older units and Sachsenhofer et al. (2009) observed on seismic prominent erosional features at the top of the Ruslar Formation. The upper contact is erosional, overlain by the transgressive Galata Formation sediments. Onshore the thickest formation is up to 70 m near Varna whilst offshore, the Ruslar Formation is recorded as being up to 500 m thick (Sachsenhofer et al., 2009).
Lithological Description

The section at Karadere is the best coastal outcrop of the coarsening-up Ruslar Formation, overlain by Galata Formation. The lowest part of the section comprises calcareous clayey siltstones with interbeds of calcareous manganese ore nodules. The occurrence of variable sandstones, gravels and conglomerates become increasingly common up section. The uppermost part of the section consists of laminated fine mudstones with thin (<5 cm thick) but regular interbeds of medium- to coarse-grained, moderately well sorted sandstone with some ripple beds. Stoykova & Juranov (2005) report calcareous nannofossils and diatoms from this locality whilst Doglioni et al. (1996) identified plant fragments but no microfossils. The manganese deposits are widely recognised as indicating condensation and that sediment-starvation played a role during deposition of the formation (figure 2.35).

Stoykova & Juranov (2005) state that regionally, the Ruslar Formation can consist of
- Clays (grey, grey-green or brown in colour, either non- or partially calcareous);
- Sandstones (grey, fine- to medium-grained with muddy matrix, weakly cemented);
- Siltstones (dark grey to greenish, weakly cemented, finely bedded, containing coarse grains of quartz and glauconite);
- Marls (silty, thinly bedded, green and contain thin layers of shale),
- “Spongolites” and diatomites (in isolated layers within other lithologies);
- Tuffs;
- Manganese ores (generally found at the base of the formation, both in concentrated ore zones tens of metres thick or as isolated interbeds).

Ajdanliksky & Vangelov (2004) describe 60-70 m thick outcrops of the lower part of the Ruslar Formation near Rudnik village with manganese mineralization in both carbonate and oxide form overlain by a 25-30 m interval of grey, compacted, carbonate-rich silty clays grading into finely laminated clays (~20-25 m thick) containing discrete horizons of quartz sands. The same authors describe three
sand/clay packages up to a total of 90 m thick separated by clay horizons along the Kamchia River valley.

Sachsenhofer et al. (2009) describe the Ruslar Formation as being made up of finely laminated pelitic rocks with rare sandstones, siltstones and limestone beds and emphasise the presence of manganese mineralisation in the lower part of the formation (NP Zone 22 [Pshekian] age). The manganese layer contains tuffitic layers and is overlain by a layer of grey, dense carbonaceous clays.

**Review of Tectono-sedimentary Interpretations from Published Literature**

Bokov et al. (1979) describe the clay-rich early Oligocene sedimentation to have occurred in discrete depocentres (six separate locations were identified by these authors in the study region). As the Oligocene progressed, these individual basins are thought to have decreased in size as sedimentation in-filled accommodation space created by tectonic subsidence. Ori (2004) interpreted the typical outcrops of Ruslar Formation to represent deposition in a very low-energy environment with some currents of wave action able to rework the sediment interface and the presence of wave laminae suggests a shallow water environment below wave base level. The same study located one sand body which was interpreted as coastal sediment accumulated in a beach environment (shoreface sediment accumulated in the external part of a high-energy beach).

Sachsenhofer et al. (2009) infer an outer shelf to shoreface facies for the Ruslar Formation. The same researchers also used oxygen content to determine that dysoxic to anoxic conditions with medo- to euhaline salinities prevailed during deposition of the Ruslar. Manganese deposits, as characteristically found at the base of the Ruslar Formation, are documented as forming in sediment-starved seafloor settings where metal oxides are directly or indirectly precipitated out of the sea water over thousands of years or much longer time periods (Tucker, 2001). This would suggest that the base of the unit was deposited during a very tectonically quiescent period, followed by background silt deposition with only sporadic inputs of sands
through marine flows. The Oligocene manganese deposits are recognised as part of the “Circum-Black Sea” metallogenic zone (Popov, 2002) which extends to the South Ukraine, South Russia and Georgia.

Evidence from seismic lines as used by Sachsenhofer et al. (2009), Popov & Kojumdjieva (1987) and Marinov (1997) suggests the Ruslar Formation was deposited between periods of significant erosion triggered by uplift of the Balkanides and is related to the development of a W-E directed channel belt.

*Figure 2.35* Large concretion at base of finely laminated, silty Ruslar section at Karadere (hammer head at bottom of photo for scale)
2.12 GALATA FORMATION

Synonymy

First recognised by Popov & Kojumdgieva (1987).

Type Locality

Two localities are recognised in the literature, Karadere on the coast and a quarry at Novo Oryahovo inland (the latter inaccessible for this study). Typical Galata Formation is found in coastal cliff sections all around the Cape Galata headland (figure 2.37).

Lower and Upper Boundaries

Stoykova & Juranov (2005) suggest that the Galata Formation at Karadere is of Tchokrakian to Karaganian (Middle Miocene) age, based on comparison with other regional outcrops. Other authors give a wider age range of Tarkhanian (Mid-Miocene, Langhian) to Konkian (Mid-Miocene, upper Langhian to Serravallian) or even Lower Sarmarian (Mid-Upper Miocene, Upper Serravallian to Tortonian) (Popov & Kojumdgieva, 1987; Ajdanliksky & Vangelov, 2004). Ajdanliksky & Vangelov (2004) state that the top of the unit is marked by a sharp lithological boundary into the Evksinograd Formation and the maximum recorded formation thickness is >200 m, exposed south of Varna. Doglioni et al. (1996) go into greater detail on the basal contact of this unit with the Ruslar Formation and describe an 8° angular unconformity with strong evidence for erosion e.g. clasts of Ruslar Formation which are incorporated into the base of the Galata Formation. Ori (2004) describes a strongly erosional surface at the lower contact of the Galata Formation with the Oligocene and measured a 10° angular unconformity.
Lithological Description

The Galata Formation is dominantly composed of poorly-cemented sandstones with subordinate claystone and sandy clay interbeds and rare seams of unconsolidated gravels, marls and sandy limestones (Popov & Kojumdjieva, 1987; Ajdanliksky & Vangelov, 2004) (figure 2.38). The fining-upward nature of this unit, with gravels and sandstones common at the base and increasing frequency of seams of clays and sandy limestone up-section, is well recognised by all literature describing it. Two main localities are described by Stoykova & Juranov (2005) – Karadere (studied during this research) and Novo Oryahovo Quarry. The Novo Oryahovo Quarry was unfortunately inaccessible for study so descriptions are derived from Archer (2004) as cited in Stoykova and Juranov (2005). The Galata Formation at the Karadere locality is a fining-up sequence with 2-3 m of breccia containing 1-2 m diameter, angular, chaotically distributed clasts of Ruslar Formation, at the base grading into a clast-supported conglomerate (~2 m thick with rounded, spherical, siliciclastic, pebble to cobble-sized clasts of medium-grained red sandstones, mudstones and quartz clasts) (figure 2.36). This then gradually fines through to a matrix-supported conglomerate (2-3 m thick) which is sharply overlain by medium- to coarse-grained sandstone. Within clast-ridden sections the clasts themselves are aligned along bedding and Stoykova & Juranov (2005) report small-scale faulting (offsets 0.1-0.3 m) of presumed syn-sedimentary/soft sedimentary deformation origin.

Doglioni et al. (1996) describe the Galata Formation as containing clast-supported conglomerates with sandy matrix along with coarse, cross-stratified quartz-rich sandstones infilling channels up to 10 m thick. Stoykova & Juranov (2005) describe these sandbodies as consisting of moderately well sorted, possibly planar cross-bedded channel sandstones with sharp erosive bases and basal lags of moderately rounded pebbles. They also describe observations of fine mudstone overbank deposits 0.3 m thick at the margins of sandbodies.

Looking at the basal contact, Ori (2004) describes erosional depressions filled with organised (stratified and imbricated) polymictic conglomerates (clasts 5-30 cm in b-
axis dimensions) and clay clasts or large (1-2 m) fragments of Oligocene fine-grained deposits. Palaeocurrents were measured to the NNE (figure 2.36).

The Novo Oryahovo Quarry (originally described by Archer, 2004; cited in Stoykova & Juranov, 2005), akin to the Karadere locality, contains channel-fill sediments, fluvial conglomerates and “shoreface tidal sands”. The following description is derived directly from this research. The section is approximately 50-60 m thick and is seen to display a fining-upwards sequence from conglomeratic channels with erosive bases on top of thick sands through to fine-grained, silty sediment at the top. The channel-fill (the aforementioned top of the section) comprises interbedded fine-grained sandstones and grey mudstones unconformably overlying coarser, fluvial sediments. “Fluvial conglomerates” described from the section comprise poorly sorted, matrix-supported, rounded pebbles (average 4-5 cm, maximum 20 cm diameter). Bed features such as foresets are reported in better sorted sandstones and sediment transport to the south-east (N120º) is inferred.

The final lithofacies in the Novo Oryahovo Quarry, that of “shoreface tidal sands” (Archer, 2004), is made up of massive sandstones (50-60 m thick) overlying the conglomerates. Texturally the sandstones are fine- to medium-grained (with variable sorting) and poorly consolidated but occur in 0.1-0.3 m thick tabular and trough cross-bedded units. Foresets (<0.5 m thick) generally prograde to the northwest (N320º) but rare herring-bone cross-bedding indicates some possibly tidally-influenced, progradation to the southeast (approximately 140º). Lunate dunes and small sand waves are inferred in this 20-25 m thick section of cross-bedded sands at the top of the quarry. Underlying the cross-bedded sands are massive, featureless sands 5-15 m thick commonly with the thinnest, coarser, poorly sorted tabular sandstones deposited on top. The thickest sands have been recorded as prograding to the NW (approximately N320º) towards a proposed palaeoshoreline.

Review of Tectono-sedimentary Interpretations from Published Literature

The conglomeratic and sandy exposures at Novo Oryahovo Quarry are interpreted by Archer (2004) to represent a high energy, possibly braided fluvial system established
after a eustatic sea-level drop which caused cannibalisation of the underlying shoreface sands. The tidal influence also invoked in the description of this locality is thought to be dominantly to the northwest (approximately N320º) towards a hypothesised palaeoshoreline with current-influence waning up-section. Sachsenhofer et al. (2009) describe the outcrops south of Varna along Cape Galata to be of shallow marine deposition with predominantly beach sand, tidal and deltaic channel facies with occasional interdistributary fluvial to lagoonal deposits rich in land plants which yield calcareous nannoplankton indicating Middle to Upper Miocene dates (Ori, 2004; Čorić & Zetter, 2004; cited in Sachsenhofer et al., 2009). Ori (2004) interprets the basal sedimentology as showing braided stream-type erosion and deposition and an absence of debris flow indicative of a well developed fluvial system (the contact being a low-stand induced by tectonic movements). Coarse, tabular sandstones are interpreted as the product of channel migration in a deltaic environment with laterally coeval inter-channel deposits consistent with the deltaic interpretation (grey sandstones and muddy siltstone strata with current and wave ripples). The overall concept for the Galata Formation is one of a variety of paralic environments with a variety of facies including:

- A fluvial system entering a marine area dominated by moderately strong tidal currents with a weakening fluvial influence up-section;
- Sand waves generated in an open sea but with strong currents directly affected by basin morphology;
- Fine-grained intervals akin to coastal lake or lagoon deposition;
- Offshore facies with hummocky cross-stratification;
- Landslide accumulations (rare) of blocks of pre-Galata units from gravitational instability of the channel walls of incised valleys.

Ajdanliksky & Vangelov (2004) define the deposition of the Galata Formation as occurring on the margin of the Kamchia Basin on a stable strip of land in a shallow shelf setting which is periodically flooded by the basin waters. Maximum rates of sedimentation and basin filling are represented by the Galata Formation with minor regression at the end of deposition of this unit and marking the start of finer grained
or carbonate deposition. Basin morphology during this period of the Black Sea is not clearly defined (Ori, 2004).
Figure 2.36 Sandy and pebbly bi-directional foresets at Cape Galata (locality 40.2). North is the right-hand side of the photo.

Figure 2.37 Galata Cape [UPS/UTM 0575135, 4772902] cliffs approximately 15 m high, predominately thickly bedded with small conglomeratic lenses and foresets.
Figure 2.38 Clean, granular, unconsolidated Galata Formation in quarry south of Zdravets [UPS/UTM 05583932, 4774419]. Unfortunately samples of this locality could not be studied petrographically as thin-sections could not be made of the loose material.
2.13 REVIEW OF STYLES OF STRUCTURAL DEFORMATION IN EAST BULGARIA

The intention of this section is to give a brief overview of the nature of structural styles as observed during the fieldwork of this study. As this project is heavily focused on the petrographic provenance story, a more in-depth section would be inappropriate but suggestions for further work are included in Chapter 5.

North of the Emine Line (figure 2.2), the sequence of the Balkan thrust-wedge/foreland basin through to the Moesian Platform in the north is well exposed on the East Bulgarian coast and there is an excellent record illustrating structural variation from orogen to foreland. To the south are the older, more extensively deformed sections within the thrust-wedge whilst further north, inherited extensional structures, such as the east-west trending Golitsa and Bliznatzi faults, are seen to have significant control on the overprinted pattern of thrusting and compression.

The Irakli and Obzor Synclines (located on figure 2.2) provide evidence of the shortening experienced in advance of and within the growing thrust wedge. The Irakli fold is a sub-horizontal, upright syncline plunging 8º towards 284º (figure 2.39). The Obzor fold is an overturned syncline with a moderately inclined axis (~40º SSW) (Sinclair et al., 1997) verging N-NE. As shown on figure 2.3, the overturned limb of the Obzor Syncline is significantly thinner than the northern limb, which also contains Lower Eocene slumps and olistostromes not seen in the southern, overturned limb. The north-vergent deformation is common to all sequences deposited prior to the Mid-Eocene unconformity that marks the end of thrusting. One exception to this is small-scale (tens of metre-scale rather than the kilometre-scale deformation of the Obzor and Irakli folds) south-vergent, back-thrusts (figure 2.40) seen in the southern limb of the Irakli Syncline within the Emine Formation. These back-thrusts dip at a sharper angle than the limbs of the Irakli Syncline itself. These structures may have been induced in this turbiditic succession in response to the formation of the Iralki Syncline and formed by accommodating deformation through initial slippage between interbedded weak mudstones and competent sandstones followed by break-through faulting. The presence of back-
thrusting was documented by Doglioni et al. (1996) but was not recognised by Sinclair et al. (1997).

On a smaller scale, within the Emine Formation turbiditic sequence there are intrabed soft sediment deformation structures such as load-and-flame and slump structures (figure 2.7). Directly south of the thrust separating the Obzor and Irakli Synclines, the competency contrast between turbidite sequence lithologies is again evident as dm-thick sandstone and mudstone interbeds appear injected or slipped, cutting through similar interbeds of sandstone and mudstone, forming an extremely complex cliff of thrusted/slipped turbidites within the carbonate Byala Formation (figure 2.41). It appears that the majority of deformation is taken up by flexural slip, even further north within the Byala Formation and Gebesh Flysch Formation (figure 2.27) where tight, upright synclines and anticline pairs with a wavelength of approximately 10 metres occur with the common regional NW-SE fold axis.

Deeper Mesozoic extensional faults, originally in a half-graben setting downthrowing to the south, are well imaged on north-south seismic sections (figure 2.42). These structures were reactivated as steep reverse faults (an example inverted fault is shown in figure 2.43) during the later contractional phase as the locus of compression migrated north across the foreland as evident from the southerly thickening of the Byala sequence against the thrust faults. Figure 2.44 shows a coastal structural section including the reactivation on pre-existing faults as mapped by Doglioni et al. (1996). The last deformation event affecting the coastal region was related to the final Miocene stages of Black Sea extension and this is manifest as a series of N-S normal faults downthrowing to the east, forming the sharp edge of the present day coastline.
Figure 2.39 Stereonet plot for the Irakli Syncline (deformed Emine Formation)

Figure 2.40 Back-thrust within Emine Formation at locality 14.5. Sense of vergence is to the south
Figure 2.41 Variation in tectonic grain within the Byala Formation (locality 16.22). Note the various angles of bedding – all of which are created structurally rather than stratigraphically.
Figure 2.42 Interpreted regional south-north offshore seismic line used here to illustrate steep extensional Mesozoic faults below the End Palaeocene unconformity (section courtesy of Melrose Resources plc). North is on the right of this section.
Figure 2.43 Photo and field sketch of reverse fault in Lower Byala Formation (locality 16.9).
Figure 2.44 Coastal and inland cross-sections with location map from Doglioni et al., (1996) illustrating styles of folding in the foreland basin and steep thrusting to the north.
CHAPTER 3

PETROGRAPHY & PROVENANCE

3.1 INTRODUCTION

Provenance studies using petrographical analysis were traditionally developed to analyse the light fraction of siliciclastic sediments (sandstones) through the use of ternary diagrams of quartz, feldspars and lithic fragments (Dickinson & Suczek, 1979; Dickinson, 1982). Variations on the components plotted on these diagrams enabled characteristic “fields” to be recognised which are in turn used to distinguish the sedimentary products of deposition in different plate tectonic settings. Dickinson (1985) worked on ancient sands and distinguished four major provenance terranes: stable craton, basement uplift, magmatic arc and recycled orogen domains, all of which could be defined using a combination of four types of ternary plots. Methods other than petrography for provenance analysis, such as heavy mineral analysis, fission track thermochronology and isotopic studies (Allen & Allen, 2005) are now often used to supplement findings, however, this particular research has focused on petrographical investigation and subsequent data analysis of the light mineral fraction of the clastic sediments sampled, an approach permitted by the regionally widespread but sedimentologically and compositionally distinct clastic formations and the high resolution biostratigraphical dating of these units. An assessment of the likelihood of finding clastic sediments with appropriate reservoir quality in hydrocarbon prospective basins can be made from knowledge of the source geology and sediment delivery system.

Fore-arc and foreland basins can contain large amounts of volcaniclastic material, which commonly degrade reservoir properties due to post-depositional breakdown of unstable clasts into clay minerals. It is the clastic sediments on the southern (orogenic) margin in the evolving back-arc basin to retro-arc foreland basin that are being studied here. An assessment of the reservoir potential of onshore outcrops of clastic units, taking into account diagenetic and transport effects on sediment texture
when further into the offshore basin, will be valuable in helping to predict reservoir presence and quality in areas with exploration potential in the Black Sea and analogous settings.

This chapter presents the data collected and analysed for the purpose of petrographical description and provenance analysis of the southern basin margin of the north Balkan back-arc basin and retro-arc foreland basin. Onshore samples were collected during two field seasons covering the clastic formations from the southern margin of the basin as thoroughly as possible. Offshore (core) thin-section samples were obtained from sediment cores stored in Sofia in Bulgaria. A thin-section database is presented in Appendix II. The primary method of quantitative analysis was point-counting of petrographic thin-sections using the Gazzi-Dickinson method. In addition, full petrographic descriptions were made of characteristic sections of each unit to further inform the judgements made on provenance.

This chapter firstly presents the methodology and data utilised in this study with a mention of the statistical aspects of provenance analysis. Discussion of results is systematically organised by formation starting with outcrop samples and then discussing well core samples (thin-sections from which were provided by Melrose Resources plc). Included also is a brief mention of styles of diagenesis affecting the Balkan foreland basin sediments as revealed by the petrographical work. At the end of this section is a review of the pertinent literature covering sediment provenance in foreland basins. The raw data for the provenance analysis may be found in Appendix II.
3.2 **PROJECT METHODOLOGY**

Small-format thin-sections of all samples (Appendix II lists samples taken and full point-count results) with a grain size greater than fine-sand were produced and 300 grains were counted in each section. 300 grains is a widely accepted, statistically valid number of counts to make – some authors (*e.g.* Galehouse, 1971) advocate counting only 250. Van der Plat & Tobi (1965) and Weltje (2006) provide good discussion of the reliability of point-count results. A modified Gazzi-Dickinson counting method was used which minimises the effect of grain size on the count (see Ingersoll *et al.*, 1984, for discussion). In each section, 300 grains were counted in 6 columns of 50 grains each so as to cover as large an area of the slide as possible to minimise the effect of sorting and lamination. Occasionally, this grid system of counting was not possible due to the size of rock slice on the section but for each section looked at, the best attempt was made to look at the whole area of rock. It should also be noted that each count was done “blind” *i.e.* the sample location and formation was not identified until after point-counting had been completed so as to ensure there was no operator bias during analysis.

The following framework components (and their codes) were counted:

- Qm  Monocrystalline quartz
- Qp  Polycrystalline quartz
- QR  Quartz in a lithic fragment
- Kf  Potassium feldspar
- Af  Altered feldspar
- P   Plagioclase
- Kfs Potassium feldspar with significant alteration to sericite
- Pfs Plagioclase with significant alteration to sericite
- Per Perthitic feldspars
- PR  Plagioclase in a rock fragment
- Lm  Metamorphic lithic fragments
- Lv  Volcanic lithic fragments
Ls Sedimentary lithic fragments (not including pseudomatrix which was
discounted on account of its ductile nature)
Lc Carbonate (sedimentary) lithic grains
M Mica
Hm Heavy (opaque) minerals
B Bioclasts
G Glauconite

In certain samples (e.g. in the Kozichino Formation), these classes were subdivided if
there appeared to be a particular population of feldspar (e.g. perthites or
plagioclase/potassium feldspar with well developed sericite). Other subdivisions
where appropriate included carbonate grains as a separate class for the Atanas,
Bardarevo and Gebesh Formations. This subdivision has no statistical impact on
subsequent collation of data as the subgroups are absorbed into standardised grain-
type groupings as used by Dickinson (1974).

From the raw counts, a number of ternary provenance diagrams (Dickinson &
Suczek, 1979) were drawn up using the CSpace 1.01 plotting program. Provenance
associations displayed in ternary plots were originally proposed by Dickinson &
Suczek (1979) and Dickinson et al. (1983) and have been used extensively in
published literature (figure 3.1). Although this methodology is widely accepted, the
work of such as Mack (1984) should be regarded to acknowledge that fool-proof
conclusions are not necessarily achievable as there are compositional anomalies e.g.
sandstones deposited during changes in tectonic regimes, weathering effects causing
overrepresentation of stable quartz, sandstones deposited in as yet unrecognised
tectonic settings and the role of carbonate grains in provenance analysis. Sandstones
were classified using the Folk (1974) method. This chapter is organised to present as
much data graphically as possible to enable easy comparison of the results from each
formation.
Figure 3.1 Provenance diagrams used for terrane discrimination (after Dickinson & Suczek, 1979). An additional ternary plot of feldspar-volcanic lithics-sedimentary lithics (F-Lv-Ls) was also used in this study for further discrimination of tectonic domains. Source: Hulka (2005).
3.3   Petrography and Provenance of the Emine (back-arc) Basin & Kamchia (retro-foreland) Basin

3.3.1   Lower & Upper Emine Formations

3.3.1.1   Sample Localities

Five Lower Emine and six Upper Emine samples obtained from onshore exposures were thin-sectioned and point-counted. Onshore samples were taken predominantly from the coastal region between Elenite (samples 5.1 & 5.2) and Cape Emine (samples 6.1, 6.2, 6.3, 7.1-7.6, 8.1-8.8) and inland on the road to Kozichino (14.2 & 14.3). Of these 21 samples, 16 were suitable for thin-sectioning (although five of the sections were too fine grained for reliable point-counting or were micritic). Four Lower Emine Formation samples (in age order: samples 5.2, 6.1, 6.2, 6.3) and seven Upper Emine Formation samples (8.8, 7.5, 7.1, 7.2, 8.5, 8.4, 8.2) were point-counted. The raw counts are tabulated in Appendix I.

3.3.1.2   Petrographical Descriptions and Point-Count Results

Texturally, the Lower Emine framework grains are typically medium grained, moderately to well sorted and the dominant grains have low to moderate sphericity. Muddy laminae show preferential orientation of grains but most grains are either isolated or merely touch due to the abundance of calcite cement so evidence of compaction is limited, however, the monocrystalline quartz has undulose extinction and all ductile grains (those not counted as framework grains due to their weak strength), including mica, are commonly deformed. Greater than 90% of quartz grains are monocrystalline, commonly with undulose extinction and inclusion trails. Feldspar is a minor component but is dominantly plagioclase or microcline with evidence of sericitisation. Bioclasts include fine-shelled gastropods, fine bivalves and brachiopod shell fragments and very rare planktonic foraminifera. Lithic fragments consist predominantly of rounded muddy clasts and very rare igneous lithics of unknown origin. Glauconite and chlorite are present in trace amounts.
There is minor clay matrix present but ductile lithics have been commonly deformed to form pseudomatrix which is often pore occluding (photomicrographs 2C & 2D of figure 3.2) and probably formed prior to cement deposition (bioclasts are preferentially concentrated in muddy clast-rich regions). Pervasive blocky calcite cement accounts for ~40% of slide area and has fully destroyed any primary intergranular pore system (photomicrographs 2A & 2B of figure 3.2) apart from where inhibited by the presence of clay pseudomatrix. There is poorly developed secondary porosity in rare partially dissolved grains (usually along dissolved feldspar twins) but this has negligible connectivity.

The Upper Emine samples are slighter finer than those of the lower package (very fine grained on average, particularly fine quartz is found within mud-rich laminae) and possess moderate sorting. Quartz is generally subangular to very angular (photomicrograph 5C of figure 3.3) but more commonly subrounded in clay-rich laminae. All grains have a moderate to high sphericity and lithics are commonly partially dissolved. Fine sub-mm scale compositional laminae subdivide the samples and porosity is present in micro-fractures and pore spaces determined by these laminae. Isolated rings of clay are present and may either surround sandstone intraclasts or be some remnant of fine-scale bioturbation. Cement is abundant and limits grain contacts although where grains are touching, grain fragmentation is common. Pressure solution is widespread on ~50% of grain margins but with restricted development. Deformed ductiles, concavo-convex contacts where cementation is restricted and fracturing are other indicators of compaction. Quartz is >95% monocrystalline with few inclusions and extinction is more commonly undulose than straight. Lithic fragments are dominated by very turbid fragments, probably of igneous origin – they often contain porosity and alteration to small heavy mineral grains. Ductile argillaceous clasts are less common and are often deformed to form pore-occluding pseudomatrix. Rare polycrystalline quartz present containing mica and other inclusions is probably of igneous origin. Albite and perthite dominate feldspar content although feasibly some of the large turbid grains counted as lithics may be orthoclase although the shapes are not characteristic of feldspar. Mica is concentrated in clay-rich laminae and are commonly short, stubby and
straight (photomicrograph 5D of figure 3.3) or less commonly longer and deformed. Glauconite is found as small, fairly rounded, but often fractured and oxidised grains. Most quartz-rich regions have no matrix although grain boundaries are obscured by pressure solution. Detrital clay matrix is preferentially concentrated in certain laminae and surrounding or within very sparse but large intraclasts or bioturbated/reworked material. Elsewhere, deformed and extended sedimentary lithics form pore-occluding pseudomatrix. Calcite cement covers ~25% of rock area and is patchy and often poorly developed where intermingled with clay matrix but it is well developed where the rock is rich in quartz and poor in dissolved grains. Extensive partial dissolution of lithics is common and there is restricted sericitisation of feldspar. Few oversized pores remain due to dissolution and cement infilling. Porosity is approximately 5% on average, mainly from dissolution of labile grains (photomicrograph 5C of figure 3.3) and pressure solution with some minor additional primary intergranular porosity where pores are protected from cement i.e. between shelter quartz grains or around muddy laminae.

Compositional analysis of the Emine Formation samples fall within the litharenite classification. The Upper Emine Formation samples show a tendency to be more lithic-rich than the Lower Emine but all fall along a similar trendline, all without significant feldspar content. Only four of the 21 samples taken were carbonates primarily consisting of micritic mud with minor bioclastic content (mollusc, planktonic foraminifera, calcispheres, brachiopod shell fragments, fine-shelled gastropods, and fine-shelled bivalves).

The Lower Emine sandstones plot in the sublitharenite, arkosic litharenite (one sample) and litharenite domains of Folk (1974). The QtFL plot show the Lower Emine samples plot in the uppermost part of the recycled orogen domain and the QmFLt plot (figure 3.4) show them again to plot closely together in the quartzose recycled region. The LmQtLvLs plot show samples to be poor in volcanic lithics in the Lower Emine and they contain variable amounts of metamorphic lithics and quartz (from ~10-50%). The QmPK diagram demonstrates the difference between the monocrystalline quartz-rich Lower Emine and the relatively quartz-poor Upper
Emine and the former plot right at the apex of the ternary diagram in the continental block domain. The relatively mature signature of the Lower Emine is also shown on the FLvLs plot as the samples are much poorer in feldspar than the Kozichino Formation and have a much lower Lv:Ls ratio than the Upper Emine Formation and plot on the sedimentary lithic-rich side of the diagram. The volcanic lithic content of the Upper Emine Formation is the highest of any of the Emine sequence sampled as evident on the LvLsLm plot of figure 3.4 even when polycrystalline quartz is counted within the metamorphic lithic total (figure 3.29).

Compositionally the Upper Emine samples plot mainly as litharenites but also some as arkosic litharenites. The QtFL plot shows that the Upper Emine Formation is less feldspar-rich than the Kozichino Formation and contains less total quartz than the Lower Emine Formation, counter-intuitively (given age relations) giving it a less mature signature – this is further discussed later in this section. Similar to the QtFL plot results, the QmFLt plot show the Upper Emine samples to contain a higher number of total lithics than the Lower Emine. The Upper Emine Formation is one of only a few units of the entire sequence to plot within the arc-orogen source field of the LmQtLvLs plot which attests to its richness in volcanic lithic grains compared to the other formations within the Balkan foreland basins. There is negligible potassium feldspar content within the Upper Emine Formation and the samples contain relatively less monocrystalline quartz than present in the Lower Emine, again confirming it as being compositionally less mature. The total feldspar content of the Upper Emine is low compared to its lithic content, the volcanic component of which is variable but most samples, the volcanic lithic content is much higher than any other formation.
Figure 3.2 Photomicrographs of thin-section sample 2 illustrating representative Lower Emine
Figure 3.3 Photomicrographs of thin-section sample 5 illustrating representative Upper Emine
Figure 3.4 Ternary provenance plots for the Lower and Upper Emine Formations:
- Plot a (QtFL): Qt = total quartz including polycrystalline and monocrystalline, F = total feldspar, L = total lithic content excluding polycrystalline quartz
- Plot b (QmFLT): Qm = monocrystalline quartz only, Feldspar = total feldspar, Lt = total lithic content including polycrystalline quartz
- Plot c (LmQtLvLs): Lm + Qt = metamorphic lithics and total quartz, Lv = volcanic lithics, Ls = sedimentary lithics
- Plot d (QmPK): Qm = monocrystalline quartz only, P = plagioclase, K = K-feldspar
3.3.1.3 Interpretation of Petrographical Findings

There is a clear compositional contrast between the upper and lower units of the Emine Formation which is so strong that the two formations fall into very different provenance domains when plotted on ternary diagrams. The Lower Emine shows a distinct cratonic interior or recycled orogen signature whilst the Upper Emine falls in a mixed arc-orogen classification, the trend between these two possibly highlighting increasing evidence of arc unroofing during orogen development. A significance of this result is that it highlights a lack of arc signature in the Lower Emine Formation, a fact which may have otherwise been overlooked given the obvious stratigraphic field relations (the Lower Emine onlapping directly onto the Cretaceous volcanics at Tankovo). The implication of this may be that, supported by the overwhelmingly consistent palaeocurrent data (figure 2.10), the source of the Lower Emine must have been a considerable but possibly indefinable distance to the west and the back-arc basin at this time was dominated by sediment feeding along-strike from a continental sediment source where arc volcanism was not yet dominant. The stronger arc signature of the Upper Emine is attributable to either a change in sediment source location or a change in the dominant geological process of the Lower Emine source from cratonic recycling to sediments feeding from an arc volcanic dominated source.

In thin-section petrography the provenance of the volcanic lithic fragments is unfortunately unidentifiable but further chemical analysis may be able to pin-point potential parent rocks.

The Fildani & Hessler (2005) study in the Rocas Verdes Magallanes Basin (c.f. §1.3.1.2) identifies an increasing arc influence up-section during the extensional phase of basin development prior to compression. The findings of the Emine Formation compositions suggests in light of this analogue that deposition was still during the basin extension phase.
3.3.2 Kozichino Formation

3.3.2.1 Sample Localities

Samples for this formation are taken exclusively from around the village of Kozichino where the type localities for this formation are. During the 2006 field season, five samples were collected from the two major localities north (samples 30.1, 30.2, 30.3) and south (samples 31.1, 31.2, 31.3) of the village and an additional one was collected from the road approaching Kozichino from the east (sample 14.1).

3.3.2.2 Petrographical Descriptions and Point-Count Results

The Kozichino samples are generally of coarse sand grade although samples such as 30.3 show bimodal grain size distribution and contain abundant granules. All samples are only moderately to poorly sorted. Quartz grains are well rounded and frequently show embayments and some inclusion trails indicative of an igneous source (photos of sample 30.1 of figure 3.5). Feldspar is commonly also rounded and found generally as larger sericitised grains. The poor sorting and close packing in most of the Kozichino samples resulted in a grain-supported texture and concavo-convex contacts were seen in abundance in such as sample 30.1 (figure 3.5) but extensive and presumably early calcite cementation in other samples such as 14.1 minimised grain contacts. Evidence for compaction include micas that are seen to be extensively deformed and bent, undulose extinction in monocrystalline quartz and some muddy sedimentary lithics have been compacted into pseudomatrix. On average >80% of the quartz grains are monocrystalline with some undulose extinction. The Kozichino sandstones are rich in feldspar, on average ~25% of framework grains, with potassium feldspar being the dominant type present, often with considerable sericitisation. Long micas are commonly present with a split and deformed habit and comprise up to 10% of the rock. There is negligible bioclastic, glauconite or heavy mineral content in any of the rocks point-counted and there is a dominance of sedimentary lithics (up to 15% of total grains), most commonly muddy or silty although igneous (volcanic) lithics are present in smaller quantities. There is
some pseudomatrix from degradation of muddy lithic fragments and there is also common grain-rimming muddy matrix (see photo 30.3 ppl of figure 3.5). In terms of authigenic mineralogy, calcite cement is very pervasive in some samples, often drusy and inhibited where clay matrix is common. It is worth noting that these are generalisations about the Kozichino samples and the sampling was not taken from a single lithofacies and quite significant variation in petrographic features were observed, possibly as a result of this – please see Appendix I for reference logs showing the bed types from which the samples were taken.

The sandstones from Kozichino point-counted plot as lithic arkoses to arkosic litharenites and constitute some of the least quartz-rich rocks sampled from the basin. The QtFL plot show the samples to have an overall approximate 1:1 ratio of feldspars to lithic fragments and they contain less polycrystalline and monocrystalline quartz than either then Lower or Upper Emine Formations. On the QmFLt plot, all samples plot exclusively within the “mixed” arc-recycled field and again appear to have the most “arc-like” signature of any other formation. The lithic LmQtLvLv plot shows some significant variation in the composition of the lithic content of the Kozichino samples (figure 3.6). Sedimentary and metamorphic/polycrystalline quartz lithics dominate and on average there is a ratio of 2:1 Ls:(Lm+Qt) and most samples plot within the collisional orogen source field. The QmPK diagram highlight that the K-feldspar to plagioclase ratio of the Kozichino Formation is the highest out of any of the samples and they all lie at one extreme of the trendline, away from the most mature, monocrystalline quartz-rich apex of the plot. Again in the FLvLs plot, the feldspar-rich, volcanic lithic-poor, immature textural maturity of these samples is shown and they are seen to plot in a similar are to some of the Atanas and Bardarevo samples. Even excluding polycrystalline quartz in the LvLsLm plots (figures 3.29 & 3.30) the Kozichino samples are skewed unmistakable towards the metamorphic lithic-rich side of the ternary diagram.
Figure 3.5 Photomicrographs of thin-sections 30.3, 14.1 & 30.1 illustrating Kozichino Formation
Figure 3.6 Ternary provenance plots for the Kozichino Formation:

- Plot a (QtFL): Qt = total quartz including polycrystalline and monocrystalline, F = total feldspar, L = total lithic content excluding polycrystalline quartz
- Plot b (QmFLt): Qm = monocrystalline quartz only, Feldspar = total feldspar, Lt = total lithic content including polycrystalline quartz
- Plot c (LmQtLvLs): Lm + Qt = metamorphic lithics and total quartz, Lv = volcanic lithics, Ls = sedimentary lithics
- Plot d (QmPK): Qm = monocrystalline quartz only, P = plagioclase, K = K-feldspar
3.3.2.3 Interpretation of Petrographical Findings

The Kozichino Formation shows a signature which appears to be extremely rich in arc-derived components, far more so than either the underlying Lower or Upper Emine Formations. It is likely, given the geographically restriction nature of the unit and the unsystematic palaeocurrents, that this deposit is only local and probably derived directly from an arc source, with limited recycling of sedimentary units already incorporated into the wedge, if any exist by this time. Further to this, it is possible that the Upper Emine Formation is acquiring its arc-related signature from interaction with deposits emanating from the arc and thrust wedge itself, such as the Kozichino Formation, as sediments are transported east down the trench axis in advance of the growing thrusted mass. Figure 3.7 illustrates the evidence supporting this possible relationship between the Emine and Kozichino Formations. The only evidence appearing to contradict this direct arc source is the skew of lithic content towards the more polycrystalline quartz/metamorphic lithic-rich side of ternary diagrams such as figure 3.8. This pattern may be explained if the quartz within the Kozichino sandstones is derived from much older plutonic sources in a catchment in the hinterland of the wedge. This is possible as any wedge development will be at an early stage and the drainage divides may be on the far side of the wedge itself.
Figure 3.7 Observations on changing provenance trends between the Lower Emine and Upper Emine and time-equivalent Kozichino Formations
Figure 3.8 Ternary plot detailing breakdown of lithic content highlighting differences between Upper and Lower Emine Formation (the metamorphic lithic count includes polycrystalline quartz). The Lower Emine samples are open squares, Upper Emine samples are black circles and the Kozichino Formation samples are green hexagons.
3.3.3 BARDAREVO FORMATION

3.3.3.1 Sample Localities

Only two samples of Bardarevo Formation Sandstones have been sampled and as such the results are not statistically valid although the lack of consistency in the results is probably what would be expected for such a mixed-origin conglomeratic unit. The samples plot as an arkose (sample 17.2 from Bardarevo) and a litharenite (sample Melrose-34) and were both derived from large blocks contained within the unit. The matrix of the Bardarevo Formation is too fine to obtain point-count samples from.

3.3.3.2 Petrographical Descriptions and Point-Count Results

The two Bardarevo samples are very different compositionally and texturally: 17.2 is a lithic arkose whilst Melrose-34 is a carbonate-rich litharenite. Sample Melrose-34 is very poorly sorted, containing grain sizes between fine sand and granular lithic fragments. The larger grains are generally well rounded and often fractured (see photomicrograph 34F of figure 3.10) whilst the smaller grains, especially the quartz, are subangular. There is no regular alignment of grains and there is good packing of grains given the poor sorting although evidence for compaction is limited, probably on account of this tight original packing. Sample 34 is the most quartz-poor sample of all those point-counted but a third the quartz present is polycrystalline and >80% has undulose extinction. There is <5% total feldspar and that present is heavily altered and there is no mica. Bioclasts include echinoderm plates and thin shells (photomicrograph 34E of figure 3.10) but comprise only 4% of total grains. Detrital carbonate grains and sedimentary lithics, including mudstones and heavily fossiliferous siltstones, make up 26% of grains. Calcite cement is seen to infill dissolved shells and is present throughout the sample whilst mud matrix is limited to pseudomatrix surrounding sedimentary lithic fragments. Sample 17.2 comprises a quartz-rich lithic arkose with significant monocryalline quartz, K-feldspar and mica in an organised, moderately well sorted fabric – compositionally and texturally in
total contrast to sample 34. As these samples are of a heterolithic conglomeratic unit, these differences are unsurprising.

The QtFL plot shows that, despite the wide difference in its composition, the Bardarevo samples, like majority of the rocks in the sampled localities, plot within the recycled orogen field although sample Melrose-34 is extremely rich in lithic fragments. The QmFLt plot shows samples to lie within the quartzose recycled and transitional recycled regions. The LmQtLvLs lithic plot shows consistency in the origins of the lithics in the samples and both plot within the collisional orogen source domain and show a high ratio of Ls:Lv noticeably higher than many of the Upper Emine and Kozichino samples which stratigraphically underlie the unit. The QmPK shows samples lying along the quartz-rich end of the trendline that all outcrop samples fall on, well within the mature end of the continental block province. A wide range of F:Ls ratios are exhibited by the two Bardarevo samples on the FLvLs plot but both are poor in volcanic lithics.

3.3.3.3 Interpretation of Petrographical Findings

The interpretation of the source and depositional history Bardarevo Formation is unfortunately not furthered by light fraction petrography given the heterogeneous nature of the conglomerate and difficulties obtaining representative sampling. Field observations of the larger scale geometries and occurrence of the Bardarevo Formation, indicating its deposition in a mass transport unit, are the most informative indicators of formation generation.
Figure 3.9 Ternary provenance plots for the Bardarevo Formation:

- Plot a (QtFL): Qt = total quartz including polycrystalline and monocrystalline, F = total feldspar, L = total lithic content excluding polycrystalline quartz
- Plot b (QmF Lt): Qm = monocrystalline quartz only, Feldspar = total feldspar, Lt = total lithic content including polycrystalline quartz
- Plot c (LmQtLvLs): Lm + Qt = metamorphic lithics and total quartz, Lv = volcanic lithics, Ls = sedimentary lithics
- Plot d (QmPK): Qm = monocrystalline quartz only, P = plagioclase, K = K-feldspar
Figure 3.10 Photomicrographs of thin-section Melrose-34 illustrating a litharenite Bardarevo Formation sample
3.3.4 Atanas Formation

3.3.4.1 Sample Localities

Five samples of the Atanas Formation were taken from the Mona Petra site on the southern overturned limb of the Obzor Syncline (samples 10.1, 10.3, 10.4, 10.7 & 10.8) and six were taken from the Cape Atanas (samples 1.1, 15.1, 15.2, 15.3, 15.4, 15.7) on the north side of the same syncline.

3.3.4.2 Petrographical Descriptions and Point-Count Results

Atanas samples are very fine grained on average with overall poor sorting though moderate sorting within individual laminae. Most grains have moderate sphericity with a commonly bladed/tabular shape (especially quartz) and are angular to subrounded. Clays, mica and bioclasts are strongly oriented parallel to one another and are preferentially concentrated in laminae (photomicrograph 12E of figure 3.11) and quartz-rich laminae also possess vague fabric despite the grain morphology. 90% of grains are touching, the remainder having concavo-convex grain contacts. Compaction is evident from the parallel mica (photomicrograph 12A of figure 3.11), some layer-parallel fracturing of grains, pressure dissolution in clean quartz-rich regions and deformation of ductile lithics. Quartz grains are overwhelmingly monocrystalline with straight extinction and common fractures but rare inclusion trails and dissolved margins. Over 80% of the lithic content are muddy sedimentary clasts, 10% are micrite clasts and 10% comprise highly altered and frequently dissolved igneous fragments (the latter is visible in XPL in photomicrograph 12D of 3.11). Bioclasts include unidentifiable but well oriented thin shells (?bivalve) which dominate the fossil assemblages, gastropod fragments, planktonic foraminifera and possible mollusc. Mica is concentrated within certain laminae and are mostly straight but split along their length where parallel to the lamination whilst those transverse to the lamination are significantly bent. Feldspar comprise well rounded grains, generally smaller than the quartz grains and most commonly albite with abundant grains altered to sericite. Glauconite grains are present in trace quantities
and normally show brown colouration indicative of oxidation. Heavy minerals and rutile are also present in trace quantities. Detrital muddy matrix occurs in seams where the rock is rich in sedimentary clasts (photomicrographs 12C & 12D of figure 3.11) i.e. in approximately 15% of the area. Matrix and compaction (dense grain packing) is responsible for significant porosity degradation. Maximum porosity is ~5% in quartz-rich seams and consists mainly of intergranular primary porosity with minor isolated porosity along split mice grains. Connectivity is poor, as the available pores are narrow and isolated.

The Atanas Formation sandstones all contain >50% quartz but with variable ratios of feldspar:lithics and as such range in classification from subarkose, through lithic arkose and arkosic litharenite to sublitharenite. There are some compositional differences between the two sampling localities, which will be discussed further. The QtFL plot of all samples show they are dominantly found on the quartz-rich side of the recycled orogen field. One sample, 10.1, is particularly rich in quartz and feldspar and plots within the craton interior domain. All samples are mature and generally contain <8% polycrystalline quartz. The QmFLt plot discriminates better between tectonic domains and more samples plot within the craton interior, transitional continent and mixed fields as well as within the quartzose recycled area. No samples show an arc signature due to their high quartz contents and only some plot within the mixed arc-cratonic zone. The LmQtLvLs plot again demonstrates a similar story as the majority of samples plot within the collisional orogen source although three samples plot outwith this domain. The ratio of sedimentary:volcanic lithics is consistently high in all samples. The Atanas samples plot along the same QmPK trendline as the other formations and compositionally they cover the whole range. Only the Kozichino samples plot with higher K:P feldspar ratios and lower quartz contents. The lithic plot (FLvLs) show all samples to have a high Ls:Lv ratio but this plot also highlights the variability of the feldspar-to-lithic ratio demonstrating that some samples may be fed from recycled sediments whilst others show a dominance of feldspars.

3.3.4.3 Interpretation of Petrographical Findings
The Atanas Formation is an inherently easy formation to sample due to the predominance of medium grain sandstone. This high sample number may be expected to produce wider variability in grain component composition than in other poorer sampled formations but the compositions are still remarkably consistent, falling in the recycled orogen domains on each ternary diagram. Compared to formations reviewed thus far, *i.e.* looking at the potential for recycling from pre-existing basin sediments, the Atanas shows a signature, composition and texture most like the Kozichino Formation. Compared to the Kozichino Formation, however, the total proportion of quartz is higher, as might be expected if there has been more extensive winnowing of unstable volcanic grains during sediment reworking, transportation and deposition but the proportion of feldspar compared to sedimentary and volcanic lithic content is also much higher in the Atanas than in the Kozichino Formation. It is likely that the Atanas Formation is tapping the orogenic hinterland but one is seeing the increasing influence of the thrusted recycled orogen source as the wedge has grown and incorporated pre-existing formations, with a proportionally smaller component of directly arc-derived material.

The sample locations of the Atanas Formation for this study came from Cape Atanas on the northern limb of the Obzor Syncline and from Mona Petra on the southern overturned limb (as colour coded on figure 3.13). On the QFL plots of figure 3.13 the two locations show distinct populations, the Cape Atanas samples showing more of a quartz-rich, orogenic/cratonic signature compared to the Mona Petra (and Melrose) samples. The LvLmLs and PQmK plots show little variation between the two populations indicating that the lithics and feldspar content compositions are similar. In one scenario, the increased maturity of the Cape Atanas samples may be used as a proxy for transport distance and this detail would support the compositional evidence that transport of these sediments may have mixed with arc-derived sediments on the southern margin of the basin whilst being transported along the strike of the basin.
Figure 3.11 Photomicrographs of thin-section Melrose-12 illustrating Atanas Formation (of the Mona Petra compositional group)
Figure 3.12 Photomicrographs of thin-sections 10.7, 15.1 & 15.2 illustrating Atanas Formation (of the Cape Atanas compositional group)
Figure 3.13 Ternary provenance plots for the Atanas Formation:

- Plot a (QtFL): Qt = total quartz including polycrystalline and monocrystalline, F = total feldspar, L = total lithic content excluding polycrystalline quartz
- Plot b (QmFLt): Qm = monocrystalline quartz only, Feldspar = total feldspar, Lt = total lithic content including polycrystalline quartz
- Plot c (LmQtLvLs): Lm + Qt = metamorphic lithics and total quartz, Lv = volcanic lithics, Ls = sedimentary lithics
- Plot d (QmPK): Qm = monocrystalline quartz only, P = plagioclase, K = K-feldspar
3.3.5 MESHILKA FORMATION

3.3.5.1 Sample Localities

The Meshilika Formation was only sampled in the one recorded location along the coastline (Meshilika Place) so although the unit is suggested to be a heterogeneous mass flow deposit, the samples are very tightly clustered. It is unknown whether the material sampled was from a clast or matrix due to the very mixed appearance of the unit although given the cohesiveness of that sampled compared to most of the very easily eroded matrix, the samples are probably from clasts. Similar to issues with the Bardarevo Formation, a substantial amount of the unit did not yield suitable samples in terms of grain size, hence the poor sampling.

3.3.5.2 Petrographical Descriptions and Point-Count Results

The three Meshilika samples contain grains between very fine and granular and average medium grained – as implied, sorting is poor to very poor. Grains are subrounded to subangular and there is slight alignment of elongate grains although most have moderate to high sphericity. The rocks are tightly packed and show significant compaction with frequent concavo-convex contacts, grain contact dissolution and crushing of bioclasts and other fragile clasts (photomicrograph 11.2 ppl of figure 3.15). In terms of detrital mineralogy, monocrystalline quartz comprises ~50% of total framework grains and polycrystalline quartz is subordinate although the monocrystalline quartz is frequently veined and micro-fractured. Feldspar content ranges between 13-17% and plagioclase feldspar is most common although all varieties are present in roughly equal percentages. Relatively few altered feldspar, heavy minerals, bioclasts (photomicrograph 11.2 ppl of figure 3.15) or mica are present. In terms of lithics, metamorphic fragments are conspicuously absent and silty sedimentary lithics dominate and there are minor quantities of detrital carbonate grains. Matrix and cement are both minor as tight primary depositional packing occludes most pore space.

Given the close proximity of the sampling of this unit, the samples point-counted all plotted very tightly clustered on the QFL plot (figure 3.14) and are all arkosic
litharenites compositionally. The points also all plot firmly within the recycled orogen domain of the QtFL plot and on the QmFLt plot all samples have <10% polycrystalline quartz so they plot in the mixed arc-orogen zone and as quartzose recycled. Again, on the LmQtLvLs plot, the restricted variation in composition is highlighted as the points cluster firmly within the collisional orogen sources field. The QmPK plot shows that the Meshilika Formation samples possess the third lowest quartz contents compared to their feldspar content after the Kozichino Formation and some of the Atanas samples. There are a range of Plagioclase:K feldspar ratios from the samples but no extremes. The FLvLs lithic plot shows samples group in the feldspar-rich end of this diagram, overwhelmingly dominated by sedimentary lithics.

3.3.5.3 Interpretation of Petrographical Findings

The Meshilika Formation samples all fall within recycled orogen domains on ternary plots although it should be reiterated that the point-counted samples were all derived from the same location, most likely a single large block within the unit. This clustering of points suggests a single source, most likely reworked orogenic material. It should be noted, however, that the samples contained significant bioclastic material (up to 10% of framework grains), notably dominated by *Nummulites* foraminifera as noticed too in the bed composition of some of the Meshilika blocks (c.f. §2.6). This may suggest sourcing from *Nummulite*-rich deposits to the north in the Dikilitash Formation (figure 2.1) as well as from orogenic rocks from the south. The Meshilika succession underlies a major unconformity (the Illyrian Unconformity, figure 2.1) which is though to represent a period of significant deformation and erosion thus the Meshilika and Bardarevo Formations may be precursory tectonic instability to this major event.
Figure 3.14 Ternary provenance plots for the Meshilika Formation:

- Plot a (QtFL): Qt = total quartz including polycrystalline and monocrystalline, F = total feldspar, L = total lithic content excluding polycrystalline quartz
- Plot b (QmFLt): Qm = monocrystalline quartz only, Feldspar = total feldspar, Lt = total lithic content including polycrystalline quartz
- Plot c (LmQtLvLs): Lm + Qt = metamorphic lithics and total quartz, Lv = volcanic lithics, Ls = sedimentary lithics
- Plot d (QmPK): Qm = monocrystalline quartz only, P = plagioclase, K = K-feldspar
Figure 3.15 Photomicrographs of thin-sections 11.1, 11.4 & 11.2 illustrating Meshilika Formation
3.3.6 Gebesh Formation

3.3.6.1 Sample Localities

A substantial proportion of the Gebesh Formation is too fine grained to point-count (samples should be approximately medium-grained sandstone) so despite excellent outcrop only three thin-sectioned samples were recovered which could be point-counted (samples 12.8, 12.9 and Melrose-18 all from Kamping Luna just north of Obzor). Unlike the sampling problems with the Meshilika and Bardarevo Formations though, this formation consists wholly of in situ sedimentation rather than heterolithic deposition. Compositionally the samples range between arkosic litharenite and litharenite.

3.3.6.2 Petrographical Descriptions and Point-Count Results

The coarsest samples of Gebesh were studied for point-counting and these were on average fine sand grade to medium silt grade with medium to good sorting within individual laminae but moderate overall. Quartz grains are typically angular with low to moderate sphericity and micas and lithics have low sphericity. Cross-lamination with a distinct truncated contact is visible macroscopically (photomicrographs 18A & 18B of figure 3.17). There is layer-parallel orientation of mica and flattening of ductiles (probably depositional but with some reorganisation due to compaction). Touching contacts with dissolved margins are common where quartz-rich but elsewhere mud restricts pressure put on contacts although few grains are isolated. Compaction is seen in sub-parallel flattening of micas (photomicrograph 18E of figure 3.17), close and irregular packing (compaction accompanied by in situ fracturing of quartz in non-mud-prone laminations), pressure solution of quartz and deformation or argillaceous fragments. Quartz is >95% angular and monocrystalline, commonly with dissolved margins, rare fractures (possibly due to small average grain size) and few inclusions. Lithic fragments comprise ductile argillaceous clasts forming pseudomatrix and partially dissolved/ altered (? )igneous clasts along with rare squashed fossiliferous siltstone.
The Gebesh is a very micaceous rock and all mica grains are well oriented. Feldspar consists of very small fragments of commonly sericitised albite whilst there are also rare grains of angular and clear calcite within thicker laminae. Apatite, glauconite and bioclasts (highly perforated (?) diatomite shell, calcispheres and possible Nummulite or other planktonic foraminifera) are other accessory grains. Pseudomatrix is formed by deformed argillaceous fragments and concentrated in alternating laminae (photomicrograph 18E of figure 3.17). Detrital matrix is irregular within laminae but overall accounts for ~10%. The lack of cementation is presumably due to high clay concentration and because of laminae forming barriers to pore fluid flow. Partially pore-occluding calcite cement is present in minor amounts. Porosity is mainly intergranular (although the rock is densely packed) with enhancement by pressure solution (photomicrograph 18C of figure 3.17) and it is greatest in the fine, clean, quartz-rich laminae. The rock is extremely heterogeneous and there are a multitude of sedimentary structures forming fabrics at a number of scales.

Both the QtFL and QmFLt diagrams (figure 3.16) agree on an orogenic signature for the Gebesh Formation samples, plotting respectively within recycled orogen domains and quartzose recycled domains. The very high sedimentary to volcanic lithic ratio means that the Gebesh Formation samples are at the quartz-poor end of the collisional orogen source domain of the LmQtLvLs lithic plot. The samples have a high quartz-to-feldspar ratio and negligible potassium feldspar content. In the FLvLs plot, sedimentary lithics are shown to dominate over volcanic lithics and feldspar and the Gebesh Formation samples have the consistently highest sedimentary lithic content out of the formations encountered thus far.
Figure 3.16 Ternary provenance plots for the Gebesh Formation:

- Plot a (QtFL): Qt = total quartz including polycrystalline and monocrystalline, F = total feldspar, L = total lithic content excluding polycrystalline quartz
- Plot b (QmFLt): Qm = monocrystalline quartz only, Feldspar = total feldspar, Lt = total lithic content including polycrystalline quartz
- Plot c (LmQtLvLs): Lm + Qt = metamorphic lithics and total quartz, Lv = volcanic lithics, Ls = sedimentary lithics
- Plot d (QmPK): Qm = monocrystalline quartz only, P = plagioclase, K = K-feldspar
Figure 3.17 Photomicrographs of thin-section Melrose-18 illustrating Gebesh Formation
3.3.6.3 Interpretation of Petrographical Findings

The recycled orogen signature and high ratio of sedimentary compared to volcanic lithics that the Gebeš samples show suggest that like both the Emine Formations, this unit was not sourced from the arc or developing wedge but was deposited longitudinally along the front of the growing orogen, probably sourced from the west. Compositionally the Gebeš are very similar to the Lower Emine Formation (figure 3.4) although the Gebeš is richer in sedimentary lithics (figure 3.29 & 3.30). Sedimentologically, the lateral and vertical uniform depositional character of this turbiditic group is also akin to the Emine deposition and although because the formation is generally finer and there are no strong palaeocurrent indicators, it is entirely conceivable that deposition was continuous along the trough axis from the west. The inferred fine-grained matrix of the mass flow-deposited Meshilika Formation could conceivably have been derived from the Gebeš Formation although this is hard to confirm although XRD of the clays may provide such proof.
3.3.7 Obzor Conglomerate Formation

3.3.7.1 Sample Localities

Four of the Obzor Formation samples are derived from outcrop from the Obzor Hill locality (samples 35.5, 35.6, 35.7 & 35.8) whilst the other three samples come from “Obzor Formation” identified in the onshore R79 well (samples 12, 13 & 14). The outcrop samples studied were obtained from the matrix of the Obzor Conglomerate, avoiding any clasts larger than granule-sized. These two groups show distinct compositional groups and although there will be discussion of the along-strike variability in the samples later, the petrographical and point-count descriptions will focus on the outcrop samples to maintain consistency of approach with the other formations.

3.3.7.2 Petrographical Descriptions and Point-Count Results

The outcrop samples are poorly to very poorly sorted and show a bimodal sediment size distribution commonly with very coarse to granular grains of igneous origin in a very fine to fine-grained matrix. The larger grains are generally angular to subangular single crystals showing common fracturing and only limited evidence of rounding. The shape of these grains is faithful to the habit of their composition because of the limited weathering e.g. clinopyroxenes are generally equant or tabular. The matrix is generally muddy although where discrete grains are visible they too show only limited rounding. The fabric of the Obzor samples is unsystematically chaotic and varies between clasts floating in a matrix (photomicrograph 35.7 of figure 3.19) to tightly packed and crushed grains (photomicrograph 35.9 of figure 3.19) and the nature of grain contacts varies accordingly from isolated to touching although there is very little pressure solution and few concavo-convex contacts with fractured grains being most common. Syn-deposition compaction is evident from tight packing and in situ fracturing of grains.
In terms of detrital composition, each of the Obzor samples contain more than 70% igneous lithic fragments which range from grains composed of individual crystals of orthopyroxene, biotite, augite, quartz and olivine, to fragments of volcanic rock with phenocrysts and a variety of igneous groundmass textures including plagioclase laths and spherulites. A significant number of the igneous lithics have seen mineral degradation into clays, possibly an indication of the former presence of feldspar or other unstable minerals. Quartz outwith volcanic lithic fragments, is a minor component but dominantly monocrystalline with straight extinction. A maximum of 3% feldspar was seen in only one sample and these grains were too heavily altered to identify original mineralogy. No mica, bioclasts, glauconite, carbonates or metamorphic lithics are present in any of the Obzor outcrop samples. The R79 well samples show a more varied composition and contain trace amounts or more of all the aforementioned components and in these samples, sedimentary lithic content dominated significant over volcanic lithic numbers. The contrast between these two sample locations is discussed further in chapter 4.

The outcrop rocks are dominantly grain-supported and show little primary matrix, instead composed mostly of pseudo-matrix (up to 50% of section area) possibly from mineralogical decay of labile grains. The pore system is mainly made up of thin grain-rimming porosity and there is very minor good inter-granular space as packing of the rock is tight, especially as sorting is moderate at best. Grain size varies widely from silt grade to granular. Monomineralic volcanic grains show very little rounding or alteration although in situ fracturing is common whilst lithics composed of many mineral types are often rounded or eroded, possibly inherently expected due to weaker strength. No cementation indicative of fluid flow is evident.

The outcrop samples all plot firmly within the Folk litharenite sandstone classification field and on the QtFL plot they appear as undissected arc-derived provenance. The polycrystalline content of the samples is minimal and lithic fragment content is so high that on the QmFLt plot, the samples occupy the lithic recycled domain. This volcanic signature is also confirmed on the LmQtLvLs plot where the outcrop samples plot within the arc-orogen source so although not
exclusively arc-derived there is a strong arc-influence and possible mixing with orogenic sourced material. The QmPK feldspar plot shows that one sample (35.7) plots within the dissected arc field (although Qm and P together only account for 6% of total grains) and the other samples fall at the lower end of the continental block field, all being fairly quartz-poor. The separated lithic plot (FLvLS) shows the significant concentration of volcanic lithics within the Obzor Formation and again highlights the direct arc source of these sediments. The ternary diagrams in figures 3.29 & 3.30 also serve to confirm that the Obzor Formation is the richest in igneous lithics and show a distinct paucity of other lithic fragments.
Figure 3.18 Ternary provenance plots for the Obzor Conglomerate:

- Plot a (QtFL): Qt = total quartz including polycrystalline and monocrystalline, F = total feldspar, L = total lithic content excluding polycrystalline quartz
- Plot b (QmFLt): Qm = monocrystalline quartz only, Feldspar = total feldspar, Lt = total lithic content including polycrystalline quartz
- Plot c (LmQtLvLs): Lm + Qt = metamorphic lithics and total quartz, Lv = volcanic lithics, Ls = sedimentary lithics
- Plot d (QmPK): Qm = monocrystalline quartz only, P = plagioclase, K = K-feldspar
Figure 3.19 Photomicrographs of thin-sections 35.7, 35.5 & 35.9 illustrating Obzor Formation
3.3.7.3 Interpretation of Petrographical Findings

The compositional differences between the Obzor Formation outcrop samples and the R79 well core samples are significant enough that the two groups plot in entirely separate regions. R79 is located close to Byala, 14 km north of Obzor Hill and the samples are from depths of 1145, 1258 & 1442 m TVD. The R79 core samples show a recycled orogen/continental compositional signature in contrast to the outcrop samples which suggest an entirely different source catchment. Given the observed restricted geographic spread of the Obzor Formation in the field it is plausible that the two formations are time equivalents but do not represent the same depositional event. As seen throughout the history of the basin, there is continuous deposition in the basin longitudinally along the strike of the orogen, punctuated by episodic local deposition fed from the wedge of which the Obzor Formation is interpreted to be one. Other local “Dvoynitsa Group” (pers. comm. K. Stoyakova, 2006) conglomerates were seen in an inland section called “Chudnite Skali” (UTM/UPS GR 523500, 475600) and these are logged sedimentologically in figure 3.20 for comparison. Given the apparent provenance differences, it is here interpreted that the Obzor Formation in well R79 is a separate depositional event to that represented by the sediments at Obzor Hill. From the textural and compositional information gathered it is not possible for the R79 samples to be a transported or otherwise winnowed product of the outcrop-type samples due to the high feldspar and quartz content of the former not seen at all in the outcrop samples.
Figure 3.20 Field sedimentary log of the Green Clay to “Dvoynitsa Group” conglomerate contact at Chudnite Skali (UTM/UPS GR 523580, 4755939). Scale in metres; grain size varying from clay to pebble size.
3.3.8 Dolen Chiflick Formation

3.3.8.1 Sample Localities

The only Dolen Chiflick samples of suitable grain size for point-counting were taken from the Velichikovo railway cutting (37.8, 37.10 & 37.11) and one sample (Melrose-38) from the Chairdere section. The paucity of suitable samples is due to the inherently fine-grained nature of the unit.

3.3.8.2 Petrographical Descriptions and Point-Count Results

The Dolen Chiflick samples are quite variable but grain size averaged fine sand and they are generally moderately well sorted, especially with regard to the size of quartz grains in argillaceous patches where the rock is bimodal with large quartz grains in a finer granular calcite matrix. The larger quartz grains possess rounded edges but are commonly fractured whilst smaller grains are often angular to subangular. Detrital glauconite is preferentially rounded. Irregular porous fractures and clay-rich regions are present with no obvious laminae. Shelly fragments are also most intact in finer grained realms where there is the most calcite cement (photomicrograph 38C of figure 3.22). Most discernable large grains are isolated or merely touching their neighbours due to the concentration of cement (photomicrograph 38C of figure 3.22). Little compaction is evident due to early cementation. Quartz grains are well sorted and rarely fractured and >80% monocrystalline and dominated by straight extinction. Glauconite is present in small subrounded grains with common fracturing. Lithic fragments are mainly argillaceous and rare altered igneous clasts although overall lithic content is very low. Large fragments of shell are rare but are replaced by calcite where present. Commoner bioclasts include thin bivalve shell fragments, planktonic foraminifera (photomicrographs 38C & 38D of figure 3.22) and thicker shelled (?) gastropods. Feldspars are commonly sericitised or very clear, small rounded grains with no dissolution but plagioclase twins are common. Mica is very rare and makes up only up to 3% of framework grains. There is moderately common matrix but the habit varies from grain-coating and within pores to merely irregular
distribution. Pervasive pore-occluding calcite cementation is very dirty and contains quartz, clay and possible detrital calcite grains. Calcite cementation also occurs in bioclast voids and replacement of bioclastic fragments, feldspar and glauconite by calcite is common. Quartz margins may have been protected from dissolution by clay coatings. Negligible porosity is apparent in the samples apart from thin fracture porosity and very limited secondary porosity from partial dissolution of cement (left hand top corner of photomicrograph 38C of figure 3.22).

The three samples from Velichikovo were all shelly but their sandstone classification varies between subarkose and sublitharenite to litharenite. Despite the close proximity of sampling locations there is a high variability in the composition of these rocks although they all fall within the recycled orogen field of the QtFL plot (figure 3.21). As quartz content is high in all samples the QmFLt also shows that the Dolen Chiflick has a cratonic interior/continental recycled signature although proportions of monocrystalline to polycrystalline quartz vary. Again the variability in the Dolen Chiflick is shown in the lithic plot (LmQtLvLs) and there is a lack of clustering although most points plot in the collision orogen source field and just one of the Velichikovo samples (37.13) plots outside this with a higher volcanic and metamorphic lithic content. All the samples from Velichikovo have high bioclast content between 19-47% but bioclasts are not counted as framework grains with a generically locatable source by the Gazzi-Dickinson method. The QmPK plot, much akin to the other formations cluster around the quartz-rich end of the continental block field and do not show much distinction. Finally, the FLvLs plot shows the samples all falling on the feldspar and sedimentary lithic-rich orogenic-type side although ratios between these two components vary considerably.
**Figure 3.21** Ternary provenance plots for the Dolen Chiflick Formation:

- Plot a (QtFL): Qt = total quartz including polycrystalline and monocrystalline, F = total feldspar, L = total lithic content excluding polycrystalline quartz
- Plot b (QmFLt): Qm = monocrystalline quartz only, Feldspar = total feldspar, Lt = total lithic content including polycrystalline quartz
- Plot c (LmQtLvLs): Lm + Qt = metamorphic lithics and total quartz, Lv = volcanic lithics, Ls = sedimentary lithics
- Plot d (QmPK): Qm = monocrystalline quartz only, P = plagioclase, K = K-feldspar
*Figure 3.22* Photomicrographs of thin-section Melrose-38 illustrating Dolen Chiflick Formation

- Photomicrograph 38A (PPL) shows a setting heavily calcite cemented.
- Photomicrograph 38B (PPL) depicts common isolated grains due to cementation.
- Photomicrograph 38C (PPL) highlights sub-angular fine monocristalline quartz.
- Photomicrograph 38D (XPL) features a thick-shelled gastropod.

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3.3.8.3 Interpretation of Petrographical Findings

The Dolen Chiflick Formation shows variable compositions, possibly on account of the localities sampled, the paucity of suitable samples and the apparent “dual” character of the formation at Velichikovo (c.f. §2.9 for lithological descriptions). The samples appear to have a cratonic/recycled continental signature and this, together with suggestions of W-E depositional palaeocurrents, suggests that like the Emine Formation, the Dolen Chiflick was a formation deposition laterally along the front of the developing orogen. This is in spite of the more localised nature of the unit and the lithic content of the samples (figures 3.29 and 3.30) show a higher proportion of volcanic lithics than in other formations not sourced directly from the arc/wedge. This may reflect some influence and reworking of thrust-incorporated units as well as material sampled from further west, possibly outwith the influence of the growing thrust. The high bioclast and carbonate grain content may suggest recycling of carbonate units from the Moesian Platform possibly as the basin narrows and the thrust wedge loads the overthrust plate thus uplifting and eroding the northern side of the basin. Doglioni et al. (1996) suggest that this unit is turbiditic and the sedimentology and petrographical findings agree with this statement although the composition, trace fossils and bed thickness information suggests that this unit may have been deposited significantly shallower than such as the deepwater Emine Formations. The Dolen Chiflick Formation may be the earliest formation indicating fairly unequivocally that the basin is moving from an underfilled (flysch) to overfilled (molasse) stratigraphic setting (figure 1.9).
3.3.9 Arnautler Formation

3.3.9.1 Sample Localities

The seven samples point-counted were from the Chairdere (38.8 & 38.9), Goren Chiflick (37.1, 37.2, 37.3 & 37.4) and Rudnik (35.2) localities. All samples comprise bioclast-rich sandstones and the medium to coarse-grained parts of the formation is naturally suitable for point-counting.

3.3.9.2 Petrographical Descriptions and Point-Count Results

The Arnautler samples point-counted were on average medium to coarse sand grade with the bioclastic components being generally coarse or granular in grain size. Sorting is moderate to poor and grains vary between angular, especially the quartz content (photomicrograph 38.8 of figure 3.24), to subrounded. Quartz is noticeably equant and bioclasts have generally maintained their original shape with only minor fragmentation and rounding although compaction of the overall fabric is obvious and shells are often embayed by other framework components. No particular fabrics were observed and the rock is tightly packed where there has been no significant cementation. In terms of detrital mineralogy, the Arnautler sands are variably bioclastic (7-60% of total framework grains) and lack any considerable feldspar content (5-9% with commonplace altered feldspars). The quartz content is >75% well sorted, medium sand grade, monocrystalline grains with 50:50 undulose:straight extinction patterns. Mica and heavy minerals are rare and glauconite present only in trace amounts. Lithic content is dominantly sedimentary and consists of sand grains and siltstone. The bioclastic content is diverse and includes granule-size fragments of bryozoans, bivalve and brachiopod shells, echinoderms, Nummulites and other foraminifera (dominantly planktonic). Approximately 60% of the Arnautler samples looked at petrographically show good to excellent porosity and clay matrix is sparse although calcite cement is sometimes pervasive (photomicrograph 38.8 of figure 3.24), particularly in quartz-dominated regions and may have been derived from partial dissolution of carbonate shells.
The framework (non-bioclastic) components of the sandstone lead to a Folk classification of subarkose to sublitharenite for most samples, some being marginally richer in lithic content. The QtFL plot (figure 3.23) demonstrates good clustering of all samples within the recycled origin despite the numerous sampling localities there is good consistency on most of the ternary diagrams used. The QmFLt plot also shows this quartzose recycled signature as the proportion of monocrystalline quartz is no more than 13% in any sample. The lithic content of the Arnautler sands is predominantly sedimentary with only one sample showing significant metamorphic lithic content (sample 38.8) on account of the polycrystalline quartz content rather than specifically from metamorphic lithics. The QmPK diagram also emphasises the continental block origin of the framework grains of these samples as they contain negligible feldspar although this may be a reflection of their depositional environment and possible higher energy regimes than some of the other formations as the grain size tends towards upper medium to lower coarse sand grade.
Figure 3.23 Ternary provenance plots for the Arnautler Formation:

- Plot a (QtFL): Qt = total quartz including polycrystalline and monocrystalline, F = total feldspar, L = total lithic content excluding polycrystalline quartz
- Plot b (QmFLT): Qm = monocrystalline quartz only, Feldspar = total feldspar, Lt = total lithic content including polycrystalline quartz
- Plot c (LmQtLvLs): Lm + Qt = metamorphic lithics and total quartz, Lv = volcanic lithics, Ls = sedimentary lithics
- Plot d (QmPK): Qm = monocrystalline quartz only, P = plagioclase, K = K-feldspar
Figure 3.24 Photomicrographs of thin-sections 38.8, 37.3 & 35.2 illustrating Arnautler Formation
3.3.9.3 Interpretation of Petrographical Findings

The Arnautler sands are the earliest formation in the Emine/Kamchia Basin sequence with a consistently significant bioclast content although this is not apparent in terms of provenance evaluation on the ternary diagrams displayed as bioclasts are not counted as framework grains. The bioclasts are not manifest as being heavily recycled \textit{i.e.} they are probably not derived from existing units but represent primary deposition. Overall, the Arnautler Formation appears to be more consistent with the Lower Emine Formation rather than such as the Kozichino Formation in that a distal cratonic source with only minor volcanic input could be inferred. Although by this time any orogenic wedge would have been far more developed the proportion of polycrystalline, recycled quartz and volcanic lithic grains one would expect with sourcing from the wedge is low.

The FLvLs plot (figure 3.23) shows that the one sample from Rudnik (35.2) has more feldspar than sedimentary lithics whilst the rest are dominated by sedimentary lithics with subordinate volcanic content (<14%) possibly indicative of a smaller transport distance from source or less contamination by recycling of sedimentary units in the wedge setting. This single sample may also hint at greater variation in composition occurring within this formation over the geographic spread of the unit.
3.3.10 Ruslar Formation

3.3.10.1 Sample Localities

The three Melrose samples (Melrose-58, -60 & -91) come from the Karadere (Black Cape) exposure and the other two (37.5 & 37.6) are taken from outcrops on the bank of the River Kamchia near Pchelnick. The Ruslar Formation is a very fine grained to silty formation and thus it was extremely difficult to find samples of appropriate grain size – most of these samples are fine to medium sand grade.

3.3.10.2 Petrographical Descriptions and Point-Count Results

The Ruslar Formation is generally silt grade to very fine grained though the samples studied here were of the coarser fraction. All samples possess moderate to good sorting, especially of the quartz content which varies between angular and rounded whilst feldspar shows variation between subangular and subrounded. Quartz possesses low to moderated sphericity and frequently appears embayed where surrounded by matrix. There are no obvious fabrics other than a vaguely parallel trend of the largest grains and isolated muddy patches (photomicrograph 91A of figure 3.26). The rock is matrix/cement-supported (photomicrograph 91B of figure 3.26) and grains are in minimal contact due to cement and matrix presence. Micas are overwhelmingly straight but cementation prevents an accurate estimate of compaction though there is limited pressure solution where the rock is quartz-rich suggesting compaction may have pre-dated cementation. In terms of detrital mineralogy, the Ruslar Formation is dominated by monocrystalline quartz (>95%) with undulose extinction and few fractures or inclusions (photomicrograph 91B of figure 3.26). Volcanic lithic fragments are occasionally present but highly altered and partially dissolved and have created oversized pores and regions of sericite. Where only moderately altered, the igneous lithics appear to be composed of quartz, orthopyroxene and other phenocryst laths in a fine matrix. The feldspar content is variable but often comprises perthite, albite and microcline in small clear tabular grains with little alteration. Glauconite is present in trace amounts as well rounded.
small grains with occasional circumgranular dissolution which has created a thin porosity. Micas are stubby, slightly bent or fractured medium size detrital grains (photomicrographs 91E & 91F of figure 3.26). Patchy clay matrix is common in the samples but only in isolated regions and cement is responsible for most of the pore occlusion where present. The Karadere samples show extensive pore occlusion whereas the Pchelnick samples generally have moderate porosity with large primary intergranular pores. Sample Melrose-91, as illustrated, has pervasive pore-occluding equant drusy calcite spar cement. Pores are commonly lined with dark brown/reddish clay/manganese matrix.

Most of the Ruslar Formation samples are rich in small angular fragments of monocrystalline quartz and as such plot as subarkose or sublitharenites on the Folk classification (figure 3.31). On the QtFL ternary diagram (figure 3.25) all samples plot in the recycled orogen field. The QmFLt plot separates the samples out and the Karadere samples Melrose-58 & -60 possess a more transitional recycled signature whilst the rest fall within cratonic/quartzose recycled domains – this may be a reflection of sediment transport to be discussed further in the interpretation. There is no major clustering of lithics on the LmQtLvLs plot and there is a mixed collision and arc orogen source pattern with no clear distinction. Total feldspar content is never above 22% so the QmPK trends shown by these samples are in line with the other mixed signal formations up within the continental block zone. Samples on the FLvLs plot again show no clear grouping and volcanic lithic content never exceeds 21% thus demonstrating that most samples fall along the orogenic sourced side of the ternary diagram although admittedly, they are more variable in spread than a lot of the other formations.
Figure 3.25 Ternary provenance plots for the Ruslar Formation:

- Plot a (QtFL): Qt = total quartz including polycrystalline and monocrystalline, F = total feldspar, L = total lithic content excluding polycrystalline quartz
- Plot b (QmFLt): Qm = monocrystalline quartz only, Feldspar = total feldspar, Lt = total lithic content including polycrystalline quartz
- Plot c (LmQtLtvLs): Lm + Qt = metamorphic lithics and total quartz, Lv = volcanic lithics, Ls = sedimentary lithics
- Plot d (QmPK): Qm = monocrystalline quartz only, P = plagioclase, K = K-feldspar
Figure 3.26 Photomicrographs of thin-section 91 illustrating representative Ruslar Formation
3.3.10.3 Interpretation of Petrographical Findings

The Ruslar Formation showed variation in composition according to the sampled locality, the Karadere samples being more quartz-rich than the Pchelnick samples, however, overall they consistently show a recycled orogen composition and may have been sourced from the increasingly mature thrust wedge, potentially from the west where the orogen was at a more mature stage of development. The Ruslar Formation is the only Oligocene unit and is regionally widespread with thickening offshore (Sachsenhofer et al., 2009). As such, it may be inferred that, despite the absence of palaeocurrent indicators, deposition was from the west into a basin deepening to the east. This would be in line with the increasing maturity seen between Pchelnick and Karadere. Unlike the Dolen Chiflick Formation, bioclast and carbonate content is low, suggestive of a lack of bioclasts in the depositional setting or any input from any platform sediments. The lithic content (figure 3.29) shows increased metamorphic content compared to the underlying Eocene units, possibly from recycling of clastic units incorporated into the thrust wedge. This compositional information agrees with the seismic evidence that has shown the Oligocene to be affected by periods of significant uplift of the Balkanides as sediments are most likely to have been derived at least in part from the growing orogen, particularly if there was diachronous collision, with the orogen developing earlier in the west than the east as some of the compositional evidence suggests.
3.3.11 GALATA FORMATION

3.3.11.1 Sample Localities

Eight Galata Formation samples were point-counted: Melrose-66, 36.1, 36.2, 36.3 & 36.4 from Karadere (aka Black Cape, UPS/UTM location 0573159, 4752282) and 40.3, 40.4 & 40.5 from Cape Galata. Because the Galata Formation is of Mid Miocene age, the rock in some locations such as the quarry south of Zdravets (OMV field guide locality VI-13, this study location 41.2 as located on figure 2.24), was very unconsolidated and could not easily generate thin-sections so there is inherent bias in the samples point-counted.

3.3.11.2 Petrographical Descriptions and Point-Count Results

The Galata samples vary between coarse sandstone and granular conglomerates although the quartz grains making up the bulk of the matrix are medium sand grade and grains are moderately sorted on average. Quartz grains are commonly subangular to rounded and have a low to moderate sphericity although, where present, granules have a moderate to high sphericity and show more evidence of rounding. There is rarely any preferred distribution of clasts or matrix or grains in sedimentary fabrics. Grains are generally isolated as calcite cement is pervasive in all sections and as such the degree of compaction is also hard to assess. Greater than 80% of the quartz present has undulose extinction and >40% are polycrystalline or possess a stretched metamorphic texture. Feldspar is commonly semi-altered and partially resorbed perthites and microcline are the most common although there is also rarer albite. Lithic fragments include stretched metamorphic quartz, muddy siltstone, highly hydrothermally altered and veined quartz of igneous origin (photomicrographs 66E & 66F of figure 3.28), micrite, muddy mica-rich sandstone, possible calcite-cemented sandstone (with large matrix-to-grain ratio), fossiliferous well sorted biosparite (including micrite-replace Nummulites, bivalve shell, foraminifera, small gastropods) and fine grained igneous rocks with small laths of (?)biotite in a feldspar-rich groundmass with sericitised feldspar-filled amygdales.
Bioclast content of Galata Formation is negligible and the only heavy minerals present are unidentified small reddish grains. Mica is similarly rare and is normally found as rare split grains within the calcite cement. Matrix is rare within the formation, found only as thin grain-rimming habit or in isolated and irregularly shaped patches most commonly in associate with clay-replaced dissolved-out labile grains. Quartz cement occurs as well developed overgrowths (although apparently without the characteristic sharp straight edges) on approximately one third of grains where not rimmed by matrix. Calcite cement is very pervasive through these samples and is pore occluding and occurred pre-compaction as the quartz grains are very loosely packed. The samples picked have a bias towards being cemented for thin-section production reasons and the Galata Formation in certain locations was entirely uncemented. Clay replacement of labile grains is rare. Some dissolution of quartz grain margins occurs in regions without well developed cement but dissolution is minor and porosity is very poor where dissolution has not occurred.

The Galata samples all plot together within the recycled orogen field on the QtFL plot (figure 3.27) but the significant polycrystalline quartz content results in a slightly mixed to transitional recycled classification on the QmFLt diagram. Variation in composition is seen in the lithic plot but most points plot within the collision orogen source although a high volcanic lithic content is seen in a couple of samples which plot within or near the arc orogen source region. A dominance of K-feldspar is seen on the QmPK plot (figure 3.27) but the samples are all relatively rich in quartz and plot within the continental block province. Figure 3.29 shows that the Galata Formation possesses the highest proportion of metamorphic lithics out of all formations studied when polycrystalline quartz is included within the metamorphic lithic count.
Figure 3.27 Ternary provenance plots for the Galata Formation:

- Plot a (QtFL): Qt = total quartz including polycrystalline and monocrystalline, F = total feldspar, L = total lithic content excluding polycrystalline quartz
- Plot b (QmFLt): Qm = monocrystalline quartz only, Feldspar = total feldspar, Lt = total lithic content including polycrystalline quartz
- Plot c (LmQtLvLs): Lm + Qt = metamorphic lithics and total quartz, Lv = volcanic lithics, Ls = sedimentary lithics
- Plot d (QmPK): Qm = monocrystalline quartz only, P = plagioclase, K = K-feldspar
Figure 3.28 Photomicrographs of thin-section 66 illustrating representative Galata Formation
3.3.11.3 Interpretation of Petrographical Findings

Despite the varied sample locations, the compositional story for the Galata Formation appears to be remarkably uniform and indicates a high level of clastic maturity and regional consistency indicative of a significant amount of mixing and recycling. The Galata Formation samples have the highest proportion of metamorphic lithics and polycrystalline quartz which suggests recycling from units in the thrust wedge rather than from distal areas to the west, especially as the lithic content tends towards being also quite volcanic-rich. Palaeocurrent data showing flow toward the north-west (c.f. §2.12) also concurs with this hypothesis. The texture of the samples also agrees with the shallow marine depositional environment proposed by many authors (Sachsenhofer et al., 2009; Archer, 2004) and the restricted N-S geographical spread of Galata Formation hints at a tight basin during deposition with strong flow and rapid deposition suggested by the well developed foresets observed at many localities.

As can be seen in figure 3.29 and from the observation that the Galata Formation contains the highest proportion of polycrystalline quartz, the formations younger than Obzor show a gradual trend towards increasing content of polycrystalline quartz, as would be expected from either a system in which sedimentary units are gradually piling up within the wedge over time, creating a greater mass of deformed quartz or from a complex which is unroofing deeper over time, exposing increasing metamorphic grades of sediment which are being recycled into the basin. Study of the exhumation history of the sediment sources would be the only method available which could pin-point the most likely scenario.
Figure 3.29 Ternary plots by individual formation of lithic component compositions normalised to 100%.

Ls - sedimentary lithics and carbonate grains
Lm - metamorphic lithics including polycrystalline quartz
Lv - volcanic lithics
Figure 3.30 Ternary plots by individual formation of lithic component compositions normalised to 100%. Ls - sedimentary lithics and carbonate grains, Lm - metamorphic lithics without polycrystalline quartz, Lv - volcanic lithics
Figure 3.31 Folk sandstone classifications of all samples point-counted for this study.
Figure 3.32 Ternary plot of total feldspar content (F), volcanic lithic (Lv) and sedimentary lithics (Ls) for all formations. The Obzor and Upper Emine Formations can be seen to be the richest in volcanic lithic fragments.
CHAPTER 4

PALAEO-DEPOSITIONAL SYNTHESIS

4.1 INTRODUCTION

By integrating existing literature and new findings from this study (outcrop sedimentology, petrographical findings and provenance interpretation), this chapter presents palaeo-depositional models for each of the sequences as presented in each of the chronostratigraphic sequences (figure 4.1). The intent of this section is to compile the data and suggest regional basin configurations, possible sediment sources and other features pertinent to the interpretation and reconstruction of depositional environments. The high-level description of regional tectonic activity in §1.4 and details of regional volcanic activity in §2.11 are also of direct relevance to interpretations made here.

Reconstruction of source areas hinges on accurate pin-pointing of geography during deposition. This cannot be simply derived from consideration of events during the time period under scrutiny here. In terms of inherited structure into which the Cretaceous to Miocene stratigraphy is deposited this research is not presenting any new regional tectonic information but is merely working within existing configurations as suggested by such as Doglioni et al. (1996), Sinclair et al. (1997) and Vangelov & Sinnyovsky (2001). The task of establishing sources is further complicated by plate-scale extension following post-Eocene orogenic collapse controlled by plate movements in the Carpathian and Aegean arcs. The most recent estimate of the amount of post-Eocene extension thought to have occurred in the Rhodope (between the Moesian Platform to the Gulf of Corinth) was calculated by palaeomagnetic work to be approximately 265 km with a large component of rotation into the Aegean back-arc, most of which occurred largely before 15 Ma (van Hinsbergen et al., 2008). As the pivot point of structural rotation is thought to be located on the western margin of the Moesian Platform, the Balkan foreland basins
are likely to have experienced significant extension post-Eocene and this overprint will be manifest in the present configuration of geological units (figure 4.2).

Figure 4.1 Chronostratigraphy of the onshore geology of Eastern Bulgaria (Peck & Sinclair, 2005 [Melrose Resources in-house report])
Figure 4.2 Kinematic and geodynamic reconstructions of the (middle) Miocene west Aegean and southern Carpathian rotations of van Hinsbergen et al. (2008). Rotation of the west Aegean domain is suggested to have a pivot point in the centre of the rotating domain due south of the western limit of the Moesian Platform. To the east, rotation was accommodated by (roll-back-related) extension in the Aegean back-arc. To the west, rotation was accommodated by escape if the Tisza block into the Carpathian back-arc, triggered by eastward roll-back of the Carpathian subduction zone, and coeval rotations along the northern edge of the Moesian Platform related to activity of the south Carpathian STEP fault (van Hinsbergen et al., 2008).
4.2 RECONSTRUCTION OF DEPOSITIONAL ENVIRONMENTS

4.2.1 SEQUENCE 1: MAASTRICHTIAN (LOWER EMINE)

4.2.1.1 Tectonic Setting & Depositional Environments

The Lower Emine Formation is thought to have been deposited in a deep-water marine setting into an elongate trough-like basin subordinate or piggy-back to a major extensional back-arc basin (figure 4.4). The northern edge of the basin is defined by early Mesozoic faults whilst the southern margin is formed by the uplifted mass of Cretaceous volcanics in the Srednogorie Zone which was being eroded and experienced some localised instability as displayed by the Tankovo boulder beds (c.f. §2.2.1). At this time there is no evidence for active extension controlling the depocentre since bed thicknesses are uniform.

4.2.1.1 Provenance from Sedimentology & Petrography

The Lower Emine Formation represents dilute deep-water turbiditic deposition along the basin trough axis from west to east. Given the mature sediment texture, cratonic/recycled orogen signature of sediment composition (c.f. §3.3.1.3) and this uniformly strong palaeocurrent, the source is not likely to be local (i.e. from the Srednogorie) but rather from older intrusive igneous/metamorphic rocks in the Rhodope to the west. Possible source regions as definable from present-day geology are highlighted on figure 4.3. Unfortunately the exhumation history of the Rhodope is complex and poorly understood but high-grade metamorphics are understood to have been buried and exhumed during the Cretaceous to Paleogene (and into the Oligo-Miocene in northern Greece) and overlain by Eocene to Oligocene sediments and volcanics (van Hinsbergen et al., 2008). From analogues (e.g. Fildani & Hessler, 2005), the reason for the lack of direct sourcing from the wedge may be that, despite the lack of extensional structures underlying or incorporated into the Lower Emine Formation, the basin may have still been in an extensional phase and as such
compression in the back arc is thought to have not been initiated during this period and, although uplifted, the Srednogorie Zone would have been relatively stable.

4.2.2 SEQUENCE 2: PALAEOCENE (UPPER EMINE & KOZICHINO)

4.2.2.1 Tectonic Setting & Depositional Environments

The first pulses of thin-skinned compression and inversion are seen to occur during the Middle Cretaceous (Robb, 1998) but evidence of this in the foreland is seen only from the Palaeocene onwards. Deposition of the Upper Emine Formation is very similar to the Lower Emine Formation in terms of the deep water deposition processes occurring and it is likely that the geometry of the Palaeocene basin into which deposition was occurring was also akin to that during the Late Cretaceous (figure 4.5). However, the coarse high-density fan deposits of the Kozichino Formation provide evidence for topographic growth and possible instability on the compressive margin to the south of the basin. The sedimentology of the Kozichino Formation does not suggest a mass flow but rather a less energetically extreme submarine fan which in turn provides evidence for a potentially significant transport distance and consequent broad catchment area and thus very distant tectonic activity on the incipient wedge to the south. The north of the basin is still defined by pre-existing Mesozoic faults although extension is thought to have ceased by this stage.

It is thought that tightening of the basin system started in the west and propagated through the system gradually eastwards i.e. the present day coastal outcrops studied were at the eastern terminus of the final orogen and maximum compression and the locus of deformation was to the west. Robb (1998) provides seismic evidence for thrusting direction to be primarily southwest to northeast and this inferred diachroneity may also be evident from biostratigraphic dating of regional unconformity surfaces which occur along the strike of the orogenic wedge (e.g. the end Palaeocene or mid-Eocene Illyrian unconformities) (c.f. 5.3).
4.2.2.2 Provenance from Sedimentology & Petrography

Like the Lower Emine Formation, from palaeocurrent indicators the Upper Emine Formation displays eastward flow but there is a shift from ESE deposition to SSE (c.f. §2.2) which may attest to diachronous tightening of the basin to the west and a slight shift in source regions or transport pathways. There is still a trough-like geometry to the depocentre in advance of the incipient orogenic wedge and deposition was down the axis of this trough, flowing towards the east. Petrography of the Emine Formation samples uncovered that the Upper Emine have a signature far more suggestive of direct arc sourcing than the Lower Emine. Two potential explanations for this are apparent: namely either the source area for the Upper Emine shifted quite significantly to tap volcanic material or there was contamination of the Emine turbidites by fan material derived directly from the southern (arc/wedge) margin of the basin such as that of the Kozichino Formation. As the compositional difference is not overly profound, it is suggested that the latter of these explanations is probably responsible, particularly as palaeocurrent indicators do not support the first explanation. The Kozichino Formation, given its strong arc signature, is thought to be a local example of sedimentation emanating from the arc as a high density submarine fan, more examples of which may have been likely but are no longer preserved.

4.2.3 SEQUENCE 3: LOWER EOCENE (BARDAREVO, ATANAS, MESHILKA, GEBESH)

4.2.3.1 Tectonic Setting & Depositional Environments

Compression continued during the Lower Eocene and further thin-skinned thrusting events during this period, as recorded from regional seismic (Robb, 1998). The depocentre of the Lower Eocene Emine Basin migrated northwards with respect to the Palaeocene Emine Basin (Doglioni et al., 1996) and the loading of the plate with the growing thrust wedge was probably responsible for inducing significant flexural subsidence in the basin. In support of this claim, the Bardarevo Formation represents debris flows into the basin from the thrust-wedge margin whilst the later Meshilika
Formation mass flow clasts are derived from the Byala Formation from deposition on the edge of the Moesian Platform (figures 4.6 & 4.7). The complicated stratigraphy during the Lower Eocene and potential for sedimentation to be derived from both margins attests to this period of instability associated with increased compression, relative basin margin uplift and depocentre tightening. Contemporaneous to this sporadic, local high energy deposition is widespread fine grained and, by inference, lower energy turbiditic sedimentation of the Atanas and Gebesh Formations, akin in depositional process to that of the earlier Emine Formations. The palaeocurrents for both Atanas and Gebesh Formations show westerly transport and the basin geometry is thought to still be trough-like along the axis of the growing thrust wedge with punctuated episodes of mass flow off the basin margins rather than a totally reconfigured basin shape.

4.2.3.2 Provenance from Sedimentology & Petrography

Provenance analysis of the Bardarevo and Meshilika Formations is inherently difficult due to the heterolithic and conglomeratic nature of the deposits and a lack of palaeocurrent indicators. Clast-types in the Bardarevo Formation include reworked tectonised micrite, siltstones, micaceous sandstone and quartzites and Stoykova & Juranov (2005) suggest these may be sourced from Upper Cretaceous units, Triassic dolomites and Jurassic quartzites. The younger Meshilika Formation contains reworked clasts of Nummulite-rich sandstones, micaceous sandstone, purple and green-grey marls, reworked Gebesh silts and volcanic debris. The petrography of these formations did not substantially enlighten further interpretation or provide statistical proof of origin although the samples from the Bardarevo Formation show a more mixed signature than the Meshilika Formation which is more likely to have sourced from Moesian Platform carbonate deposits (possibly Byala Formation). These mass flow deposits may represent episodes of basin margin slope failure, possibly triggered by thrusting events on the orogenic-wedge (southern) margin, uplift on the northern Moesian platform margin and possibly inversion on the formerly extensional Mesozoic faults at the northern edge of the basin.
The turbiditic deposition into the Emine Basin during the Lower Eocene, represented by the Atanas and subsequent Gebesh Formations, show consistent palaeocurrents to the west but their petrographic compositions vary. The Atanas Formation is generally medium grained and seen to coarsen-up through the section but steady flow conditions are implied whilst the Gebesh Formation comprises very fine, uniformly low density turbidites. The inference is that between the deposition of these two formations either water level increased significantly or sediment sourcing was from a considerably more distal location. The Atanas Formation shows some arc-influence in sediment composition and if continual basin tightening is inferred, from the observation of thrusting, the sourcing may have been more local and heavily influenced by recycled material or mass flows emanating from the orogenic margin. By contrast, the Gebesh Formation shows a more mature signature, like the Emine Formations, likely to have been sourced from distal, exhumed intrusive igneous rocks in the Rhodope with restricted erosion of underlying units or mixing with arc-derived mass flow units. The sedimentological and petrographical evidence suggests that this apparent change may be explained by a relative lowering base level and deepening water conditions at the end of the Lower Eocene, either due to tectonic uplift or eustatic sea level rise which resulted in a change in sediment sourcing from local arc-derived units to distal westerly regions.

4.2.4 SEQUENCE 4: MIDDLE-UPPER EOCENE (OVBZOR, DOLEN CHIFLICK, ARNAUTLER)

4.2.4.1 Tectonic Setting & Depositional Environments

In the Kamchia Basin, the majority of the Mid Eocene is a period of erosion or non-deposition (the “Illyrian Unconformity”) and represents a major period of compression and thrust wedge development which resulted in the uplift, deformation and erosion of pre-existing basin units (figure 4.8). The Irakli and Obzor Synclines may be dated to this period of tectonic activity. This Illyrian event shifted the depocentre of the basin further north-eastwards onto the autochthon and marks the initiation of the Kamchia Basin, as apparent on the chronostratigraphy (figure 4.1).
The Obzor Formation mass flow unit is one example of the type of mass flow being shed off the unstable southern margin onto the tilted and deformed sediments of Sequences 1 and 2 in the basin as the wedge is thrusted and thickened topographically. Any number of these geographically-restricted units may have been deposited, possibly related to the manifestation of compressional stresses on individual thrust fault planes creating blind thrusts and associated topographic disturbances. After this period turbiditic deposition resumed once more (the Dolen Chiflick Formation) but most likely in shallower water, and in a geographically more restricted basin environment, than in the Emine Basin due to the development of the thrust wedge and uplift of the Moesian Platform (inversion on the Mesozoic platform faults is likely during this period). The Arnautler Formation represents further shallow water deposition in a restricted basin but in a tectonically stable regime indicating that the intensity of compression was beginning to wane.

4.2.4.2 Provenance from Sedimentology & Petrography

The distinctive Obzor Conglomerate Formation outcrop contains well rounded clasts of volcanic igneous rocks (textures include aligned amygdales and porphyries with olivine or feldspathic laths), chalks, fine sandstone and hard micrite. The petrographical analysis looking primarily at the matrix of this clast-supported unit confirms an “arc orogen” or undissected arc origin interpretation. The well R79 “Obzor Formation” samples analysed showed a far less distinctive signature. Combined with the evidence for spatially restricted deposits of this age, it is proposed that these isolated conglomerates may represent localised pockets of high energy deposits. These may be related to channelised flow through topography formed between active thrusts prior to along-strike linkage of individual thrust faults, suggesting an over-steepened margin to the south of the basin, the result of movement on individual blind thrusts creating relief. However, in contrast to this, the rounded clasts of the Obzor Formation outcrop suggest extensive catchment areas and transport of sediment attesting to the mature development of the wedge by this stage.
The Dolen Chiflick Formation consists of bioclast-rich sandy turbidites and siltstones with a variable but cratonic/recycled orogenic signature and west-to-east palaeocurrents. As such, the unit is thought to be deposited into a basin that was restricted in area (along with a possible base level rise) and sediments derived from the west where compression was experienced more intensely. The source may have been either recycled units from earlier deposition in the Emine Basin or from exhumed metamorphics in the Rhodope, the unroofing of which was largely accommodated by tectonic denudation (van Hinsbergen et al., 2008). Shallowing-up is observed in this unit which presumably reflects high sediment flux. The subsequent basin-wide deposition of the Arnautler Formation, which also covers carbonate stratigraphy on the platform margin of the basin margin, is interpreted to have been in a shallow water, tidal or shelfal environment. The Arnautler sands are bioclast-rich (from primary deposition rather than recycling) but the framework grain point-counts showed a recycled quartzose compositional signature which could be derived from either recycled units within the orogenic wedge by this stage or from a distal cratonic source, the compositional difference between the two sources being hard to distinguish.

4.2.5 SEQUENCE 5: OLIGOCENE (RUSLAR)

4.2.5.1 Tectonic Setting & Depositional Environments

The start of the Oligocene is marked by a basin-wide erosive or unconformable surface (possibly from a global eustatic sea level drop) and the Ruslar Formation is deposited uniformly over the entire basin, filling in topography created either by compression or by tectonic subsidence (figure 4.9). The final compressive episodes within the Balkanides continued until the Middle-Late Oligocene (Robb, 1998; Sinclair et al., 1997) but post-Eocene, compressive stress was well reduced and extension was initiated in the orogenic region, forming a series of grabens in the southern Rhodope (e.g. the Mesta graben) (Burchfiel et al., 1993). This relatively tectonically quiescence is manifest in the fine grained Ruslar Formation and there are no further sporadic episodes of mass flow from the thrust wedge as seen throughout
the sequence up until the Upper Eocene. Deposition into the basin has reconfigured because of the relative decrease in tectonically-induced sedimentation from the wedge or platform margins, but the basin geometry during the Oligocene is likely to maintain the pre-existing but tightening W-E trough, closing further to the west. Within this basin and in younger units, sea level changes have a greater influence over deposition relative to tectonic control.

4.2.5.2 Provenance from Sedimentology & Petrography

The manganese-rich base of the Ruslar Formation was deposited on a very quiescent seafloor whilst subsequent sedimentation in the same unit displays facies indicative of outer shelf to shoreface environments, deepening to the west. The Ruslar Formation samples analysed petrographically showed mixed provenance varying between “arc orogen” sources and cratonic interior. This is interpreted to reflect the shift in sourcing from the dominance of the wedge and distal western sources to equal sourcing from proximal basin margins on all sides (north, west and south) of the basin. The lithic content shows increased metamorphic content (notably polycrystalline quartz) compared to the Eocene units which may be due to recycling of underlying units or unroofing of metamorphic complexes from extension in the Rhodope.

4.2.6 SEQUENCE 6: MID-MIOCENE (GALATA)

4.2.6.1 Tectonic Setting & Depositional Environments

Between deposition of the Oligocene Ruslar and mid-Miocene Galata Formations there is a significant period of non-deposition, presumably attributable to relative sea level change. Resumption of sedimentation took place after a rise in sea level and the Galata Formation is widespread over the basin (much reduced in size by the Miocene) but predominantly in paralic environments and significant cannibalisation of units surrounding the basin is observed. Deepening of the basin is to the west and transport is into the Black Sea which has opened up due to the significant east-west
extension experienced by this period (figure 4.10). This represents a major shift in basin configuration as the dominant slope is west to east rather than the formerly northern and south basin margins. Basin floor topography is not thought to be particularly pronounced as the Ruslar Formation acted to infill lows during the Oligocene.

4.2.6.2 Provenance from Sedimentology & Petrography

Palaeocurrent data from the Galata Formation demonstrates flow was primarily to the north-west in a variety of shallow-marine settings. A west-east trending basin is still evident from the restricted north-south geographical spread of sediments and strong flow and rapid deposition is inferred from the well developed foresets visible at many localities. The petrographical analysis shows a remarkable consistency in clastic composition and textural maturity indicative of significant mixing and recycling, much more so than evident in the underlying Ruslar Formation. Akin to the Ruslar Formation, sources are difficult to pin-point as the high proportion of metamorphic lithics and polycrystalline quartz may have been derived from either recycled units in the thrust wedge or exhumed metamorphic complexes in the Rhodope. This issue may only be resolved from heavy mineral analysis, however, there are present-day exposures of quartz-rich Cambro-Ordovician metamorphic units directly west of the Cape Galata headland which form a likely source region for the Galata Formation (figure 4.3).
Figure 4.3 Geological map of Bulgaria highlighting some potential Tertiary sediment sources (source: Melrose Resources)
SEQUENCE 1
Campanian to End Maastrichtian underfilled back-arc basin
LOWER EMINE

inactive volcanic arc to south

Cessation of back arc extension

boulder beds from slope instability at base of Lower Emine Fm (Tankovo locality)

deposition of Byala Formation turbidites on cratonic margin

deposition of Emine turbidites on cratonic margin

deposition of Emine turbidites on cratonic margin

deposition of Emine turbidites on cratonic margin

deposition of Emine turbidites on cratonic margin

EMINE BASIN

Golitsa Fault
major extensional fault defining northern edge of basin

Srednogorie Volcanics

Moesian Platform

Figure 4.4
Figure 4.5

SEQUENCE 2
Palaeocene underfilled foreland basin
UPPER EMINE & KOZICHINO

- Differential initial basin narrowing due to compression in the SW causing change in turbidity flow direction to SE
- Incipient thrusting on orogenic margin developing topography
- High flux of tectonically-controlled sedimentation: high density mass flows/coarse turbidites sourced directly from the remnant arc (rich in volcanic lithics) formed under sustained high energy submarine discharge from slope instability

- Upper Emine Fm acquiring arc-derived components down slope from interaction with arc-margin derived deposits?
- Wide catchment of Kozichino Fm deriving sediment from recycled plutonic basement in hinterland and arc material from developing wedge
- Inactive volcanic arc to south

UPPER EMINE FORMATION
Gm

Craton interior
Quartzose recycled
Turbidites with stronger arc-like lithic component flowing longitudinally along basin axis

Moesian Platform

Emine Basin

Srednogorie Volcanics
KOZICHINO FORMATION
Gm

Mixed
Archean
Arc
SEQUENCE 3
Lower Eocene underfilled retro-arc foreland basin
BARDAREVO & ATANAS

Large-scale, chaotic blocks of micrite, adaitone, micaeous sandstone and quartzites
in a fine-grained matrix suggestive of mass transport unit derived from wedge margin

Atanas sands show arc-like signature: sourced from volcanic
hinterland to west developed west in west. Source more
proximal than that of the Emine Formation turbidites
thus may represent basin narrowing to west

BARDAREVO FORMATION

Moesian Platform

lower Atanas represents low density turbidites
(dominant background muds)
up-section grades into high-density sand-rich flows
deposited under steady flow conditions

EMINE BASIN

shift in main basin depocentre to north

basin floor forms offshore potentially lateral equivalents
to Atanas Fm

growing frontal wedge and compressoin of basin

Golitsa basement fault

Quartzose recycled
transitional recycled
quartzose recycled

Figure 4.6

south

north
SEQUENCE 3
Lower to early Mid Eocene underfilled retro-arc foreland basin
MESHILIKA & GEBESH

Meshilka clasts include fumusite-rich sands, micaceous sands, grey-green marls and micrite blocks.

Growing thrust wedge and continued compression of basin.

Deeping up during deposition of Gebesh Fm.

Large, >10 in scale heterolithic blocks set within muddy matrix consistent with mass flow deposits or middle fan environments.

Low density fine sand and mud turbidites with tentative palaeocurrent to east down basin axis.

Sands possess mixed orogenic signature and are likely to be sourced longitudinally down orogenic front.

Shift of platform causing margin instability.
Figure 4.8

SEQUENCE 4
Mid - Upper Eocene overfilled retro-foreland basin
OBZOR, DOLEN CHIFLICK & ARNAULTER

- Isolated lobes of mass flow sourced from the thinned volcanic arc: rounded clasts including volcanics textured igneous rocks
- Significant growth of topography on orogenic margin
- Strong compression experienced on individual thrust faults releasing foreland basin
- Formation of Obzor and Inaki Synclinorium during Ktunjan (Mid Eocene) Unconformity event

KAMCHIA BASIN

- Northward shift of basin depocentre
- Mesoian Platform
- Arnaudier Formation deposited over Mesoian Platform margin

- Isolated lobes of mass flow sourced from the thinned volcanic arc: rounded clasts including volcanics textured igneous rocks
- Significant growth of topography on orogenic margin
- Strong compression experienced on individual thrust faults releasing foreland basin
- Formation of Obzor and Inaki Synclinorium during Ktunjan (Mid Eocene) Unconformity event
SEQUENCE 5
Oligocene overfilled retro-foreland basin
RUSLAR

Rich in polycrystalline quartz, may be due to
recycling of underlying units or unroofing of
metamorphic complexes from extension in the Rhodope

deposition into the basin reconfigured
because of the relative decrease in
tectonically-induced sedimentation from
the wedge or platform margins

tightening W-E trough, closing further to the west

outer shelf to shelf
depositional environments,
deepening to the west

fine-grained manganese-rich base
of the Ruslar Formation deposited
on a very quiescent seafloor

uniform deposition filling in topography
created by compression or subsidence

mixed provenance reflects the shift to equal sourcing
from proximal basin margins on all sides of the basin

start of the Oligocene marked
by a basin-wide unconformable
surface (possibly from eustatic
sea level drop)

final compressive episodes
in Middle-Late Oligocene

Figure 4.9
SEQUENCE 6
Mid-Miocene stable basin at western margin of incipient Black Sea
GALATA

- Paleocurrent data demonstrates flow was primarily to the north-west in a variety of shallow marine settings.
- Deepening of the basin to the west and transport of sediment into the Black Sea (opposed due to west-east extension).
- West-east trending basin and restricted north-south geographical spread of sediments.
- Rise in sea level gave rise to widespread deposition of Galata Formation across basin in prodelta environments.
- High proportion of metamorphic lithics and polycrystalline quartz derived from either recycled units in the thrust wedge or outworn metamorphic complexes in the Rhodope.

*Figure 4.10*
CHAPTER 5

CONCLUSIONS & SUGGESTIONS FOR FURTHER WORK

5.1 DELIVERY AGAINST OBJECTIVES

The questions posed of this study were as following:

1. What was the history of sediment delivery into basins on the retro-arc side of the Balkan mountain chain from the Cretaceous through to the Middle Miocene?

2. What characterised the provenance and hence petrology of the Kamchia Basin and what does this imply for the palaeogeographic evolution of the system?

It has been established that the early basin, the Emine Basin, during the Cretaceous and Palaeocene (Sequences 1 and 2), experienced dominantly deep-water sedimentation (Lower and Upper Emine Formation) in an elongate trough along the system strike sourced from distal intrusive igneous basement to the west. The southern basin margin experienced sporadic inputs in the form of submarine fans (Kozichino Formation) directly from the southern arc/thrust wedge which began to experience compression and instability during this period and these deposits may have interacted with the basin floor Emine Formation turbidites, giving an increasing arc-like signature up-section. The mid-Eocene Emine Basin (Sequence 3) displays stronger signs of basin instability and shedding of sediment off both the northern (platform) and southern (orogenic) basin margins through high energy events (Bardarevo and Meshilika Formations). There is, however, continuation of volumetrically dominant sedimentation being transported along-strike west-to-east along the basin (Atanas and Gebesh Formations, the transition between which shows a signal of deepening water). The Illyrian Unconformity is a period of non-
deposition during the mid-Miocene representing a period of major tectonic compression and uplift creating structural features such as the Irakli and Obzor Synclines. Mid and Upper Eocene deposition was into a shallower and geographically more restricted basin, the Kamchia Basin (Sequence 4). Easterly-transported turbidites are seen in this basin (Dolen Chiflick Formation), overlying deposits of isolated conglomerates (Obzor Formation) sourced directly from recycled arc volcanics are the manifestation of movement on individual thrusts. The distinctiveness of this latter source of deposition waned as the thrust wedge grew, relative sea levels dropped and the axis of deposition moved north. The dominant control on sedimentation became increasingly eustatic rather than tectonic. By the Oligocene (Sequence 5) and after a period of non-deposition, sedimentation was uniformly low energy and shallow water (Ruslar Formation) and sourced from either recycled units in the thrust wedge or exhumed metamorphic complexes in the Rhodope, or both. By this stage the basin was increasingly restricted geographically. The youngest units studied, the Mid-Miocene Galata Formation (Sequence 6) displays high energy, directed flow in a very narrow channel-like basin into the early Black Sea which had, by this period, begun to open through east-west extension.

3. Is it possible to predict periods of flushing of high (hydrocarbon) reservoir quality clastic sediments into the deeper basin where exploration in the Black Sea is currently focused?

There is a persistent story of dominant sedimentation along the axis of the trough-like depocentres of both the Emine and Kamchia Basins, transported west-to-east throughout the entire stratigraphy and particularly during periods of relative tectonic stability. During periods of intense tectonic stress, such as the Lower and Upper Eocene (Sequences 3 & 4), this signature is diluted by sediments derived directly from the growing arc/wedge in the south. These latter sediments rarely display textures with high reservoir quality and are susceptible to diagenetic change, either positive with dissolution of labile grains forming porosity or negative through degradation of lithic fragments into clays. From outcrop distribution and facies analysis these deposits appear to rarely be laterally extensive themselves but
unfortunately there are signs of significant interaction of these wedge-derived sediments with the background turbiditic trough-deposition which bestows a higher percentage of feldspar, lithics and clay on the turbidite composition e.g. explaining the contrast between the Lower and Upper Emine Formation. Up-stratigraphy, into the Miocene (Sequence 6), the arc-derived component of sediment composition is much less concentrated due to mixing of sediments derived from all basin margins and the texture and composition of these rocks is very mature, often with little cementation. Concentrating where Galata Formation may be deposited offshore would be a continuation of this study.

In summation, there appear to be no periods in which deposits with a depositionally inherently high reservoir quality are likely to feed into the Black Sea basin but there is potential for reworking and diagenesis to improve the reservoir quality of rocks influenced by sourcing from the arc-thrust wedge. Absolute dating of timings of movement on individual thrust faults as exposed in the study region may be useful to establish patterns to predict when periods of high faulting activity are.

4. *Do the basins of the Balkans show similar patterns of sediment filling to other examples of retro-arc basins associated with small mountain belts?*

By comparison with a limited number of analogues here, it is apparent that the Balkan basins show a typical foreland basin-type under- to overfilled stratigraphy and that dominant deposition was overwhelmingly along the trough of the elongate basin rather than from either the arc/wedge or platform margin. Whether this is statistically significant by comparison with other retro-arc foreland basins would require further investigation but the original dataset that this study provides is comparable in methodology and sample size with that of such as the Magallanes Basin (Fildani & Hessler, 2005). A comparison with study such as this of a large scale orogenic system but also with tectonically comparable basins such as the Po and Aquitaine basins, if the datasets exist, would be a natural extension to this study.
5.2 **Implications for Wider Research Areas**

The immediately obviously result of this work is an advancement in the understanding of the Cretaceous to Miocene geology of eastern Bulgaria. However, it should be recognised that the data and interpretations of this study have implications outwith this direct subject area. The following list gives some ideas of wider research themes which may benefit from the results of this study:

- Understanding of the regional evolution of Tertiary plate movements in the Aegean and Balkan regions through comparison of peripheral (Hellenide) and retro-foreland (Balkan *i.e.* this study) basin provenances and patterns of sediment filling.

- Creation of a framework to explain generic sediment filling patterns in retro-foreland basin settings through comparison with other basins such as the Po and Aquitaine.

- Comparison of sediment filling patterns in retro-foreland basins to that of peripheral-foreland basins to understand reasons for greater hydrocarbon play success in peripheral-foreland basins and potential for plays in retro-foreland basin settings.

- Provenance studies as a means of ground-truthing models of foreland basin development.
5.3 **Suggestions for Further Work**

The conclusions from this study may be further clarified by work on the following:

- XRD and heavy mineral analysis to further pin-point sediment sources, particularly to address the question of whether the Dolen Chiflick, Ruslar and Galata Formations were derived from recycled units in the thrust wedge or from exhumed metamorphic complexes in the Rhodope.

- Further tectonic study *e.g.* subsidence curve analysis, further tectonic reconstruction integrating seismic data. It would be particularly pertinent to link this work to similar done in analogous settings *e.g.* Brunet (1984).

- Further study of apparently isolated arc-derived deposits with absolute dating methods to improve understanding of movement on individual thrust planes.

- Detailed comparison with other retro-foreland basins of similar size to establish generic conclusions for such tectonic settings.

- Study of the Hellenide foreland basin at comparable times to substantiate the implications of modelling work comparing features of the retro- and pro-foreland basins such as that of Naylor & Sinclair (2005).

- Study of published thermochronology done on rocks in potential source regions, especially with regard to identifying regions of Palaeocene and Eocene exhumation and erosion.
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LAWTON, T.F. 1986. Fluvial systems of the Upper Cretaceous Mesaverde Group and Paleocene North Horn Formation, central Utah: a record of transition from thin-


POPOV, P. 2002. Alpine geotectonic evolution and metallogeny of the eastern part of the Balkan Peninsula. *Annual of the University of Mining and Geology “St. Ivan Rilski”*, 45, 33-38.


RICCI-LUCCHI, F. 1986. The Oligocene to Recent foreland basins of the northern Apennines. *International Association of Sedimentologists Special Publication*, 8, 105-139.


### APPENDIX I: SEDIMENTARY LOGS (LISTED BY STRATIGRAPHIC ORDER)

<table>
<thead>
<tr>
<th>Log number</th>
<th>Location</th>
<th>Locality number</th>
<th>Grid Reference (UPS/UTM)</th>
<th>Formation</th>
<th>Length (m)</th>
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<tbody>
<tr>
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<td>Cape Emine</td>
<td>6.1</td>
<td>[0573695, 4728213]</td>
<td>Lower Emine</td>
<td>4.40</td>
</tr>
<tr>
<td>6.2</td>
<td>Cape Emine</td>
<td>6.10</td>
<td>[0573660, 4728487]</td>
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<td>3.00</td>
</tr>
<tr>
<td>8.2</td>
<td>Northernmost exposure</td>
<td>8.9</td>
<td>[0573400, 4734965]</td>
<td>Lower/Upper Emine contact</td>
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<tr>
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<td>[0573341, 4730668]</td>
<td>Upper Emine</td>
<td>26.00</td>
</tr>
<tr>
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<td>7.1</td>
<td>[0573299, 4731209]</td>
<td>Upper Emine</td>
<td>3.60</td>
</tr>
<tr>
<td>8.1</td>
<td>North limb of Irakli Syncline</td>
<td>8.1</td>
<td>[0572753, 4733888]</td>
<td>Upper Emine</td>
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<tr>
<td>30.1</td>
<td>Kozichino “South”</td>
<td>30.1</td>
<td>[0546760, 4742391]</td>
<td>Upper Emine, Kozichino</td>
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<tr>
<td>31.1</td>
<td>Kozichino “North”</td>
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<td>[0547179, 4743540]</td>
<td>Kozichino</td>
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<td>Cape Mona Petra</td>
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<td>[0572123, 4743842]</td>
<td>Gebesh</td>
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</table>
## Sedimentary Logs Key

### Lithologies

- **Coarse grained sandstone**
- **Medium grained sandstone**
- **Fine grained sandstone**
- **Siltstone**
- **Shale**
- **Silty sandstone**
- **Limestone**
- **Sandy limestone**
- **Cherty limestone**
- **Clast-supported conglomerate**
- **Matrix-supported conglomerate**

### Sedimentary Structures

- **Ripples**
- **Soft sediment deformation**
- **Mud cracks**
- **Devitalizing structures**
- **Mud flakes**
- **Clasts (within sandstone)**

### Bed contacts

- **Sharp**
- **Gradations/Not observed**

### Bedding Structures

- **Bedding (line spacing is representative of relative bed thickness)**
- **Trough cross-stratification**
- **Bedding dip (denoted outside graphic log)**
- **Planar bedding**
- **Undulose bedding**
- **Forested dip (denoted inside graphic log)**
- **Planar cross-stratification**
- **Obscured bedding**

### Fossils

- **Crinoid ossicle**
- **Burrows**
- **Gastropod**
- **Sample - see 'description' column for sample location details**

### Lithofacies scheme

(partially adapted from Miall, 1977)

- **Lm** = nodular or massive fossiliferous limestone
- **Li** = laminated fossiliferous limestone
- **Sp** = planar cross-stratified sandstone
- **St** = trough cross-stratified sandstone
- **Sh** = horizontally stratified sandstone
- **Sm** = massive sandstone
- **Sr** = tabular rippled sandstone
- **Fm** = massive fine sandy siltstone/siltstone
- **Fl** = laminated or cross-laminated VF/siltstone/mudstone
- **Fr** = rippled fine sandstone/siltstone

### Lithofacies Associations

These give a broad interpretation of depositional environment derived from a visual estimate of related facies. Statistical validity was not possible with the given amount of data. The interpretation column provides further details of environments.
<table>
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<th>LOG # 6.2</th>
<th>Hamish Stuart</th>
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<td>University of Edinburgh</td>
</tr>
<tr>
<td>Location no.: 810</td>
<td>GPS/GR Base [0573660, 4728487] sea level</td>
</tr>
<tr>
<td>Logger: HLS</td>
<td>Date: 03/04/06</td>
</tr>
</tbody>
</table>

**LOWER EMINE FM**

### Stratigraphic Log

<table>
<thead>
<tr>
<th>Interval (m)</th>
<th>Sedimentary Structures</th>
<th>Bedding</th>
<th>Lithofacies</th>
<th>Description</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00 - 0.50</td>
<td>parallel lamination</td>
<td>normal</td>
<td>green siltstone</td>
<td>stratified lenticular sandstone</td>
<td>Developing structure indicate fluid flow and rapid depositional events</td>
</tr>
<tr>
<td>0.50 - 1.00</td>
<td>parallel lamination</td>
<td>normal</td>
<td>sandstone</td>
<td>lenticular sandstone</td>
<td>Stratified lenticular sandstone is common throughout the lower 1/4 of this sequence; they are characterized by low-angle, tabular deposition away from the sediment source</td>
</tr>
<tr>
<td>1.00 - 1.50</td>
<td>parallel lamination</td>
<td>normal</td>
<td>sandstone</td>
<td>lenticular sandstone</td>
<td>Stratified lenticular sandstone is common throughout the lower 1/4 of this sequence; they are characterized by low-angle, tabular deposition away from the sediment source</td>
</tr>
<tr>
<td>1.50 - 2.00</td>
<td>parallel lamination</td>
<td>normal</td>
<td>sandstone</td>
<td>lenticular sandstone</td>
<td>Stratified lenticular sandstone is common throughout the lower 1/4 of this sequence; they are characterized by low-angle, tabular deposition away from the sediment source</td>
</tr>
<tr>
<td>2.00 - 2.50</td>
<td>parallel lamination</td>
<td>normal</td>
<td>sandstone</td>
<td>lenticular sandstone</td>
<td>Stratified lenticular sandstone is common throughout the lower 1/4 of this sequence; they are characterized by low-angle, tabular deposition away from the sediment source</td>
</tr>
<tr>
<td>2.50 - 3.00</td>
<td>parallel lamination</td>
<td>normal</td>
<td>sandstone</td>
<td>lenticular sandstone</td>
<td>Stratified lenticular sandstone is common throughout the lower 1/4 of this sequence; they are characterized by low-angle, tabular deposition away from the sediment source</td>
</tr>
</tbody>
</table>

**Remarks:**
- Stratified lenticular sandstone is common throughout the lower 1/4 of this sequence; they are characterized by low-angle, tabular deposition away from the sediment source.
**Locality:** Most northerly exposure of Emine Falls south from River Vaya

**Locality no.:** 7.1 **GPS/GR: Base [5673299, 4731206]** **sea level:**

**Logger:** HLS **Date:** 04/04/06

**Description:**

**Interpretation:**

- **B 22**: Pebble conglomerate (velly pebbles at top) - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 21**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 20**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 19**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 18**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 17**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 16**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 15**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 14**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 13**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 12**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 11**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 10**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 9**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 8**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 7**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 6**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 5**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 4**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 3**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 2**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **B 1**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **C 12**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **C 11**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **C 10**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **C 9**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **C 8**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **C 7**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **C 6**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **C 5**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **C 4**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **C 3**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **C 2**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.

- **C 1**: Pebble conglomerate with pebbles at top - possibly aragonite crystals. Silted by turbidity currents and deposited on top of topset bedrock. Turbidity currents were possibly caused by the movement of sand and mud from the upstream area.
Continued on following page (note overlap)
Log 30.1 page 3/3 (note overlap)
Log 31.1 Koizhino Formation, page 1/2 (note overlap)
Log 31.1 Kozichino Formation, page 2/2 (note overlap)
Locality: Cape Mona Petra (fine scale log of overturned sequence)  
Locality no.: 10.6  
GPS/GR: [0573433, 4737019]  
Logger: HLS  
Date: 07/04/06  
LOG # 10.1

Hannah Subtil
University of Edinburgh

LOWER EOCENE, DVOINTSA GROUP

228
<table>
<thead>
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<th>Source</th>
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APPENDIX II.2: Raw Point Count Results (listed by formation)

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## Summary

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### Comment

- Total sample numbers and percentages are provided for each formation.
- The table includes a detailed breakdown of the mineral composition for each sample.
- The results are listed by formation, with each formation having its own set of numbers.
- The percentages are calculated based on the total number of points counted for each mineral type.

---

Note: The table and results are presented in a structured format for easy reading and analysis. The data includes the mineral composition percentages for each formation, with a focus on the key minerals such as Ls, Lm, Kspar, sericite, and other components. The percentages are calculated for each sample, providing a comprehensive overview of the mineralogy for each formation.
## APPENDIX II.2: Raw Point Count Results (listed by formation)

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### Additional tables and figures

**Table 1:** Summary of raw point count results by formation.

**Table 2:** Detailed point count data for individual samples.

**Figure 1:** Graphical representation of raw point count results by location.

---

**Note:** The above tables and figures provide a comprehensive overview of the raw point count results for the various formations across different locations. Each table and figure is designed to facilitate a deep understanding of the distribution and concentration of specific geological features within the sampled areas.
### APPENDIX II.2: Raw Point Count Results (listed by formation)

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### Notes
- The table above presents the raw point count results for various formations listed by formation. Each row represents a specific member within a formation, and the columns indicate the count for different members.
- The values in the table represent the counts for different elements or features within the formations.
- The formation list includes members 1 to 20, with specific values for each member.
- The data is provided in a structured format, allowing for easy analysis and comparison.