REFERENCES


This thesis was completed with the assistance of several people and institutions, all of whom to which I am extremely grateful. Foremost among them is Dr. John Miller, who encouraged and helped me in field work, lab research, writing, drafting and proofreading. I will always be thankful for high standards he set and the approach to science he has taught me. In this respect I am also indebted to my supervisor, Dr. Euan Clarkson, for his criticism, help in writing and the insights into life in general which slipped in during our digressions from science. Professors G. Y. Craig and Sir F. Stewart generously extended the facilities of the Grant Institute to me throughout my extended course of research and writing.

I have felt privileged to be able to use the facilities of the Royal Scottish Museum. Dr. Charles Waterston, Keeper of Geology, kindly extended to me the use of the Museum's facilities and arranged financial assistance for me in the purchase of a duplicate thesis collection. I would like to thank Dr. Waterston and several other members of staff, in particular Mr. Bill Baird, Mr. Bob Reikie and Miss Audrey Heatlie. Audrey helped to process and pick through the insoluble residues.

The generous financial aid of the Nature Conservancy Council made it possible to sandblast the southern quarry face of the Reservoir.

Several colleagues have helped me to identify different elements of the Petershill Fm. fauna. Mr. Murray Mitchell, from the Institute of Geological Sciences, Leeds allowed me to use the IGS collections and aided me in my initial coral identifications. I am especially grateful to Dr. Alan Timms, from the British Museum, who introduced me to the hazards of productoid taxonomy. Dr. Robert Riding performed
a similar task in introducing me to algae and their problems of classification. Dr. R. B. Wilson, of the Institute of Geological Sciences, Edinburgh, identified several specimens for me, mainly the bivalves, and confirmed my own identifications of others. Professor R. C. L. Conil, from the University of Louvain le Nueve, Belgium, was particularly helpful in identifying the foraminiferans in the Reservoir Mbr.

Several members of staff from the Grant Institute have helped to solve the numerous problems which arose during research. Mr. C. Chaplin arranged and helped to have the boreholes drilled. Mr. G. Wilson and later Miss D. Baty have assisted me in photography, while Mrs. D. Grieve, our librarian, managed to trace down even my most obscure references. In this respect I am also indebted to Mrs. M. Sutherland and Mr. C. Will, the able librarians of the Institute of Geological Sciences.

Mr. A. Sutherland has assisted me on numerous collecting trips and arranged to have this thesis bound.

I doubt that it would ever have been possible to survive writing-up without a lot of help and understanding from my friends. Mr. C. Begg’s garage proved to be a particularly consoling refuge during my moments of woe. I fear that I must have been particularly trying for Miss Stephanie Hall, to whom I am especially grateful. Mr. Peter Staffel’s support additionally extended to helping with the drafting. The presentation of this thesis owes a great deal to the flawless typing of Mrs. Lucian Begg.

Lastly, I would like to thank my parents who, by their example, have encouraged me to learn as well as take an interest in others and my surroundings.
APPENDICES
APPENDIX A
CROSS-SECTION OF THE LOWER PETERSHILL FM.

Figure A-1 is located in the back pocket so that it may be referred to while the text is being read. It shows a cross-section of the Reservoir Mbr. and the basal sandstone facies of the Silvermine Mbr., based on data presented in Ch 2, borehole information, and previous reports of the sequence (references given in Introduction and Ch 2). The configuration of the underlying lava surface is conjectural.
APPENDIX B

BOREHOLES IN THE PETERSHILL FORMATION

The first part of this appendix consists of petrographic notes on borehole cores, based on thin sections, peels, and the observable macrofauna. The second part is a drilling record. Each time the core was pulled up (pull #) the distance reached and the length of core recovered was recorded. Core barrels are cut in feet, and therefore all original measurements appear in feet and inches. The cores are presently labelled by their pull numbers. The tables provided here show what depth each pull was taken from.

Rarely, the length of core recovered exceeded the distance drilled. E.g. pull number 7 of borehole 1 recovered 28" of core while the distance drilled was only 24". This occurred due to incomplete recovery from the previous pull, number 6. In these instances the top length of core was placed in with the pull interval it was cored in.

Three separate attempts were made at sinking a borehole at Silvermine. On each, the drill fouled, possibly due to a tectonically disturbed zone. The core presently labelled as core 5 is an amalgamation of the three attempts.
Petrographic notes from
Borehole 1, Sunnyside Reservoir, NS 9833 7033

Borehole begun 50 cm below limestone/sandstone contact, at the top of the Reservoir Member.

0.0-2.75 m

3-28 cm thick, unsorted and well-sorted, fine-grained packstones and poorly-sorted crinoidal packstones alternating with 10 cm thick, black calcareous mudstones. Bioturbation moderate (30%) to extensive (60-80%) throughout limestones: Chondrites, Zoophycus, indistinct traces, and abundant faecal pellet trails. Fine-grained laminae in packstones concentrate foraminiferans (endothyrids, ammoidsids, Tetrataxis) suggesting that the assemblage is drifted. Limestone fossils: Dibunophyllum, Chaetetes, Lonsdaleia, Lithostroton, Palaeosmilia, productoids, and bryozoans. Calcareous mudstones are less fossiliferous, predominantly containing fine skeletal debris.

2.75-5.7 m

Medium thickness, grey, slightly argillaceous and argillaceous packstones and thin calcareous mudstones. Limestones predominantly composed of fine (mm-sized) skeletal debris with occasional horizons of in situ macrofauna. Bioturbation extensive. Limestone fossils: Lonsdaleia and solitary rugosans.

5.7-9.2 m

5-10 cm thick, grey argillaceous biomicrosparites, grey slightly argillaceous packstones, and rare cream micritic wackestones, alternating with thin calcareous mudstones. Mudstones are generally unfossiliferous: spirifers and strophomenids rare. Argillaceous biomicrosparites are compacted, extensively bioturbated, and contain Lonsdaleia floriformis, Dibunophyllum and other solitary rugosa. Cream, micritic wackestones have more diverse fauna including spinose productoids and cidaroid
echinoids. Chert common throughout succession.

9.2-12.7 m

5-15 cm thick (mean 5 cm) nodular cream biomicrosparites alternating with equal thickness crinoidal calcareous mudstones. Branched filamentous algae present in both limestones and mudstones. Biota (of both limestones and mudstones) includes: Eomarginifera, strophomenids, Koninckophyllium cf. dianthoides, Hexaphyllia, Dielasma, Antiquatonia, Stacheoides, Kamaena, Sphinctoporella, Fistulipora and Litucetubella.

12.7-14.4 m

transitional boundary to grey, laminated argillaceous biomicrosparites and black calcareous mudstones. Fauna sparse, mostly fragments of brachiopods, corals, bryozoans, and siliceous sponges. Sequence becomes progressively more argillaceous downward.

14.4-15.4 m

black carbonaceous shale with thin green tuffaceous laminae. Shale contains diverse, abundant fauna of pectinoid bivalves, ostracods, Lingula, Hyalostelia, and small spinose productoids. Occasional coal, plant debris, and spore laminae. Very oily horizons common; drilling water often came up in oily beads.

15.4-16.8 m

green, pasty, fine-grained, tuffaceous sandstone, slightly calcareous.

16.8-17.2 m

tuffaceous sandstone containing rounded pebbles of basalt, plant debris.

17.2-22.2 m

black, vesicular olivine basalt. Badly weathered, heavily calcitized. Phenocrysts typically altered to calcite, zeolites, or kaolinite.
Petrographic notes from Borehole 2, NS 9850 6925

Borehole was begun 675 cm below the top limestone in the Reservoir Mbr 0.0-1.3 m

medium to thick, grey, argillaceous biomicrosparites and medium to thin calcareous mudstones. Limestones are unsorted, extensively bioturbated: Zoophycus, 1 cm diameter cylindrical meandrine burrows. Extent of bioturbation decreases steadily downward from extensive (60-80%) to moderate (40-60%). The few unbioturbated beds show parallel clastic lamination. Limestone/mudstone contacts are gradational, showing signs of boudinage. Limestone composition: 60-80% (grain bulk) microspar, 10-20% fossil fragments (less than 1 mm). Few whole fossils except spirifers, beyrichid ostracods, Bairdia sp.. Mudstones have a higher proportion of fossil debris, lack whole fossils entirely.

1.3-1.7 m

medium, slightly argillaceous, grey and cream wackestones with coarse crinoidal debris laminae. Overturned, coarsely fragmented Lithostrotion colony horizon at 160 cm. Lithostrotion colony horizon contains Entomoconchus, Thalassinoides, Hexaphyllia, and spinose productoids.

1.7-4.0 m

10-30 cm thick, cream wackestones and thin calcareous mudstones. Coarse crinoidal debris laminae common. Crinoids, strophomenids, spinose productoids, ostracods, fenestellids, and Aulophyllum fungites common in the limestones.

4.0-8.5 m

medium to thin, grey, slightly argillaceous biomicrosparites. Bedding surfaces wavy, gradational, showing signs of boudinage. Limestones separated into nodular lumps. Sequence extensively bioturbated
throughout; particularly Zoophycus and Chondrites. Fossils: A. fungites, Caninia, zaphrentoids.

8.5-9.2 m

thick, cream and blue-grey micrite wackestones and mudstones. Upright, probably in situ Lithostrotion junceum horizon. ?Thalassinoides amongst L. junceum.

9.2-10.5 m

medium, grey argillaceous wackestones gradually passing downward into laminated calcareous mudstones. Extensively bioturbated. Few whole fossils. Eomarginifera longispina.

10.5-12.1 m

calcareous mudstones and thin argillaceous biomicrosparites. The proportion of carbonate decreases steadily downward. Fossils: Eomarginifera, serpulids, ostracods, Chondrites.

12.1-14.2 m

uniform grey, non-calcareous, carbonaceous shale. Fauna abundant, concentrated along laminae, consisting of Aviculopecten, small spinose productoids, Lingula, ostracods, zaphrentoids, and Productus. Plant debris laminae and brittle, black tonsteins become more common toward bottom.

14.2-15.3 m

green, laminated, calcareous tuff. Sand-size altered ? volcanicogenic fragments and very fine shell debris laminae.

15.3-17.2 m

gradual downward transition into black, non-calcareous, unfossiliferous shale. Plant debris abundant.

17.2-18.2

thin, fine-grained quartz sandstone with evenly disseminated rootlets.

18.2-19.2

olivine basalt lava, top metre extensively altered, brownish red to
purple (?), haematite stained and calcite veined. Feldspars and phenocrysts replaced by kaolinite.

19.2-20.7 m

less weathered, black vesicular olivine basalt. Phenocrysts (1-2 mm diameter) of: olivine; round fractured crystals surrounded by alteration rims of chlorite or replaced by calcite or spherulitic chalcedony feldspar; large polysynthetically-twinned oligoclase or andesine, augite; rare, twinned euhedra. Groundmass consists of feldspar, clinopyroxene, and opaque minerals. Vesicles filled with calcite, quartz and rarely zeolites.

Note: The log of a water borehole which appears on the 1898 1:10560 geological map records approximately 11 m of mixed sandstones and tuffs in 300 m north of the site of borehole 2. The difference in thickness between the 1898 borehole and that logged here suggests that the thickness of the basal sandstones and tuffs is very irregular.
Petrographic notes from Borehole 3, Petershill Reservoir, mid-reservoir NS 9851 6955.

Borehole begun 11 m from the top of the Reservoir Mbr.

0.0-1.5 m

20-30 cm thick, grey, argillaceous and slightly argillaceous biomicrosparites and slightly thinner calcareous mudstones. Bedding boundaries gradational, showing signs of boudinage. Limestones are extensively bioturbated: Zoonhycus, Chondrites, irregular meandrine (type 3) burrows, and faecal trails. Limestones predominantly composed of fine (mm sized) skeletal debris: corals, brachiopods, bryozoa, and sponges common. Macrofauna rare, concentrated at tops of limestones: Gigantoproductus, and solitary Rugosa.

1.5-4.0 m

Gradational transition into calcareous mudstones and thin argillaceous biomicrosparites. Thin laminae of black shale appear, along with rare green tuffaceous clay horizons.

4.0-7.1 m

Transition to black carbonaceous shale with thin sapropelic spore-rich laminae, coals, plant debris, and tuffaceous green clay (?tonsteins). Shale uncemented, swells and disaggregates when placed in water. Fossils: Lingula.

7.1-7.7 m

Thin tuffaceous sandstone followed by green tuff.
Petrographic notes from Borehole 4, southern end of the Petershill Reservoir, NS 9850 6945.

1.0-1.2 m

Light cream to buff, in places blue-grey, layered wackestones and mudstones with brecciated areas and stromatactoid cavities (rare). Sequence is poorly bedded. Fauna diverse and abundant, concentrated at horizons, consisting of: fenestellids, Lituotubella, spinose productoids, Entomoconchus, heterophyllid corals, and juvenile solitary Rugosa (very rare).

1.2-2.7 m

Marked clastic parting at 1.2 m, underlain by 10-21 cm thick, grey biomicrosparites and thin grey calcareous mudstones. Lithostrotoion colonies common between 2.0-2.7 m, alternating with coarse skeletal (mainly brachiopod) debris. Limestones contain abundant delicate fragments: foraminiferans, bryozoans, sponge spicules. Trace fossils include irregular, indistinct burrows, and Chondrites. Calcareous mudstones contain less abundant fauna and a higher percentage of skeletal debris.

2.7-3.6 m

20-30 cm thick L. junceum biomicrosparites interbedded with thin, argillaceous biomicrosparites and calcareous mudstones. L. junceum colonies contain Thalassinoides burrows.

3.6-4.6 m

Medium thickness, grey slightly argillaceous biomicrosparites and argillaceous biomicrosparites. Limestones are grey to cream, with occasional diffuse blue-grey patches. Branched filamentous algae pervasive throughout limestone matrix, shells extensively bored. Sparsely fossiliferous, dominated by spinose productoids. Abundant microproblematica: Kamaena, Shartymophycus.
4.6-4.8 m
	ransitional change to grey, laminated calcareous mudstones, largely unsorted.

4.8-4.9 m

thinly bedded, nodular, cream micrite wackestones with clotted fabrics. Trace fossils; Chondrites, ?Thalassicoides.

4.9-5.7 m

transitional change into black, carbonaceous shales and calcareous mudstones. Shales have an abundant, diverse fauna of bivalves, productoids, ostracods, and plant fragments. Mudstones are laminated or indistinctly bioturbated, containing Rugosochnetes, L. junceum, Antiquatonia, and zaphrentoids. Shales become more prevalent and darker towards bottom, as oily horizons, thin coals, and plant debris laminae become more common.
Petrographic notes from

Borehole 5, Silvermine NS 9912 7161

Borehole begun at top of Reservoir Mbr.

0.0-3.1 m

black to dark grey, slightly calcareous mudstones, extensively silicified. Poorly-sorted, thin shell debris laminae distributed evenly throughout. Occasional thin argillaceous biomicrosparites.

3.1-5.0 m

10-30 cm thick grey slightly argillaceous biomicrosparites and thinner calcareous mudstones. Limestone fauna sparse: Dibunophyllum, Naticopsis, chonetoid brachiopods. Extensively indistinctly bioturbated throughout.

5.0-6.0 m

medium to thick, grey, argillaceous and slightly argillaceous biomicrosparites alternating with medium thickness, black, calcareous mudstones. Beds increase in thickness downwards. Extensive indistinct bioturbation throughout. Fossils rare.

9.1-11.0 m


11.0-13.1 m

dark grey to black, argillaceous wackestones and calcareous mudstones gradually giving way to slightly calcareous mudstones. Extensively bioturbated. Shell debris horizons and rare in situ fauna, consisting of: zaphrentoid corals, Gigantoproductus, spirifers and chonetoids.
Note: Cadell (1925, p. 375) gives the following section from inside the Hilderstone Silvermine, nearby:

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<td>14-18 m</td>
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<td>28-40 m</td>
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<td>40-50 m</td>
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<tr>
<td>50-140</td>
<td>? tuffs.</td>
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*1 I have corrected Cadell's figures for tectonic dip, 20:270.
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Pull numbers are recorded on cores, stored in Edinburgh University Geology Department
Borehole 2, Petershill Lime Works

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<td>24' 10&quot; - 25' 5&quot; cored.</td>
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### Borehole 4, Petershill Reservoir.

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<th>Distance drilled in.</th>
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<tr>
<td>2</td>
<td>3 11</td>
<td>19</td>
<td>23</td>
<td>6&quot; added to 2</td>
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<td>5</td>
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<tr>
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<td>18 7</td>
<td>56</td>
<td>77</td>
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</tr>
</tbody>
</table>

### Borehole 5, Silvermine.

3 boreholes were sunk at Silvermine Quarry. The first two reached depths of 5 and 4.2 m before fouling. The third reached a depth of 11.7 m. The core was logged at the drill site by writing the depth reached on the core as it came out of the barrel. This method differs from the one I employed previously, and it was therefore not possible to tabulate the drilling data for these holes as shown for the others.
Appendix C
Clay Mineral Analysis

Procedure

Representative samples of the common lithologies were selected for insoluble residue and clay mineral analysis. A description of the petrology and coarse insoluble residue fraction (>64μ) appears in Appdx F. The samples were treated as follows for clay mineral analysis:

1. **Disaggregation** - Where possible, samples were crushed into centimetre-sized fragments. Silicified samples, sandstones, and indurated siltstones had to be powdered using a Tema disc mill, as other methods of disaggregation failed.

2. **Acid treatment** - The carbonate fraction of all samples was removed by treatment with 30% (by volume) of acetic acid, followed by several rinses in distilled water.

3. **Size fractionation** - The coarsely crushed samples were separated into >35, 200-35, and 200-240 mesh size fractions for microscopic examination (q.v. Appdx F), the <240 mesh (64μ) being retained for clay mineral analysis. After separation the <64 fraction was air dried and weighed to within ±0.01 gm.

4. **Iron oxide removal and dispersion** - Amorphous grain coatings and iron oxide cements were removed from the <64 fraction following the techniques of Mehra and Jackson (1960). After several rinses, samples were dispersed in distilled water to which a few drops of Calgon (sodium hexametaphosphate) in solution were added, followed by ultrasonic treatment for at least 10-15 minutes. This treatment was carried out to ensure that clay mineral grains had been re-separated and adequately dispersed after air drying.

5. **Size fractionation** - The <5μ fraction was selected for analysis as a compromise between not size separating and analyzing the <2μ
fraction commonly examined by oceanographers and soil scientists. In a detailed analysis of clay mineral procedures, Archer (1969) concluded that size fractionation should be avoided if possible, but that it was sometimes necessary in order to resolve clays from the masking effect of quartz. The advantage of separating the <5\mu fraction is that it is more representative of the entire sample and virtually all the <5\mu material may be separated with ease, avoiding possible error from subsampling (i.e. examining only a small proportion of the <5\mu fraction). An estimated 89% of the <5\mu material present was separated in the course of four successive sedimentation fractionations (q.v. Archer 1969).

6. Mounting - Basally orientated, (001) reflection, mounts of <5\mu fraction were prepared by evaporating drops of a dilute suspension of sample onto a porous, unglazed bathroom tile, heated to 90\degree C. The orientation of these samples was further improved by covering the coated tile with a glass slide and squeezing it in a hydraulic press (1 ton/1 minute). The effect of this treatment was to lower background slightly and increase peak intensity and resolution (e.g. Fig. C-1).

7. Operating conditions - Samples were scanned at ½\degree/minute using Ni-filtered Cu-K radiation, generated at 36 Kv and 20 Ma. First batches of samples were analyzed with a Phillips 1010/1050 wide-range goniometer, later changing to a Phillips PW19 65/40 curved carbon crystal monochromator. Filtering slits were changed from 1\degree dispersion, 1\degree scatter and 0.1\degree receiving to ½\degree dispersion, ½\degree scatter and 0.1\degree receiving. These new scanning conditions and equipment enhanced clay mineral peak resolution, particularly in the 4-8\degree 20 range.

8. Treatments - Several standard sample treatments, applied before and after mounting, helped to identify the various clay mineral groups present.
Figure C-1

Effects of squeezing.

Tracings of X-ray diffractograms showing how applying pressure to samples improves their orientation and, hence, the clarity of their X-ray trace. A shows 14 and 20° peaks of U - an orientated sample and S - the same sample squeezed under 1 ton/1 minute. Horizontal lines underneath show background intensity of 20 for each sample. B shows effects of squeezing on a poorly-defined 7.1° kaolinite peak, U - orientated, A - squeezed 1 ton/1 minute, B - 5 tons/1 minute. Although longer squeezing times enhanced orientation further still, tiles frequently shattered.
U : Untreated - basally orientated samples were maintained at a relative humidity of 56%, maintained by keeping them in a dessicator containing several grams of Ca(NO₃)₂·4H₂O, in order to equilibrate samples.

G : Glycolated - samples were placed in an atmosphere saturated with ethylene glycol at 90°C for a minimum of 6 hours to test for expansion of smectite.

H : Hydrochloric acid - samples were boiled in 6N hydrochloric acid in order to remove chlorite.

DMSO : dimethyl sulfoxide - samples were exposed to an atmosphere saturated in dimethyl sulfoxide at 85°C for 24 hours. This creates a kaolinite-DMSO complex with a d(001) at 11 Å, allowing distinction between kaolinite and chlorite.

K : Potassium hydroxide - samples were saturated in potassium hydroxide solution for 15 hours, heated for 1 hour at 90°C, rinsed and dried. This technique has been used by various authors (Weaver 1958; Walkden 1972) to measure the amount of K⁺ uptake of illite/smectite and hence, to distinguish volcanically-derived smectites from those formed by weathering of muscovites.

H : Heating - samples were heated to 350°C to collapse illite/smectites and to 550 or 625°C to destroy kaolinite. In most samples heating to 550°C was sufficient to destroy kaolinite.

Results

Residues from Petershill Fm. contained varying proportions of illite/smectite, kaolinite, chlorite and (2M) muscovite associated with quartz, feldspar, anatase, dolomite and small amounts of pyrite and gypsum. Many of the criteria employed to identify these minerals are well known and need not be repeated in detail (q.v. Carroll 1970; Walkden 1972).
Illite/smectite - This mineral is identifiable from the presence of reflections at ~10Å and at 5.0, 3.35, 2.5 and 1.5Å. In untreated samples (U, Figs. C-2; C-3; C-4; C-5), the illite/smectite (001) peak is round, crowned, or asymmetrical, occurring between 10-11Å. On glycolation the peak typically splits into two, at ~9.9 and ~11.9Å. Heat treatment and KOH saturation result in an incomplete collapse of this structure to form an asymmetrical peak in the 10.1-10.7Å region. The responses of this mineral to these treatments suggest it to be a mixed layer clay composed of illite and smectite layers, derived from the weathering of volcanic material. The marked displacement observed in the 10Å peaks towards the smectite (001) would suggest that a high proportion of expandable layers are present.

Peak positions in untreated and glycolated samples are variable (Table C-6) largely due to the types of associated minerals. Samples containing large amounts of chlorite (e.g. Fig. C-5) typically have a crowned peak in the 10-14Å range with maxima corresponding to illite, smectite and chlorite (001) reflections. Where large amounts of discrete illite are likely to be present (e.g. in clastic rocks) the 10Å peak is well-defined, asymmetrical and near the illite (001) at 10Å. In these samples it appears that the relatively high proportion of discrete illite may have displaced the illite/smectite peak somewhat. The effect of illite is more difficult to discern than that of chlorite, however, because the degree of expansion of illite/smectite is also variable (q.v. Table C-6).

Kaolinite - This mineral is identifiable by the presence of basal reflections at 7.1, 4.48, 4.39, 3.76, and 3.58Å. Treatment with DMSO expands the structure, shifting the (001) reflection to ~11Å (Figs. C-2; C-4), was a useful means of distinguishing kaolinite from chlorite. Heating to 550°C destroyed the kaolinite structure in the Petershill Fm. samples (Fig. C-5; Table C-6).
Figures C-2 to C-5 X-ray diffractograms from various lithologies.

These tracings illustrate the appearance of the more common clay mineral assemblages and their responses to various treatments. Abbreviations: U - untreated; G - glycolated; DMSO - dimethyl sulfide oxide saturated; K - potassium hydroxide treated; 550 - heated 550°C/1 hr. All peak positions given in Angströms. C-2 shows appearance of a limestone residue, almost exclusively composed of illite/smectite with a small amount of chlorite. Illite/smectite appears as a round peak at 11 Å which expands on glycolation into two peaks at 11 and 9.5 Å. Another illite or illite/smectite peak appears at 4.4 Å followed by a smaller quartz peak at 4.2 Å. Anatase and chlorite form a minor peak at 3.5 followed by a large combined quartz and illite peak (Q).

Fig. C-3 shows a diffractogram tracing of a clay wayboard predominantly composed of illite/smectite and kaolinite. Note that peak intensities of the acid-treated, glycolated sample are so much greater than those of the untreated sample that a small amount of chlorite could be present. Relatively large amounts of chlorite can be detected by the change in the shape of the U peak at 10-12 Å - Fig. C-4, a diffractogram tracing from the prominent tuff at S. Mine Lime Works. DMSO treatment of such samples clearly resolves kaolinite and chlorite. Note shift of kaolinite to 11 Å on treatment, leaving chlorite at 7.1 Å (arrow).

The black shale shown in Fig. C-5 contains large amounts of illite/smectite, kaolinite, chlorite (arrow) and minor amounts of quartz and anatase.
Fig C-5  BLACK SHALE 318
Chlorite - Chlorite displays a series of reflections at ~14 Å and at 7, 4.7, and 3.5 Å, which are unaffected by glycolation. Boiling in 1N HCl did not always remove chlorite, while boiling in 6N HCl succeeded in always removing it, possibly with some kaolinite. The relative insolubility of the Petershill Fm. chlorite suggests that it is well-crystallized.

Where large amounts of chlorite are present (e.g. Figs. C-1; C-5) a discrete peak is resolvable in the 14 Å position. Small amounts of chlorite are more difficult to resolve, as the 14 Å peak is masked by the illite/smectite combined (001) peaks. DMSO treatment was found to be the most effective method for detecting chlorite, but the technique often destroyed the tile. The other widely practised technique, acid treatment, succeeded in removing chlorite, but, unfortunately, it also enhanced the trace in general. Many samples yielded better traces after HCl treatment, even where it was likely that a small amount of chlorite had been removed. Archer (1969, p 77) attributed the improvement to further removal of grain coatings and amorphous material from the sample. Thus it was difficult to compare untreated and acid treated samples for peak area losses due to the disappearance of chlorite. By combining several techniques, however, it was usually possible to distinguish between kaolinite and chlorite.

2M mica (muscovite) - Megascopic flakes of mica were present in many residues (q.v. Appdx F). Diffractograms from these flakes (picked out by hand) showed typical 2M (h, k, l) reflections at 3.7, 3.51+3.49 (doublet), 3.18, and 3.09 Å. The presence of these peaks was then used to identify 2M micas in traces from randomly-orientated mounts of samples from throughout the sequence.

Significance of clay minerals - A comparison of the areas of the (001) peaks provides a general idea of the relative amounts of clay
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<th>Sample</th>
<th>Weight (g)</th>
<th>Clay Minerals</th>
<th>Accessory Minerals</th>
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**Notes:**
- K: Kaolinite
- C: Chlorite
- Note: The table includes weights and additional minerals present in the samples. The table is incomplete and requires further data to be filled in.
Notes:
Blank = not recorded; Dash (-) = absent; areas measured in vernier units; peak positions given in Angströms.

1. Treatment abbreviations
   U - untreated orientated sample, 56% R.H.; R - randomly orientated;
   G - glycolated; H - boiled 1 min in HCl;
   H 6N - boiled 1 min in 6N HCl; DMSO - dimethy sulfoxide treated; K - potassium hydroxide treated; 550 + 625 - heated for 1 hour.

2. 14Å Peak
   P - peak position. Peaks described as:
   S - sharp; C - crowned; B - broad; As - asymmetrical; D - well-defined; R - round. A - area of peak.

3. 10Å Peak
   P - position; symbol beneath position denotes that a single peak has split on glycolation into two. A - area.

4. 7.1Å area
   Area in vernier units of 7.1Å.

5. 3.5 area
   Area in vernier units of peak(s) at 3.5Å, Db = doublet, comprised of 3.50 + 3.57 peaks usually belonging to kaolinite and anatase.

6. Clay minerals and accessory minerals
   Top line lists clays in order of relative abundance (based on areas). K - kaolinite; C - chlorite; I/S - illite-smectite; I - illite; 2M - mica. Second line lists accessory minerals, Q - quartz; F - feldspar; A - anatase; D - dolomite.
<table>
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<tr>
<th>SAMPLE</th>
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\*1 P = present. Presence indicated by h, k, l's.
minerals present. The area of a clay mineral peak is widely accepted as reflecting the amount of clay present. In the past, many attempts have been made to quantify the differences in the amount of clays present in an assemblage by applying weighting factors in order to compensate for differences in the diffractive ability of different clay species. In this study no such attempt was made because it was impossible to separate illite/smectite, discrete illite, and muscovite, or to compare samples subjected to different treatments and analytical methods.

In order to be able to examine trends in composition, the areas of the 10\(\bar{A}\) illite/smectite and the 7\(\bar{A}\) kaolinite-chlorite peaks were recorded (Tables C-6; C-7). In some cases the 3.5\(\bar{A}\) kaolinite-chlorite peak was also recorded. The ratio of illite/smectite to kaolinite+ chlorite was determined from the relative areas of the 10 and 7\(\bar{A}\) peaks. The kaolinite to chlorite ratio was then estimated from a comparison of DMSO or heat treated samples at 7 or 3.5\(\bar{A}\). Peak area measurements are listed in Table C-6. This same data is shown in Table C-7, expressed in percentage form.

The results of this analysis suggest that volcanogenically-derived illite-smectites are by far the most prevalent clay minerals present throughout the sequence (Table C-7). They are the dominant clays in all lithologies, thus suggesting that local volcanism was a source of sediment throughout the Petershill Fm. depositional history. In a regional study of the Carboniferous of the Midland Valley (which sampled from horizons equivalent to the Petershill Fm.), Wilson, Bain, McHardy and Berrow (1972) did not find illite/smectites elsewhere in the Lower Limestone Group. They (ibid, p 142) found kaolinite to be the dominant clay mineral in limestones from other parts of the basin. This would strongly suggest that the illite/smectites of the Petershill Fm. are
derived from the local volcanics.

As might be expected, the local sediment contribution is most apparent during periods when the extrinsic sediment influx was relatively low (i.e. during limestone-forming periods, Table C-7). In the sandstones and shales of the Petershill Fm. (which presumably accumulated during periods of higher extrinsic sediment influx) the local volcanic input appears to have been diluted by kaolinite, 2M mica and, perhaps also by chlorite.

The origin of the chlorite is somewhat problematic, however. It does not appear to be present in the limestone samples, perhaps suggesting that the chlorite is allochthonous. The presence of chlorite could have been missed, as these samples were among the first analyzed. Chlorite was found in all samples analyzed in the latter part of this study, which raises the possibility that the distribution of chlorite is an artifact of the methods employed in analysis. Chlorite, particularly in small amounts, is notoriously difficult to detect, especially in the presence of illite/smectite and kaolinite. Wilson et al. (1972) did not report chlorite from elsewhere in the Midland Valley, which could suggest that the Petershill Fm. chlorite is locally-derived, associated with weathering of the volcanics. However, they could have failed to find chlorite for the same reasons that it may have been missed in this study. Thin sections of weathered lavas from the Bathgate Hills show that alteration to chlorite is a common weathering pattern. Thus, while it seems likely that the chlorite present in the Petershill Fm. sediments is of local origin more precise analyses on the limestone residues and of samples from elsewhere, need to be carried out before this suggestion can be adopted without some reservation.
APPENDIX D

GLOSSARY OF COMMONLY USED TERMS

Note: Terms with possibly ambiguous meanings are defined here; definitions of other terms in the text can be found in Bathurst (1971) and Chilingar and Bissell (1967).

ASSEMBLAGE - a group of fossils occurring along a bedding plane or within a bed. Several types of assemblages are common in the Reservoir Mbr. limestones: a) hydrodynamic - transported or moved from place of origin; b) residual - winnowed, i.e. the matrix and smaller elements have been removed; c) life-surface - an undisturbed assemblage, implying rapid burial; d) cumulative - successive life surfaces concentrated at a single horizon; and e) aggregative - behaviourally formed assemblages. These terms are defined more fully in Miller (in prep.).

BAND - a concentration of fossils spreading along a plane within or at the surface of a bed.

BIOMICROSPARITE - (q.v. Folk 1962) used to describe both wackestones and packstones where original depositional texture cannot be ascertained, or where both occur with equal frequency.

BRECCIA - an accumulation of angular fragments, larger than sand-size.

CAVITY - a megascopic hole or opening within the matrix, which may be empty, partly or wholly infilled with sediments.

DISSOLUTION - the taking up of a substance by a liquid with the formation of a homogeneous solution, in this case referring to the action of meteoric water on carbonates. Although technically less correct, "solution" has been employed in describing karst features on discontinuity surfaces because of common usage.

EROSION SURFACE - a non-genetic term describing any horizon along which erosion can be seen to have taken place.

HORIZON - the stratigraphic position of a layer or bed within a sequence.
HYDROGRAPHIC ZONES - foreshore - the zone lying between mean high and low water marks; shoreface - the next zone offshore, between the mean low water mark and the limit of strong wave action, usually marked by a change in slope; nearshore - including both foreshore and shoreface zones; inner shelf margin - a broad nearshore zone on the Florida carbonate platform, extending from the keys across an area of nearshore shoals, patch reefs, and hardgrounds to the reef ridge, which divides the inner and outer shelf margins.

LAYER - a laterally-traceable thickness of sediment which is distinguishable by grain size or fauna from adjacent layers.

SPECIES/FAUNA - the fossils of a unit are described as a) dominant - most abundant in the number or bulk, synonymous with predominant; b) ubiquitous/cosmopolitan - occurring in many facies; c) characteristic or diagnostic - particular to one or rarely two facies/substrates, useful in recognizing the facies/substrate in question.
APPENDIX B

EXPERIMENTS WITH RECENT CARBONATES

This appendix describes several of a series of experiments designed to investigate the textural and mass properties of Recent, fine-grained carbonates. The sediment employed was a poorly-sorted, mixed carbonate sand and mud, taken from Florida Bay, Florida (kindly supplied by Dr. T. P. Scoffin) consisting of *Penicillus* and *Halimeda*-derived mud, variably-sized skeletal sand debris, and a few organic fragments, mainly derived from *Thalassia* and mangroves. In the experiments, the sediment was dispersed in normal salinity sea water (courtesy of Dr. E. R. Sholkovitz) into a rectangular glass vessel measuring 18.7 cm length x 9.0 cm width x 30 cm height (Fig. E-la).

**Experiment 1** Rapid, episodic sedimentation and simultaneous framework accumulation. Figure E-1b.

Cm-sized pieces of curved plastic mesh (the type commonly used for sieving) comparable in size to the larger fenestrules of the bryozoans encountered in the Reservoir Mbr. limestones were employed to simulate ancient bryozoan fronds, (Fig. E-1b). The sediment was dispersed rapidly and evenly into the vessel and allowed to settle. Each pulse resulted in the accumulation of a mm-thick laminae, graded from sand to clay (Fig. E-1b). Each laminae blanketed the pre-existing sediment surface, evenly covering its features.

Pieces of curved mesh were introduced at irregular intervals in order to see how they would affect the texture of the accumulating sediment (see Fig. E-1b). Mesh fragments were not in three dimensional contact. A minimum of 10 hours was allowed to lapse between sedimentation intervals.

Sedimentation by this mechanism resulted in the building up of a
laminated and graded fabric showing various characteristics that might be attributable to algal binding (Fig. E-1b). The mesh had little effect on accumulation patterns, other than to introduce an uneveness to the sediment surface. Cavities did not form beneath the mesh.

The irregularity of the surface did, however, lead to the accretion of wavy, bulbous laminae, with small breaks and cutt-off laminae similar to those commonly described from algally bound sediments. Parts of many laminae were inclined at surprisingly steep angles to the horizontal. The importance of this experiment is that it demonstrated that intermittent, rapid sedimentation, over an uneven surface, is itself the only necessary requisite for the accumulation of such a fabric. The stabilizing influence of algal filaments is not necessary. The grading observed in the laminae presented here might be an obvious means of distinguishing algal and sedimentation-produced lamination. These particle size differences are, however, fairly small, and could be obscured by recrystallization. This type of lamination is generally comparable to the layering observed in some of the packstones in the Reservoir Mbr. high-carbonates (q.v. Ch 7). Although Reservoir Mbr. layered fabrics do possess abundant filamentous algae, these experiments point to a possible alternative mechanism for their genesis.

Experiment 2 The effects of disruption during sedimentation.

In experiment 1 the vessel was not disturbed while the sediment was allowed to build up. In experiment 2 the vessel was tilted (up to 12°), tapped by hand, and occasionally rocked during and after sedimentation. Minor rocking and tapping had little effect on the overall fabric of the accumulating sediment. Tapping on the side of the vessel while it was inclined at an angle of 12° (a minimal figure for depositional slopes in the Petershill Fm. limestones) had a very
interesting effect. While no immediate effect was visible, within 5-10 minutes after tapping, small cavities could be seen to form at the interface between the coarser sand-sized sediment (accumulated by rapid fallout) and the thin, much finer mud above (accumulated over many hours/days from suspension fall-out). Differential movement along this boundary by plastic flow created a series of subhorizontal cavities measuring $1.0-1.5$ mm in height and a few centimetres in width. These cavities, of tear origin, were somewhat similar, although smaller, than the early parts of stromatactoid cavities. They only formed in the uppermost two or three laminae of the sediment, at the boundary between the rapidly-settled and suspension-settled sediment.

When the vessel was returned to the horizontal for subsequent sediment addition, the cavities were closed by loosely-packed material from the cavity walls. These cavities might have been maintained open if: the vessel had been kept tilted, the suspension fall out layer had been allowed to stabilize for longer, or if a stabilizing mechanism (algae or early cementation) had been present.

Experiment 3  Attempts at producing intraclasts.

Sediments which had been allowed to sit for several months were disturbed in various ways in order to examine whether loose sediment clods, similar to the crumbly-edged intraclasts found in the Reservoir Mbr. could be formed. All experiments were carried out underwater, without allowing the sediment to dry. Various kitchen implements were used to dig into the sediment and lift off scoops and slices. Although it was found that the sediment had consolidated into a firm plastic, none of the digging around produced discrete, clod-like fragments of sediment that would remain intact after a long period of gentle rocking. It was concluded that the degree of consolidation reflected
in the intraclasts in the Reservoir Mbr. limestones was greater than that of this sediment, and that such intraclasts were therefore probably lithified contemporaneously.

Experiment 4  Sedimentation into a pre-existing framework.

Many of the details and results of this experiment have already been described in Chapter 8.

Sediment was introduced in rapid, short pulses into a pre-existing framework of mesh (shown in Fig. E-1a). The amount of sediment in each pulse was much smaller than that in previous experiments, with the result that the degree of grain segregation (grading) and lamina thicknesses were much smaller. A culture of mucilaginous algae (presumably a mixture of red and blue-green filaments, algal unicells and diatoms) taken from the Firth of Forth, was introduced into the sediment at the outset of this experiment. The culture took hold quickly and spread to cover the top sediment surface and the side of the vessel nearest the sun. This thin algal film was allowed to re-establish itself between sedimentation pulses.

The resultant fabric was examined in detail by freezing the sediment, extracting it from the vessel, and sawing it into blocks. The sides of some of these blocks are shown in Fig. E-2.

Point counts of the negatives from photographs of the block faces revealed that the meshwork only constituted 11% grain bulk (1321 points), a figure comparable with that commonly reported for the bryozoan content of ancient rocks with stromatactoid cavities. Moreover, the spacing between fronds (see Fig. E-2) as seen on the block faces, was such that they could easily be missed as framework formers in thin section.

The fabric resulting from sedimentation into a pre-existing framework produced a series of isolated cavities similar in size and
disposition to the early elements of stromatactoid cavities in the Reservoir Mbr. limestones.

These cavities, their genesis, and significance are described in Ch 11. A second, unexpected result, derived from observations on the manner in which the cavities had been infilled. The floors of some of the shelter cavities were often inclined at angles of up to 30° to 40° to the horizontal (Fig. E-2a,c).

In ancient sediments such cavity floors are commonly used as geopetal structures in order to determine palaeoslope. In calculating palaeoslope it is assumed that the floor of a primary cavity was originally horizontal and that the difference in inclination between the geopetal structure and bedding can be used to infer the sense and amount of palaeoslope.

The results of these experiments, however, indicate that the floors of cavities within a framework may not always be reliable geopetal structures. It is unlikely, however, that the inclined floors produced in situations analogous to those described here would have a consistent orientation. Thus sediment floors which can be shown to be consistently orientated (by the use of statistical analysis) may still be regarded as reliable geopetal structures.
Fig. E-1 Experiments with Recent carbonate sediments.

a. The vessel in which the various sedimentation experiments were carried out. Width of vessel = 18.7 cm. Coarse plastic mesh, simulating a bryozoan depositional framework has been placed inside, prior to Experiment 4.

b. The results of experiment 1. A regular laminated fabric built up of laminae grading from sand to mud sized particles. Note discontinuous laminae, bulbous upward-rounded and inclined lamina.
Fig. E-2 Experimental stromatactoid cavities.

All figures show results from Experiment 4, scale bars show centi-metre divisions. Rather irregular criss-crossing lines are due to ice crystals.

a. Steeply-dipping laminae beneath mesh showing that sediments infilling into mesh framework may have a high angle of repose. Each lamina represents a sedimentation pulse.

b. Small cavities developed in the shelter of flat pieces of mesh and at T-intersections.

c. A steeply-inclined infilling beneath a frond. Note that cavities are only developed beneath a few of the fronds.

d. Stacked fronds creating multiple, isolated cavities. Note how susceptible to collapse the whole fabric would be if meshwork were to partially dissolve. Note also the high angle of inclination in some infillings.

e. Cavities developed in the shelter of flat pieces of mesh, and at T-intersections. Needle at left points to unfilled skeletal (gastropod) sheltered void.
APPENDIX F
INSOLUBLE RESIDUES FROM THE PETERSHILL FORMATION

Note: The first part of this appendix is a description of specimens selected for acid dissolution, before and after treatment. Petrographic descriptions are based on thin sections, peels and hand specimens. The residues are described as they appeared under a binocular microscope and from SEM studies of selected elements (Figs. F-2, F-3).

The specimens described here comprise a representative sample of the common lithologies in the Petershill Formation.

The second part of this appendix lists these samples in stratigraphical order, showing their percentage of insoluble material, estimated percentage clay (where applicable), and dolomite. Procedural comments on how these figures were derived follow.

Samples 1205, 1204, South Mine Lime Works, collected 15.7 and 15.4 m above intermember boundary, at base of exposure.

Petrology

Both samples are fine-grained quartz sandstones, with thin silt and organic laminae. They show plane and small-scale cross-lamination. Sand grains are overgrown, such that original grain parameters are not determinable. Heavy minerals (rare) are very-well to well-rounded. Minor constituents include: large mica flakes, organic debris, yellowish altered ?volcanogenic sand grains, and pyrite. Chalcedonic quartz, calcite, and opaque Fe-oxide cements are patchily distributed.

Residue

Samples contained so little carbonate that acid treatment failed to disaggregate the rock. Samples were therefore crushed; consequently the residue was not described.
Samples 1203, 1202, 1201, South Mine Lime Works, collected 8.0, 7.0, 6.0 m above base of exposure, the intermember boundary.

Petrology

All three samples are laminated, black siltstones, predominantly composed of terrigeneous mud, organic detritus, and quartz silt, with prominent parallel sand and mica laminae. Depositional structures are obscured in 1202 by indistinct burrowing.

Residue

The sample had to be mechanically crushed, therefore residues were not examined microscopically (see above).

Sample 1200, South Mine Lime Works, collected 3.35 m above the base of exposure.

Petrology

A grey, in places yellow to blue-grey, calcareous tuff. Largely textureless, consisting of uniformly disposed clay, and intergrown calcite. Some samples contain distinct laminae of subangular, brown clasts of probable volcanic origin or laminae of fossils (foraminiferans and brachiopod fragments are identifiable).

Residue

Residue consists almost entirely of clay and chalcedonic quartz replaced skeletal and volcanic fragments, euhedra of ?apatite, and pyrite framboïds.

Sample 320, South Mine Lime Works, collected 2.4 m above the base of exposure.

Petrology

A fine-grained quartz sandstone with minor proportions of organic detritus, mica, and pyrite. No obvious depositional textures. Chalcedonic quartz and calcite cemented.
Residue

The sample was mechanically crushed.

Sample Se 194, Petershill Reservoir, south end, 1.9 cm above base.

Petrology

A cream coloured, slightly brecciated, layered wackestone. Fabric consists of alternate fragment-rich and lime mud layers, a few mm's thick. Layers are generally parallel and even in thickness, with rare erosional truncations. Skeletal debris (less than 1 mm) consists of bryozoans, brachiopods, crinoids and ostracods. In situ fossils include productoids, chonetoids, and attached foraminifers.

Residue

1. Authigenic quartz- predominant, approximately 60% of residue, occurring as: a) cryptocrystalline chalcedonic quartz replacements of matrix, often preserving algal filaments; b) skeletal replacements of the more commonly occurring fossils; c) 100-200μ doubly-terminated quartz euhedra.

2. Pyrite- common, approximately 10% of residue, occurring as: a) loose frambooids and linear chains of crystals, probably overgrowths or replacements of algal filaments (e.g. Fig. F-3b); b) skeletal replacements particularly of bryozoans (Fig. F-3e), and thick-shelled brachiopods.

3. Phosphatic fragments- very rare, perhaps 1% of residue, in the form of: round grains of unknown origin, faecal pellets (Fig. F-2e), and ? apatite crystals.

4. Heavy minerals - very rare: four fine sand size ? zircon grains.
Sample Sq 500, South Quarry, laterally equivalent to build-up flanks, 180 cm above base exposure.

Petrology.

A dark olive-grey, argillaceous biomicrosparite, showing extensive, indistinct bioturbation and Zoophycus. Fauna is rare, sparsely and evenly distributed, consisting of: chonetoid brachiopods, ostracods, spirifers, and fenestellid bryozoans. Both body fossils and Zoophycus show signs of compaction. Matrix consists of argillaceous microspar and pseudospar (30-45% grain bulk) in places extensively replaced by chalcedonic quartz. The percentages of fine skeletal fragments vary considerably, depending on degree of bioturbation.

Residue

The sample did not disaggregate due to extensive matrix replacement by chalcedonic quartz. Residue consisted of cm-sized chunks of spongy-textured chalcedonic quartz and piecemeal shell replacements. Organic matter and pyrite were trapped in these fragments, occurring as detritus and frambooids respectively. The sample contained enough hydrocarbon produce an oily film on the surface of the acid during dissolution.

Sample Se 119, South end, Petershill Reservoir. 4.5 m above base exposure

Petrology

A cream-coloured, unsorted crinoidal packstone. Matrix consists of variably-recrystallized microspar, often showing piecemeal clotting. Filamentous algae visible in parts. Large areas of matrix and parts of fossils replaced by chalcedonic quartz. Fossils (40% grain bulk) consists predominantly of crinoid columnals, concentrated in mm-cm thick layers. Crinoidal layers alternate with Schellweinella-rich layers, which have been compacted into broken, plate-like fragments. Many
inter-particle voids are unfilled with matrix. Commonly occurring fine fragments include: bryozoans, siliceous and calcareous sponges, productoid spines, and brachiopods.

Residue
The sample was too extensively silicified to disaggregate to the point that its residue could be examined.

Sample 100, from south end Petershill Reservoir, 80 cm above base of exposure.

Petrology
A 4 cm thick clay wayboard horizon. The top and bottom of clay are reddish-brown, while middle 3 cm are olive to cream or blue-grey. The clay is very pasty, containing little or no silt-sized debris. Fossils are fairly common.

Residue
1. Pyrite - predominant, approximately 95% of coarse residue, occurring as spherical framboids.
2. ?Apatite - yellowish euhebra almost certainly of apatite.
3. ?Wulfenite - euherdal plates, up to several hundred microns across, showing crystal habits and a lustre typical of wulfenite.
4. Authigenic quartz - replacements of skeletons.

Note: Although sample 100 was the only wayboard analysed in detail, several others were dissolved, and their residues examined after sieving. Several such samples contained rounded, detrital quartz silt, suggesting that at least some wayboards are of detrital origin.
Sample Se 72, from south end of Petershill Reservoir, 10 cm below top of borehole 4.

**Petrology**

An extensively brecciated lime mudstone with a diverse, in situ fauna. The primary depositional fabrics are largely obscured by brecciation. Undisturbed parts of sample show well-defined layering, consisting of fragment-rich layers (up to 60% fragments of sand size) and lime-mud rich layers (with as little as 10-15% grain bulk of fragments). Predominant fragments are: bryozoans, brachiopods, ostracods (Entomocochus), bivalves, and sponge spicules. Fragment rich-layers are poorly-sorted; some of microfauna, e.g. Tetrataxis and Lituotubella are in life attitudes, attached to the surfaces of laminae. Dolomite replacement rhombohedra are common, occurring concentrated along laminae.

**Residue**

1. Authigenic quartz - predominant, approximately 90% of residue, consisting of cryptocrystalline replacement of matrix, incorporating dolomite rhombohedra, algal filaments and void-filling mega-quartz;
2. Dolomite - abundant, 28% of residue, occurring as: a) replacement rhombohedra; b) anhedral microspar/pseudospar sized crystals.

Sample Se 200, south end, Petershill Reservoir, 2.5 m above base.

**Petrology**

A cream coloured biomicrospar with a few cm-sized blue-grey intraclasts. Intraclasts are not in three-dimensional contact. The cream matrix (65% grain bulk) consists of uniform, in places swirly or clotted microspar. Fine, unsorted, skeletal debris common including sponge spicules, productoid spines, and fragments of echinoderms, ostracods, bivalves, trilobites, and bryozoans. Sediment encrusting foraminiferans
are also common: *Tetralexis* and *Litocubella*.

Residue

1. Authigenic quartz occurring as cryptocrystalline chalcedonic quartz replacements of the matrix and skeletal fragments.

**Sample Se 5006**, south end Petershill Reservoir, 340 cm above base.

Petrology

A dolomitic laminated packestone with wavy, mm-thick wispy laminae of sub-hedral (50μ) dolomite pseudospar. Fossils (75% grain bulk) are largely fragmented, belonging to (in order of abundance): productoids, echinoids, crinoids, ostracods, calcareous sponges, other brachiopods, and bryozoans. Fossils show slight signs of compaction.

Residue

1. Authigenic quartz - predominant, 70% of residue, occurring as cryptocrystalline chalcedonic quartz replacement of the matrix and fossils, mainly brachiopods and bryozoans.

2. Dolomite - approximately 10% of residue, in the form of:
   a) 100-250μ zoned euhedra with calcite cores; staining reveals that outer zones are more iron rich;
   b) dolomite pseudospar, presumably derived from the laminae.

3. Pyrite - rare, occurring as:
   a) framboïds; b) loose octahedra; c) skeletal replacements.

**Sample 557 Sq**, from South Quarry, 60 cm above base of sequence at erosion surface A.

Petrology

Blue-grey stromatactoid cavity packstone with poorly-sorted fragments (mean size .12 mm, range up to .33 mm) of fenestellids, *Hyalostelia*, ostracods (87% disarticulated, valves oriented convex downward),
Stacheoides cf. meandriformis, gastropods, Ectuberitins, productoid shells and spines, spirifers, bivalves, calcisponge spicules, echinoid spines, echinoderm plates, Fistulipora, and trilobite thoracic segments. Allochems show a slight preferential orientation parallelizing the indistinct layering seen in the matrix. Matrix consists of clotted micrite, in places recrystallized to microspar. Stromatactoid cavities present throughout, as well as less than 1 mm sized primary shelter cavities (beneath overturned shells).

Residue
1. Authigenic quartz - predominant, approximately 75% of residue, consisting of:
   a) black to brown irregular platy fragments of clay and organic held together by cryptocrystalline chalcedonic quartz. The absence of detrital clays or argillaceous partings from thin sections suggest these fragments are a burrow infilling;
   b) skeletal replacements of filamentous algae (e.g. Fig. F-2), sponges (Fig. F-2b) and brachiopods.
2. Pyrite - rare, occurring as loose frambois and filamentous algal infillings.

Sample Ls A, from the east bank, Petershill Reservoir, 30 cm below the top limestone.

Petrology
An olive grey-brown wackestone with abundant, in situ solitary corals. Matrix consists of uniformly recrystallized microspar, showing signs of extensive indistinct bioturbation. In situ fauna include: Gigantopproductus, Antiquatonia, terebratulids, spirifers, and ostracods. Most allochemical debris is less than 3 mm, consisting of fragments of brachiopods, crinoids, ostracods, bryozoans, and foraminiferans.
Residue

1. Authigenic quartz - predominant, occurring as:
   a) cemented fragments of matrix, skeletal replacements of corals, productoid spines, ostracods and other shells,
   b) void filling mega-quartz.

2. Pyrite - rare, occurring as loose framboïds and algal filament infillings.

3. Phosphatic fragments - rare, in the form of conodonts and shell fragments.

4. Dolomite - very rare, occurring as replacement euhedra.

Samples LsD and LsE, Petershill Reservoir, east bank, 25 and 50 cm below LsA

Petrology

Both samples are slightly argillaceous foraminiferan-filamentous algal wackestones. Matrix, 40% grain bulk, consists of microspar, with loosely interwoven filamentous algae, partially enveloping small particles and occasionally showing a preferential sheet-form habit. Algal and depositional fabrics are largely destroyed by bioturbation. Allochems are dominantly less than 1 mm fragments of coral, brachiopod, sponge, bryozoans, dasycladaceans, ostracods and trilobites. Predominant whole fossils include ostracods (80% disarticulated, 50% of disarticulated shells convex up), and small foraminiferans.

Residue

1. Authigenic quartz - predominant 70-90% residue in the form of:
   a) cryptocrystalline chalcedonic quartz replacing matrix,
   b) fossil fragments.

2. Pyrite - abundant, in the form of:
   a) 10-15μ cylindrical replacements of algal filaments,
b) incomplete skeletal replacements of commonly occurring fossils, and c) coarse, polycrystalline framboids, approximately 200μ in diameter.

3. Organic matter - common, in the form of:
   a) soluble hydrocarbon found floating on the surface of the sample during iron oxide removal;
   b) fragments of spores and plant debris, and
   c) clear and brown filaments of probable algal origin.

4. Galena - very rare, occurring as microscopic cubes and octahedra.

Sample LsF, Petershill Reservoir, east bank, 25 cm below LsE.

Petrology

A slightly argillaceous bioturbated packstone. Allochems (70% grain bulk) are less than 1 mm, consisting of fragments of productoid spines, thin-shelled brachiopods, Lithostrotion, ostracods, sponge spicules, foraminiferans, bryozoans, productoids and rare crinoids and Kamaena. Whole allochems include foraminiferans (endothyrids, small plectogyral forms, ammodiscids, tubular and spherical attached forms), ostracods (90% articulated, most aligned nearly parallel to bedding), and gastropods. The matrix is indistinctly bioturbated throughout. Slight compactional re-orientation of flat fragments is observed in matrix, but most grain contacts are only slightly sutured. Ostracods and foraminiferans show slight compactional deformation. Matrix consists of uniform pseudospar and clay. Hydrocarbons are present in interstices between the mosaic of pseudospar crystals giving them unusually dark boundaries. Heating a thin section to 400°C removed the organic matter, lightening the colour of thin sections considerably.
Residue

1. Authigenic quartz - predominant 60%, occurring as cryptocrystalline chert replacements of matrix and skeletal fragments.

2. Pyrite - abundant, in the form of:
   a) 200μ euhedra; b) loose framboids; and c) algal filament infillings, approximately 30μ diameter.

Sample LsH, Petershill Reservoir, east bank, collected 50 cm below LsF.

Petrology

A slightly argillaceous unsorted lime mudstone. Uniform matrix (80%) consists of pseudospar, 50-150μ diameter, mean 70μ. Allochems, (approximately 20 grain bulk) are mostly fragments less than .7 mm in diameter, consist of Lithostrotion junceum, productoids, thin shelled brachiopods, and solitary corals. Whole shells include small foraminifera and ostracods. Chalcedonic quartz replacement of both matrix and shells is extensive throughout.

Residue

1. Authigenic quartz - predominant, consisting of:
   a) cryptocrystalline chert replacement of the matrix;
   b) fibrous chalcedony replacements of matrix and skeletal fragments,
   c) chert replacing skeletons of Lithostrotion, siliceous hexactinellid sponges, bryozoans, and algal filaments.

2. Pyrite - common, in the form of:
   a) skeletal replacements of sponge, bryozoan and Lithostrotion fragments;
   b) geopetal floors in the dissepiments and tabular chambers of Lithostrotion;
   c) algal filament infillings.
   d) less than 200μ loose framboids.
3. Phosphatic matter - rare, occurring as fragments of conodonts, serpulids, vertebrates and coarsely ribbed plates of indeterminate origin.

4. Organic matter - rare, occurring as:
   a) shiny fragments of ? plant origin lacking ornament
   b) trilete spores and ? algal unicells
   c) laminae of coalified amorphous material.

Sample LsJ, collected from the east bank Petershill Reservoir, 25 cm below LsH, lowest limestone in top excavation.

Petrology

Extensively bioturbated, grey wackestone. Multiple generations of burrows obliterate depositional textures. Common burrows include Zoophycus, type 5 burrows, and faecal trails. Matrix consists of uniformly recrystallized microspar. Skeletal debris (40% grain bulk) is dominantly less than 1 mm in diameter, consisting of corals, gastropods, productoid spines, brachiopod shells, foraminiferans (particularly Earlandia, Eostafella, and Archaediscus), ostracods (80% of shells disarticulated) and crinoids.

Residue

1. Authigenic quartz - predominant, occurring as shell and matrix replacements; very little matrix replacement (therefore estimated percentage clay is likely to be accurate).

2. Pyrite - common, as loose frambooids and skeletal replacements and filamentous algal infillings 50-60µ diameter.

3. Phosphatic fragments - very rare.
Sample 300, Petershill Reservoir, borehole 3, at surface.

Petrology

An argillaceous wackestone, showing signs of extensive indistinct burrowing later crosscut by Zoophycus. Wavy clay laminae present throughout, except where disrupted by bioturbation. 40% skeletal debris less than 1 mm, dominantly endothyrids, biserial forams, ostracods; rare bryozoans and gastropods; very rare crinoids. Matrix composed pseudospar and microspar. Both allochems and matrix are extensively recrystallized.

Residue

1. Authigenic quartz – predominant, occurring as:
   a) grey fragments of cryptocrystalline chalcedonic quartz binding together clay laminae, allochems, and preserving moulds of allochems;
   b) skeletal replacement of brachiopod spines, sponges and bryozoans.

2. Pyrite – rare, loose frambooids and skeletal replacements.

3. Organic fragments – rare, in the form of:
   a) Colourless or straw coloured filaments of probable algal origin;
   b) black, vase-shaped, spores and broken lustrous fragments of plant matter.


5. Dolomite – very rare, occurring as corroded (possibly by treatment) zoned euhedra.
Sample 301, Petershill Reservoir, Borehole 3, 33 cm.

Petrology

Grey wackestone; matrix consists of uniform microspar, showing extensive, indistinct bioturbation. Burrows lack definable boundaries but concentrate shell debris. Allochems 20% grain bulk; mean size less than 2 mm, consisting of bryozoans, foraminiferans, small productoid spines, ostracods (mostly articulated), and corals.

Residue

1. Authigenic quartz – predominant, approximately 60% of residue, occurring as:
   a) irregular fragments (still in the form of the original sample before acid dissolution). Such fragments are cryptocrystalline chalcedonic quartz replacements of the former microspar matrix. Pyrite infilled branched algal filaments, near 18μ diameter, are intergrown throughout many fragments.

2. Chalcedonic quartz replacements of feldspars (Figs. F-1; F-2) common, approximately 20% of residue. Replaced crystals are sand-size, probably formerly orthoclase. Most replacements were of single prismatic crystals approximately 250μ long, with an a:b axial angle of 63° (Fig. F-1). Simple (010) Carlsbad contact twins are common (Figs. F-1; F-2). All crystals are euhedral, lacking signs of transportation. One exceptional crystal (Fig. F-2) had grown around an organic walled filament, almost certainly of algal origin. Most crystals are completely replaced; a few are partially intergrown with kaolinite.

3. Chalcedonic quartz replacements of small skeletal fragments – common.

4. Pyrite – common, approximately 5-10%, occurring as: 20-50μ size framboids, and elongate clusters (Fig. F-2b) possibly overgrowths
of filamentous algae.

5. Organic matter - rare, approximately 8% of residue, occurring as: spores, brown or black, shiny fragments, and straw-coloured filaments, similar to those intergrown with feldspar crystals (see Fig. F-1).

6. Phosphatic fossils - very rare, consisting of: conodonts and ribbed fragments of ?fish scales.

7. Dolomite - very rare, consisting of loose euhehedral crystals.

Sample 307, Petershill Reservoir, borehole 3, 144 cm below surface.

Petrology

Medium grey, laminated argillaceous biomicrospar wackestone, showing signs of compaction throughout: completely compacted delicate fossils, slightly deformed thick-shelled fossils, pseudostylololites, and pressure solution enhanced intergrain boundaries. Matrix consists of fairly uniform 20\(\mu\) diameter microspar. Skeletal fragments (24% grain bulk) are largely less than 1 mm diameter, and consist of: foraminiferans (particularly endothyrids), brachiopod, bryozoan, and coral debris, and ostracods (50% articulated, predominantly concave-up). Obvious signs of bioturbation were absent, but could have been present, obscured by re-arrangement of compactional fabric.

Residue

1. Authigenic quartz - predominant, in the forms of chalcedonic quartz replacements of the matrix, often binding together clays, and skeletal fragments.

2. Pyrite - rare, occurring as loose frambooids.

3. Organic matter - rare, in the form of black fibrous fragments (e.g. Fig. F-3a) and hydrocarbons which floated on acid during dissolution.
Samples 308 and 312, borehole 3, taken from the 1.6 m and 2.0 m level respectively.

Petrology

Both are laminated argillaceous wackestones, showing prominent compactional laminae. Translational movement (evidence of intrastratal flow) has drawn fossils out plastically along some laminae. Signs of compaction are extensive throughout; even in robust shells, such as endothyrid foraminferans. Skeletal debris, predominantly less than 1 mm in diameter, comprising 30-40% grain bulk, consists of: a) fragments of bryozoans, corals, and ostracods, and b) whole, compacted, ostracods, gastropods, foraminferans. An exceptional spine encrustation of Stacheoides cf. meandriformis suggests that the small insitu productoids found in sample lived epifaunally. Matrix consists of uniform microspar, clays, and pyrite, with intergrown algal filaments (30μ in diameter).

Residue

1. Authigenic quartz - predominant, occurring as a matrix replacement binding together fragments of transported detritus and replaced shells.
2. Organic detritus - common, in the form of hydrocarbons, shiny black spores (Fig. F-3f), blocky ribbed fragments (F-3a), and algal filaments.
3. Detrital quartz - very rare, consisting of a few sand-size grains.
Samples 316, 317 and 318, borehole 3, Petershill Reservoir, collected at 5m, 5.5 m, 5.8 m respectively.

**Petrology**

All three samples are black carbonaceous shales showing well-developed fissility. Most specimens swell and disaggregate when placed in water; only very limited areas are cemented at all. Matrix is largely composed of clay, and organic detritus (ribbed fragments (e.g. Fig. F-3a), spores (e.g. F-3e), clearly identifiable parts of plants (e.g. F-3c,d), and coalified fragments). Fossils, comprising a variable 10-40% grain bulk in the laminae where they are present, consist of *Eomarginifera*, spirifers, bivalves, ostracods, foraminifera, and sponge spicules. A few laminae were covered in paired, horizontally-orientated *Lingula squamiformis*. Most macrofossils appeared to be in situ, however, laminae consisting of fragments were also present. The fossils only occur in discrete laminae, seldom exceeding a few millimetres in thickness. Most of each specimen is unfossiliferous.

**Residue**

1. Authigenic quartz - predominant in sample 316; organic matter is predominant in the others. Quartz occurs in the form of micro-crystalline chalcedony, binding together other insoluble elements of matrix.

2. Organic matter - in the form of hydrocarbons, and organic detritus. The proportions of both forms increase markedly downward.

3. Pyrite - abundant, also increasing downward between samples, in the form of loose polycrystalline aggregates and shell replacements, particularly of inarticulate brachiopods (Fig. F-2f).

4. Detrital quartz - sand and silt sized quartz grains, restricted to a few laminae.

5. Dolomite - very rare, in the form of a few euhedra, only occurring in 316.
Figure F-1  The commonly occurring crystal habits of authigenic feldspar crystals obtained from insoluble residues from the Reservoir Mbr. Limestones

G1. 46,5496
Fig. F-2  SEM photographs of the common insoluble residues from
the Reservoir Mbr. limestones.  9.1. 46.547 D

a. Plant fragment: note medial suture, which suggests that fragment
may have been calamitid.
Scale bar = 72μ.

b. Siliceous sponge microsclere. The axial hollow provides evidence
that the microsclere originally belonged to a siliceous sponge.
The microsclere is preserved as a chalcedonic quartz replacement.
Scale bar = 74μ.

c. Authigenic feldspar crystal. A single prismatic crystal of an
authigenic feldspar, replaced by chalcedonic quartz.
The euhedral habit and engulfed organic filament (almost certainly
of algal origin) provide evidence of authigenic origin for the
crystal.
Scale bar = 43μ.

d. Close-up of filament engulfed by former authigenic feldspar.
Scale bar = 13μ.

e. Phosphatic faecal pellet.
Scale bar = 260μ.

f. Pyrite-replaced ribbed shell, probably belonging to an inarticulate
brachiopod.
Scale bar = 250μ.
Fig. F-3  SEM photographs of the common insoluble residues from limestones and shales in the Reservoir Mbr.  

a. Coarsely-ribbed plant fragment, and fine-grained organic debris typical of black shales.  
Scale bar = 100μ.

b. Elongate cluster of octahedral crystals, probably formed by overgrowth on algal filament.  
Scale bar = 24μ.

c.+d. Well-preserved plant fragment, note that stomata are present (close-up F-2d).  
F-2c scale bar = 74μ; F-2d scale bar = 24μ.

e. Pyrite internal mould replacement of a trepostomatous bryozoan, probably a form similar to Tabulipora.  
Scale bar = 67μ.

f. Slightly compacted spore, showing surficial ? fungal infestation.  
Scale bar = 44μ.
Part II - Percentages of insoluble residue in the samples analysed.

Note on procedure

Samples were first cleaned of surface dirt, then dried and crushed into approximately 1 cm sized fragments. 30% acetic acid was used to dissolve samples. Non-calcareous samples, and silicified samples which did not react, were removed from the acid, rinsed, and powdered using a jaw crusher and a tema. Their insoluble residues were not examined visually as they did not contain sedimentologically valuable information.

For ease of examination, residues were separated by wet sieving, as shown on Table F-4. The less than 240 mesh fraction was sub-sampled for clay mineral analysis.

Estimated percentage clay

This calculation was made in order to provide an approximate estimate of the percentage of detrital clay in each sample. It was only performed on limestone samples, as a means of determining a relative measure of their original detrital content. Because nearly all limestones contain significant percentages of chalcedonic quartz occurring as a matrix replacement, it was impossible to be assured that all the clay-sized material had been freed during acid treatment. Some samples failed to disaggregate at all and therefore their clay contents could not be estimated. This problem is insurmountable in working with slightly silicified limestones. Mechanical crushing (the only other means of reducing a samples particle size) had the disadvantage that it also reduced authigenic quartz to clay-sized particles, thus making it impossible to separate detrital from authigenic constituents. The high proportions of authigenic quartz in some samples account for the high insoluble residue percentages even though these samples were classified as being nearly pure carbonates. Moreover, some of the clay in these samples could be seen to be authigenic, occuring as kaolinite.
void linings. The descriptive term has been applied to the sample as it was when it was deposited, not to its current composition.
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1estimated visually
2weight loss on boiling residue in HCL-calculated as % of sample
3see Table F-5

* = not measured - sample finely ground prior to treatment
- = not determined
blank = not present.
Table F-5 (below) shows how estimated % clay was determined.

\[
\text{TABLE F-5}
\]

\[
\text{SAMPLE} = \text{Carbonate} + \text{Residue}
\]

\[
\begin{align*}
\text{material} & > 240 \\
\text{largely authigenic material:} & \\
\text{chal qtz} & + \\
\text{pyrite} & \\
< 240 \text{ mesh} & \text{largely detrital:} \\
\text{clay, organic matter} & + \\
\text{authigenic material:} & \\
\text{chal qtz} & + \text{pyrite}
\end{align*}
\]

\[
\% \text{ clay} = \frac{\text{wt. Residue} - A}{\text{wt. Sample}} \times 100
\]

The estimated % clay was calculated by subtracting the weight of non-clay residue from the total weight of the residue, and calculating the result as a % of the total weight of the sample. This figure is a maximum for the total amount of clay, as it must also include some authigenic clay-sized chalcedonic quartz, pyrite, and authigenic clay.
APPENDIX G

TRACE FOSSILS FROM THE RESERVOIR MBR.

Note: The first part of this appendix consists of a description of the common trace fossils in the Reservoir Mbr. These traces have been numbered 1-9 for use in subsequent references (e.g. Fig. G-6). The three morphotypes of *Thalassinoides* (numbers 7a, 7b, 7c) were kept separate in order to illustrate that they are consistently found together.

In part II, the results of the comparative test (referred to in text, Ch 5) are given. The ichonofauna of 71 vertically-sliced plaquettes and peels was tallied (Fig. G-6). The relative area bioturbated by each of the trace fossil groups A, B, C (cf. Ch 5) was then estimated on the 33 largest specimens which did not show signs of extensive compaction (Table G-7). Prior to carrying out this part of the study, the actual areas bioturbated by the different trace fossil groups were drawn out and measured accurately with a planimeter on three specimens. The visual estimates of the areas bioturbated on these specimens were found to coincide fairly closely with the actual measured area (±15% area). Thus it was felt that the visual estimates provided an accurate approximation. Note that the areas listed (Table G-7) are only for the last burrowing event. Samples with undisturbed depositional textures, such as layering were considered to be apparently unbioturbated.
Part I  TAXONOMIC DESCRIPTIONS

**Type 1  Sinuous cylindrical burrow**

**Description**  Sinuous cylindrical burrows, 3-4 mm in diameter, appearing in full-relief. Internal structure poorly-defined, probably a meniscus backfilling, similar in colour and composition to matrix. Burrow boundaries indistinct.

**Comments**  Type 1 burrows are only found in carbonaceous black shales.

**Type 2  Indistinct burrows**

**Figs. 5-3; 5-4**

**Description**  A group of burrows, lacking well-defined boundaries and internal structure. Preserved as a swirly texture of laminae similar in composition to matrix, but often containing strings of faecal pellets. External form usually not visible, occasionally round, or upward-domed, mushroom-shaped. Burrows only preserved in full-relief, often exichnial.

**Type 3  Zoophycus  Massalongo 1855**

**Fig. 5-3**

**Description**  Inclined spiral laminae 0.9 mm thick, lobate in plan-view outline, spreading from a vertical axial tube approximately 1 cm diameter. Laminae variably inclined, in some lithologies altered by compaction. Spacing between laminae also variable. Preserved in full-relief.

**Comments**  Zoophycus is the most abundant trace fossil in the Reservoir Mbr. It is a useful index of substrate consistency in itself. In gel substrates, burrows may be traced for a considerable vertical
distance (up to 40 cm), an indication of the depth to which sediments could be penetrated. In argillaceous, gel substrates, laminae arch around burrows, while in plastic substrates, the sediment does not show signs of compaction around the burrow laminae.

**Type 4  Planolites  Nicholson 1873**

**Description**  An unbranched sinuous cylindrical meniscus-backfilled burrow, 8-10 mm in diameter. Burrows are usually orientated subhorizontally. Fills consist of tightly packed, shallow, meniscus-shaped backfillings of concentrated skeletal fragments and clay. Incomplete backfilling often results in a small hole being left in the middle of the burrow. Burrows preserved in full-relief.

**Comments**  It is easily possible to confuse some cross-sections of Zoochicus and Planolites, as both consist of meniscus backfillings. The two can be distinguished, however, as Zoochicus is formed of alternately reworked and undisturbed lamellae (Simpson 1970) whereas the backfills of Planolites consist of entirely reworked sediment.

**Type 5  Loosely backfilled burrows**

**Description**  A group of 1-3 cm diameter variably-shaped, sometimes circular, or branched, burrows appearing in full-relief. Burrow walls are sharp and lack signs of mixing, lining or cracking. Infillings are coarser and more loosely-packed than matrix, often showing meniscate or concentric laminae.

**Type 6  Segmented burrows**

**Description**  Cylindrical, irregularly meandrine, unbranched full-relief burrow, 3 mm in diameter. Tightly backfilled with alternate meniscus-shaped laminae and strings of elliptical faecal pellets; each pellet approximately 250 μ long. The meniscus-shaped laminae are light, whereas the pellets are dark grey, giving the burrow a distinctly segmented appearance.
Type 7  Thalassinodes  Ehrenberg 1944

Thalassinoides paradoxica  (Woodward) 1962
forma minuta (forma nov.)

Figs. G-1 to G-5

Diagnosis  Morphologically similar to T. paradoxica, sensu Kennedy (1967), but smaller in size; tunnels usually near 5 mm external diameter and seldom exceeding 15 mm. Burrow walls may be sediment lined, blue-grey stained (?mucus lined), or entirely unlined.

Holotype  Petershill Reservoir, Bathgate, West Lothian. Viséan age, V₃C.

Introduction  The ichnogenus Thalassinoides and the ichnogenera with which it commonly overlaps, Ophiomorpha and Teichichnus (Frey, Howard and Pryor, 1978) are among the best known environmental indicators from Mesozoic and younger sediments. Thalassinoid burrows have not, however, hitherto been formally described from the Palaeozoic, although several authors have reported their presence or probable occurrence (Chamberlain and Clark 1973; Gutschick and Rodriguez 1977; Morrow 1978). The Reservoir Mbr. specimens are well-preserved and are therefore given a formal description in order to facilitate identification elsewhere, and extend the range of Thalassinoides to the Viséan.

Thalassinoides burrows provide information on substrate consistency as well as being a characteristic element of the level-bedded, high-carbonate biomicrosparrite facies.

The Reservoir Member material consists of three types of burrows (A, B, C; Fig. G-4) usually found together in the same specimen (e.g. Fig. G-2c). Their close association, almost certain intergradation, and morphological similarity with burrows similar to previously-described Thalassinoides, form the basis for concluding that the three burrow types belong to the same ichnogenus.
Figure G-1  General appearance of Thalassinoides paradoxica forma minuta (forma nov.). Photos of holotype.
Traces preserved in convex epirelief, on the undersurface of a bedding slab of Lithostrotion colonies. Prominent burrows have been darkened for emphasis. RSM 1979.1.1

a. Subhorizontal gallery system, general view.

b. Same specimen. Close-up of oversized branching point. Such enlargements are typical of the intersections of several tunnels.

c. Same specimen Y- and T-intersections. The coarse, somewhat ropy exterior appearance of burrow lining is typical of Type A linings.
Description
An irregular burrow system of vertical (usually lined) shafts spreading into sub-horizontal branched tunnels at one or more levels. The sub-horizontal elements, which are both lined and unlined, form a Y- and T-branched system bifurcated at irregular 2-5 cm intervals (Fig. G-1). Parts of tunnels are often swollen, particularly at branching points (Fig. G-1). Branches often much smaller than main tunnels (Fig. G-1).

Shafts commonly 7-20 mm in exterior diameter, usually ellipsoidal or round, extending vertically up to 20 cm. The axial parts of such tunnels often open, approximately 5 mm in diameter. Horizontal tunnels are irregular in cross-section, of similar diameter to shafts, and may extend up to nearly 1 m.

Scratch marks, commonly reported from elsewhere, were not preserved in the Reservoir Mbr. material.

Internal structures
Type A burrows (Figs. G-2b, c; 6-10c, f). Burrow with dark, concentrically laminated sediment lining, usually composed of material more argillaceous than the surrounding matrix. Such linings normally stand out sharply from the matrix because of the higher proportions of incorporated clay. The concentric lamination within the lining (Fig. G-2b) clearly establishes that the sediment has been biologically manipulated. Lined burrows are typically oversized, and only the axial third of a tunnel cross-section is open (Figs. G-2b; G-4). Type A burrows weather preferentially, leaving round or ellipsoidal pockmarks on bedding surfaces (Fig. 9-3a). Such marks are another characteristic means of identifying Thalassinoides.

Comments
Type A burrows are generally similar to Recent shrimp burrow linings described by Shinn (1968) and Braithwaite and Talbot (1972).
Figure G-2 Thalassinoides burrows: appearance on polished plaquettes. All scale bars are 1 cm; vertically orientated rock slices.

a. A Type B burrow among the corallites of a Lithostrotion junceum colony. The wall of each burrow is stained dark blue-grey. Note that the stain decreases in density away from the burrow wall. The infilling consists of cream biomicrospar, similar in composition to matrix, but lacking staining. RSM 1974.1.2

b. Oblique section through a Type B, sediment lined, burrow with an open axial tunnel (spar infilled). Burrow system also developed among Lithostrotion corallites. RSM 1974.1.3

c. Typical appearance of Thalassinoides. At top, a sediment-lined Type A burrow (A) extends sub-vertically and may interconnect with an infilled and broken Type B (B) underneath. The Thalassinoides system appears to have disrupted a Chondrites (C) system. Note that in this, the usual preservation state, T. burrow galleries are not particularly obvious. Note also that a sediment surface encrustation of Fistulipora (F) provides evidence of substrate firmness and stability. Fistulipora growths also form a multiple encrustation on a productoid spine (arrow at left of 1 cm scale bar) indicating that the productoids lived epifaunally on this substrate type. RSM 1974.1.4

d. Type C Thalassinoides burrow, infilled with darker meniscus-backfilled, argillaceous sediment. Arrow points to sharp burrow wall, a sign of sediment cohesiveness. The matrix in which burrow was formed is an infilling in a crack along erosion surface A interpreted as a subaerial discontinuity. These burrows establish the marine origin of the fill. RSM 1974.1.5

e. A re-excavated Type B burrow. Right and left halves of slice through a core are mirror images, each being 2.5 cm in diameter. Several intervals of re-excavation have led to the formation of concentric, blue-grey stained burrow walls (arrow). The core shows a section through a horizontal tunnel and a connection to a vertical shaft (righthand core). RSM 1974.1.7
TyDe B burrows (Figs. G-2; G-3; 5-5; 3-5). Burrows lacking a sediment lining, but rimmed by a blue-grey stain (interpreted as a mucus secretion). This supposed mucus secretion, or lining, is preserved as a blue-grey stain, a few millimetres to a few hundred microns thick, which decreases in density away from the original tunnel wall (Fig. G-3). The stained rim is composed of micrite, denser than the surrounding microspar matrix and often containing a higher proportion of fine-grained pyrite. The stain most often appears to penetrate directly into the matrix, although it has also been found in sediment infillings of the same composition as the enclosing matrix, re-excavated burrows and lining fractures (Figs. G-2; G-3; 3-5). Blue-grey stained sediment fragments are common within Type B burrows and throughout the matrix in which the burrows are found.

These presumed mucus-lined burrows most often form part of the horizontal parts of the Thalassinoides system. They have often become infilled and subsequently been re-excavated, as described in Fig. G-3. Such burrow fabrics are typical of Type B burrows and therefore also of T. paradoxica forma minuta.

The blue-grey stain is likely to have formed where the burrower has forced a cementing mucus into the matrix, or perhaps plastered a mixture of sediment and mucus on the burrow wall. Several authors (q.v. Braithwaite and Talbot 1972; Frey, Howard and Pryor 1978; Elders 1975, p 528; Weimer and Hoyt 1964) have found that Recent Thalassinoides-producing organisms may line their burrows similarly. The stain is clearly of biological origin as it is also found lining the re-excavated parts of burrows (Figs. G-3; G-2e).

Comments Type B burrows show evidence of limited early lithification. Angular fragments of blue-grey stained matrix and the sharpness of the walls themselves indicate that type B walls were very firm
The matrix consists of cream coloured biomicrospar which has been stained blue-grey at the burrow walls (dense stippling). The earliest burrow (1) is infilled with sediment similar in composition to the matrix. A second burrow (2) has been excavated within the infilling in the first, and also has a blue-grey stained wall. Burrow 2 is in turn concentrically lined with sediment, and has an open axial void, which is infilled with sparry cement.

Multiple excavated burrows provide evidence that the blue-grey staining is of biological origin, as it is associated with the former sediment-clearing and stabilizing activities of a burrower.

Note that the stain is denser and thicker on larger tunnels, suggesting they were either occupied for longer or that they required greater strengthening.
In some cases, however, walls have fractured, a sign of brittle consistency. Fracturing can be seen to have occurred while the gallery system was still inhabited, as fractured burrows have been re-excavated and re-lined.

Fragments of blue-grey stained burrows are often rounded, and appear to have been transported. It is likely that such rounded particles are exhumed former burrow linings, similar to those widely reported in present day environments were callianassid shrimp burrows are widespread (Enos and Perkins 1977). Thus type B burrows are closely analogous to Recent callianassid shrimp burrows in that they are sites of early lithification, and form sedimentary particles.

Type C burrows (Figs. G-2; 3-5, G-4; 7-2a). These portions of the Thalassinoides system are entirely unlined, and usually fairly large (8-16 mm), forming sinuous, subvertical shafts. Argillaceous meniscus backfillings are particularly common (Figs. G-2; G-4; 3-5;11-12). The burrow walls and infillings are often slightly dolomitized.

Comments Type C burrow walls provide the most reliable means of determining substrate consistency, as they lack any lining or sign of re-enforcement. The walls are often extremely jagged and uncompacted; a sign that the enclosing substrate was very cohesive.

Occurrence Thalassinoides paradoxica forma minuta burrows are most abundant, best preserved, and typically associated with Lithostrotion junceum colonies that that coalesced to form thickets (q.v. Ch 9).

Discussion The various types of Thalassinodes walls and infillings are shown in Fig. G-4. In order to further ascertain whether these morphologically different types of burrows belonged to the same system, a comparative study was made between burrow types (A, B, C) and infillings (1, 2, 3, 4, 5, Fig. G-4). The results, tabulated below, suggest
Fig. G-4  Thalassinoides burrows: wall types, infillings, preservation.

Generalized illustrations of several aspects of Thalassinoides burrows.

The common wall types (a, b, c) and infilling sediments (1-4) described in text and used in a small comparative study are shown (q.v. Table G-5). Infilling sediments were described as being passively deposited (fills 1, 4), or reflecting the dwelling activities of the burrower (fills 2, 3). Empty (sparry calcite cement infilled) burrows were also present (5). Compaction and disruption by subsequent burrowing often makes it difficult to recognize the original burrow system.
that the common infillings occur with equal frequency in each different type of burrow. The presence of similar types of passive and manipulated infillings in the three wall types confirms that burrows A, B, C do indeed belong to the same ichnotaxon.

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<tr>
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</table>

\[ n = 17 \text{ specimens} \]

Preservation Thalassinoides burrows are seldom preserved intact. Very often they have collapsed or been broken by subsequent generations of burrowing (Figs. G-2; G-4). Plaquettes and thin sections seldom reveal the characteristic morphology of the burrow system. Some Thalassinoides may only slightly resemble a bioturbated fabric (e.g. Fig. G-2c). Thalassinoides burrows do, however, possess distinctive wall structures and contribute recognizable detrital particles. By learning to recognize these products, apart from the burrow system itself, the presence of Thalassinoides may be established elsewhere.

Comparison with previous reports Several elements of the Reservoir Mbr. Thalassinoides are comparable to features observed by previous authors in Recent and ancient burrows. Some of these have already been referred to. In addition, Kennedy and McDougall (1969) found that Cretaceous age Ophiomorpha (a genus intergrading with Thalassinoides) could be lined, meniscus back-filled, or pellet-lined. Although mucous linings identical to those described here have not been reported previously, it is well known that many of the crustaceans
which produce thalassinoid burrows routinely line parts of the gallery
with mucus or a mucus-sediment mixture.

Bromley and Frey (1974) and Frey et al. (1978) have described in detail the morphological and structural variation in the intergrading ichnogenera that produce thalassinoid burrows. Bromley and Frey (ibid) and Frey et al. (ibid) state that the variations within a burrow system are attributable to behavioural adaptations by the dweller to sediment consistency, environmental instability, and burrow purpose (e.g. feeding, dwelling, brooding).

Continually-occupied elements of the system are usually well-maintained and oversized, whereas feeding tunnels are more likely to be ephemeral and therefore susceptible to collapse. Their descriptions of both Recent and ancient thalassinoid burrows suggests that the variation observed in the Reservoir Mbr. Thalassinoides is to be expected in such a multi-purpose burrow.

Originator of the burrow Thalassinoides burrows are commonly attributed to a variety of decapod crustaceans (Bromley and Frey, ibid). These authors have reported that the number of Thalassinoides-producing organisms and the range of environments which they may inhabit is much wider than originally thought. Burrows have been reported in both fresh water and marine environments, in depths to 700 m. Thus the traditional view of Thalassinoides as a reliable circa-littoral indicator has had to be abandoned (Frey et al., ibid).

Environmental interpretation based on Carboniferous Thalassinoides is further complicated because the range of decapods does not extend into the Lower Carboniferous (Glaessner 1969, p 434). Morphologically similar Eocarid shrimps are common in the Midland Valley Carboniferous and of a suitable size to have produced the Reservoir Mbr. Thalassinoides. If such an assumption is warrantable, then Eocarida should be added to
the list of Thalassinoides producers.

A variety of criteria, including the presence of abundant algae, and calcareous sponges, and the position of the facies in the sequence, suggest that the Reservoir Mbr. facies with Thalassinoides formed in a nearshore to shallow offshore environment (Ch 9). The previous reports of a Palaeozoic Thalassinoides (refs. given) have also been interpreted as occurring in shallow water. Although it is premature to draw firm conclusions, it appears that Palaeozoic Thalassinoides burrows, like more modern counterparts, are most likely to occur in shallow marine environments.

Type 8  Agglutinated micritic tube

Description  A cylindrical tube, 3 mm in diameter, with an axial void 1 mm in diameter. Tube fairly straight, orientated near vertical and curved at depth; seldom exceeding 1 cm total length. Tube walls consist of dense micrite agglutinating fine skeletal debris. Preserved in full-relief.

Type 9  Chondrites  Von Sternberg 1833

Figs. G-2, 3-4, 3-5

Description  A small form, 3 mm in diameter, branching downward at irregular intervals. Usually found draft-filled with sediment more argillaceous than matrix. Preserved in full-relief.
Part II  THE COMPARATIVE STUDY

Fig. G-6  The trace fossil composition of 71 specimens, listed in stratigraphical order and grouped by lithology. Light stippling shows the two substrate-related trace fossil groupings.

Table G-7  Estimated percentages of bioturbation. Percentages of each sample by trace fossil groups (A, B, C) shown.
A = indistinct burrows; B = Zoophycus, segmented form, loosely backfilled and cylindrical backfilled forms, and Planolites; C = Chondrites, Thalassinoides, and agglutinated tube.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Lithology</th>
<th>Area sample cm²</th>
<th>Area unbiot'd</th>
<th>Area %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>argill</td>
<td>160</td>
<td>80</td>
<td>0</td>
</tr>
<tr>
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<tr>
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<td></td>
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</tr>
<tr>
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<td></td>
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<td>60</td>
<td>20</td>
</tr>
<tr>
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<td></td>
<td>120</td>
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<tr>
<td>2-1</td>
<td></td>
<td>100</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
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<tr>
<td>10 A</td>
<td></td>
<td>60</td>
<td>60</td>
<td>17</td>
</tr>
<tr>
<td>11 A</td>
<td></td>
<td>60</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>11 B</td>
<td></td>
<td>70</td>
<td>0</td>
<td>70</td>
</tr>
<tr>
<td>10=N</td>
<td></td>
<td>Σ 701</td>
<td>49</td>
<td>31</td>
</tr>
<tr>
<td>E-3</td>
<td>slightly</td>
<td>70</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>argill</td>
<td>65</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>155 Sq</td>
<td>lst</td>
<td>30</td>
<td>0</td>
<td>70</td>
</tr>
<tr>
<td>127 B</td>
<td></td>
<td>70</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>127 C</td>
<td></td>
<td>80</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>125 H</td>
<td></td>
<td>160</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>12 A</td>
<td></td>
<td>35</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>125 G3</td>
<td></td>
<td>120</td>
<td>0</td>
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</tr>
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<td></td>
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<td>35</td>
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<td>85</td>
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<td>133 Sq</td>
<td></td>
<td>144</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>2 Sq</td>
<td></td>
<td>140</td>
<td>0</td>
<td>30</td>
</tr>
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<td>12=N</td>
<td></td>
<td>Σ 989</td>
<td>49</td>
<td>47</td>
</tr>
<tr>
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<td>0</td>
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<td>100</td>
<td>80</td>
<td>0</td>
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<tr>
<td>LLs 5</td>
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<td>180</td>
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<td>10</td>
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<td>90</td>
<td>95</td>
<td>0</td>
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APPENDIX H
BIOSTRATINOMY OF ANTIQUATONIA BANDS

The attitude and articulation ratios of productoids in the high-carbonate biomicrosparite facies and the build-up is shown. Genera examined include Antiquatonia, Eocmarginifera, Dictyoclostus, Pugilis, and Gigantop productus (G. in flanks only). The density was recorded by counting the number of shells with hinge widths greater than 1 cm as they were exposed on at least five 100 sq cm horizontal surfaces. Beds are presented in stratigraphical order. In the build-up, the number of centimetres above the base is additionally listed.
<table>
<thead>
<tr>
<th>Facies</th>
<th>Sample Size</th>
<th>% A</th>
<th>% B</th>
<th>% C</th>
<th>% D</th>
<th>% Artic</th>
<th>% Overt</th>
<th>Density</th>
<th>Comments</th>
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<tr>
<td>a. high-carb bmap</td>
<td>32</td>
<td>43</td>
<td>25</td>
<td>22</td>
<td>10</td>
<td>68</td>
<td>35</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>b. high-carb bmap</td>
<td>81</td>
<td>27</td>
<td>37</td>
<td>23</td>
<td>13</td>
<td>54</td>
<td>50</td>
<td>-</td>
<td></td>
</tr>
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<td>c. build-up - 400</td>
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<td>14</td>
<td>46</td>
<td>13</td>
<td>27</td>
<td>60</td>
<td>73</td>
<td>-</td>
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</tr>
<tr>
<td>d. build-up - 200-300</td>
<td>55</td>
<td>49</td>
<td>34</td>
<td>11</td>
<td>6</td>
<td>83</td>
<td>40</td>
<td>30</td>
<td></td>
</tr>
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<td>e. build-up - 250</td>
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<td>90</td>
<td>3</td>
<td>-</td>
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<td>0</td>
<td>77</td>
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<td>23</td>
<td>77</td>
<td>23</td>
<td>-</td>
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<td>g. build-up - 180</td>
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<td>62</td>
<td>32</td>
<td>3</td>
<td>3</td>
<td>94</td>
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<tr>
<td>h. build-up - 180</td>
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<td>48</td>
<td>38</td>
<td>5</td>
<td>9</td>
<td>86</td>
<td>47</td>
<td>75</td>
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</tr>
<tr>
<td>i. build-up - 130</td>
<td>26</td>
<td>65</td>
<td>31</td>
<td>0</td>
<td>4</td>
<td>96</td>
<td>4</td>
<td>-</td>
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</tr>
<tr>
<td>j. build-up - 100</td>
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<td>100</td>
<td>20</td>
<td>5</td>
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<td>23</td>
<td>27</td>
<td>21</td>
<td>29</td>
<td>50</td>
<td>50</td>
<td>-</td>
<td>infill crack in surface A</td>
</tr>
<tr>
<td>l. build-up - 50</td>
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<td>65</td>
<td>30</td>
<td>0</td>
<td>4</td>
<td>95</td>
<td>34</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>m. flank beds</td>
<td>100</td>
<td>50</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>50</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>n. flank beds</td>
<td>100</td>
<td>30</td>
<td>43</td>
<td>12</td>
<td>15</td>
<td>73</td>
<td>57</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>o. flank beds</td>
<td>70</td>
<td>37</td>
<td>45</td>
<td>13</td>
<td>5</td>
<td>83</td>
<td>50</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>p. flank beds</td>
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<td>12</td>
<td>24</td>
<td>37</td>
<td>27</td>
<td>36</td>
<td>51</td>
<td>-</td>
<td>shell debris beds</td>
</tr>
<tr>
<td>q. flank beds</td>
<td>61</td>
<td>11</td>
<td>20</td>
<td>38</td>
<td>31</td>
<td>31</td>
<td>51</td>
<td>-</td>
<td>shell debris beds</td>
</tr>
<tr>
<td>r. flank beds</td>
<td>91</td>
<td>31</td>
<td>31</td>
<td>16</td>
<td>22</td>
<td>62</td>
<td>54</td>
<td>-</td>
<td>shell debris beds</td>
</tr>
<tr>
<td>s. flank beds</td>
<td>29</td>
<td>44</td>
<td>30</td>
<td>18</td>
<td>8</td>
<td>74</td>
<td>38</td>
<td>-</td>
<td>shell debris beds</td>
</tr>
</tbody>
</table>
APPENDIX I
ANALYSIS OF GEOPETAL STRUCTURES

Introduction

Differences in orientation between geopetal infillings in primary cavities and that of bedding were used as a means of determining palaeo-slope. At two localities, Galabraes Quarry (NS 986 699) and at South Quarry (NS 985 695) the orientation of geopetal structures differed significantly from that of their enclosing beds. The data from these two exposures and their analysis is summarized here. This work was carried out with the guidance of Dr. R. F. Cheeney; a detailed explanation of the methods and formulae employed here appear in Cheeney (manuscript), to which the reader is referred for a fuller explanation.

Many of the statistical calculations were executed with either a programmable calculator, or using the Edinburgh Regional Computing Centre program BINGO. Thus the less significant, intermediate procedural steps have been omitted.

Two types of geopetal structures were measured: a) sediment infillings in the visceral cavities of large brachiopods; b) infillings in the lumen of crinoid columns.

Galabraes Quarry

1. Measurement

Twelve orientation measurements were taken of geopetal structures and their nearest bedding plane (Table I-1, columns C, D). The first geopetal structure and its adjacent bedding plane were re-measured after each measurement in order to establish the accuracy with which measurements could be made (Controls, Table I-1).

2. Accuracy

Bedding control measurements were plotted as poles on a standard stereographic projection net and analysed as a Fisher distribution, as follows:
Table I-1 Measurements of geopetal structures and bedding, eastern face, Galabraes Quarry

<table>
<thead>
<tr>
<th>Controls (replicates of 1)</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bedding</td>
</tr>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>1 08:024</td>
<td>09:224</td>
</tr>
<tr>
<td>3 08:111</td>
<td>09:229</td>
</tr>
<tr>
<td>4 08:204</td>
<td>06:230</td>
</tr>
<tr>
<td>5 09:206</td>
<td>06.5:231</td>
</tr>
<tr>
<td>6 09:206</td>
<td>09:230</td>
</tr>
<tr>
<td>7 09:211</td>
<td>06:228</td>
</tr>
<tr>
<td>8 09:220</td>
<td>08:235</td>
</tr>
<tr>
<td>9 10:105</td>
<td>08:230</td>
</tr>
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<td>07:230</td>
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<tr>
<td>11 09:200</td>
<td>06:220</td>
</tr>
<tr>
<td>12 09:204</td>
<td>08:230</td>
</tr>
</tbody>
</table>

The orientation of bedding and geopetal structures is specified by the angle of dip (2 digits) and dip direction (3 digits - clockwise in degrees from magnetic north).
a. the position each pole was described with respect to north, east, and down (Table I-2, $X_n$, $X_e$, $X_d$).

b. directional cosines were determined in order to derive the mean resultant length $R$; analogous to the Rayleigh test mean resultant employed in testing circular distributions (Table I-2).

c. the concentration parameter, $k$, of the data about $R$ was determined (Table I-2) and used to calculate the angle $d$. The angle $d$ specifies the radius of a cone of confidence on the stereographic projection within which the true mean pole to bedding is likely to be found. In this case, significance was sought at the 0.1 probability level.

d. the bedding data were found to be closely clustered, with a small $2.3^\circ$ angle $d$, indicating that error in measurement was not significant (Table I-2).

3. Mean orientation of bedding

The mean orientation of bedding was calculated by the same method as that used to check measurement accuracy (see above). The data and resultant figures are given in Table I-3, and shown plotted in Fig. I-5, along with the cone of confidence. Data were found to be closely clustered about a mean of 5.3 : 110; with an apical angle of 4.5° (significance sought at 0.1 significance level).

4. Determination of mean geopetal structure attitude

Geopetal structures appear in quarry faces as apparent dips. The chances that the direction of maximum geopetal dip and the strike of a quarry face should coincide are very small. Thus geopetal structures must be plotted as plunge directions on a stereographic projection and analyzed as a Bingham distribution.

The apparent dips (plunges) of geopetal structures plot as a
### Table I-2

**Accuracy measurement test**

<table>
<thead>
<tr>
<th>Control measurements</th>
<th>Replication</th>
<th>Xn</th>
<th>Cn</th>
<th>Xe</th>
<th>Ce</th>
<th>Xd</th>
<th>Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>of bedding</td>
<td>(replicates of 1)</td>
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<td>08 : 024</td>
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<td>08</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>08 : 213</td>
<td>82</td>
<td>86</td>
<td>08</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>08 : 111</td>
<td>87</td>
<td>98</td>
<td>08</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>08 : 204</td>
<td>82</td>
<td>87</td>
<td>08</td>
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</tr>
<tr>
<td></td>
<td></td>
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<td>09 : 206</td>
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</tr>
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<td>09 : 206</td>
<td>82</td>
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<tr>
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<td></td>
<td>7</td>
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<td>09 : 220</td>
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<td>09 : 200</td>
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<td>87</td>
<td>09</td>
<td></td>
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<td></td>
<td></td>
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<td>09 : 204</td>
<td>81</td>
<td>86</td>
<td>09</td>
<td></td>
</tr>
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</table>

\( n = 12 \)

\[
\text{R} = \sqrt{\left(\frac{C_n}{n}\right)^2 + \left(\frac{C_e}{n}\right)^2 + \left(\frac{C_d}{n}\right)^2} = 0.9978 = \text{mean resultant length}
\]

concentration parameter \( k = \frac{1}{1-R} = 454.5 \)

\[ k' = n \ R \ k \]

cone of confidence \( d = \cos^{-1} \left(1 + \frac{\log_e(a)}{k'}\right) = 2.3^\circ \)

\( \log_e(a) = -4.61 \) @ 0.01 significance level.
girdle distribution whose center is the pole normal to the plane of maximum geopetal dip. This pole may be calculated from the girdle distribution itself. Such a distribution is considered to have three principle axes \( t_1, t_2, t_3 \), each of which has an associated principle value \( T \), a measure of the variance about a particular axis. The shortest axis of the distribution, designated \( t_1 \) by convention, corresponds to the pole of the great circle on which the distribution lies. By calculating \( t_1 \) and establishing the relationship between \( t_1 \) and the mean pole of bedding, it is possible to determine original palaeoslope.

The principal axes and the associated principal values of geopetal structures are specified by the matrix \( T \) (Table I-4), which is obtained by pre-multiplying the matrix of the directional cosines (D, Table I-4) by its transpose \( D' \). The eigenvectors of a matrix such as \( D \) correspond with the principal axes of the original distribution, while the eigenvalues specify the lengths of the axes.

The eigenvectors were obtained by successive iterations of an eigenvector value first estimated from the plot of the distribution (Table I-4, B, C). Once the eigenvectors of \( t_1 \) and \( t_2 \) have been calculated it is possible to actually measure \( t_2 \) on a stereographic projection (measured as the direction normal to the plotted solutions for \( t_1 \) and \( t_3 \)). The eigenvalues, \( T_1, T_2, T_3 \), may be calculated by pre-multiplying the eigenvectors by the matrix \( D \). The calculated values are shown on Table I-4, E.

5. Calculation of the cone of confidence about \( t_1 \)

Table I-4 lists the formula for calculating the angle \( a \), the radius of the cone of confidence. Significance was sought at the 0.1 level. Values of the angle \( b \) were chosen so as to facilitate plotting the cone. The values obtained for \( a \) were then plotted in the principal plane of \( t_1 \) and \( t_3 \). These values and \( t_1 \) are shown in Fig. I-5.
Table I-3  Mean orientation of bedding, Galabraes Quarry

<table>
<thead>
<tr>
<th>Measurement, n</th>
<th>X_n</th>
<th>C_n</th>
<th>X_e</th>
<th>C_e</th>
<th>X_d</th>
<th>C_d</th>
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<td>08</td>
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<td>2</td>
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<td>86</td>
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<tr>
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<td>78</td>
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<td>14.5</td>
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<td>88</td>
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<tr>
<td>6</td>
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<td>92</td>
<td>03</td>
<td></td>
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<tr>
<td>7</td>
<td>88</td>
<td>90</td>
<td>03</td>
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<tr>
<td>8</td>
<td>86</td>
<td>83</td>
<td>08</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>9</td>
<td>87</td>
<td>93</td>
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<td>12</td>
<td>90</td>
<td>78</td>
<td>12</td>
<td></td>
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</tr>
</tbody>
</table>

| EC_n | 1.0420 | EC_e | .3817 | EC_d | 11.853 |

R = .9920  
k = 125  
k' = 1488  
d = cone of confidence = 4.5°
Table 1—

Determination of geopetal orientation

<table>
<thead>
<tr>
<th>A. General measurements</th>
<th>( x_e )</th>
<th>( x_n )</th>
<th>( c_e )</th>
<th>( c_n )</th>
<th>( x_d )</th>
<th>( c_d )</th>
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<td>1 09 : 224</td>
<td>135</td>
<td>133</td>
<td>81</td>
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<tr>
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<td></td>
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<tr>
<td>3 07 : 217</td>
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<td>126</td>
<td>83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 11 : 162</td>
<td>199</td>
<td>72</td>
<td>79</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>5 01 : 164</td>
<td>164</td>
<td>74</td>
<td>89</td>
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<td></td>
</tr>
<tr>
<td>6 09 : 163</td>
<td>161</td>
<td>73</td>
<td>81</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 08 : 210</td>
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<td>120</td>
<td>82</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 20 : 214</td>
<td>149</td>
<td>112</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 07 : 207</td>
<td>152</td>
<td>117</td>
<td>83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 16 : 244</td>
<td>115</td>
<td>148</td>
<td>72</td>
<td></td>
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</tr>
<tr>
<td>11 16 : 243</td>
<td>116</td>
<td>148</td>
<td>74</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 09 : 254</td>
<td>106</td>
<td>162</td>
<td>81</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

\[ \text{matrix } D = \]

\[
\begin{pmatrix}
6.86 & 2.666 & -1.786 \\
2.666 & 1.484 & -1.601 \\
-1.786 & -1.601 & 1.012
\end{pmatrix}
\]

\( T = \begin{pmatrix} 5.146 & 2.666 & -1.786 \\ 2.666 & -7.516 & -1.601 \\ -1.786 & -1.601 & -10.988 \end{pmatrix} \)

Estimates of eigenvectors

<table>
<thead>
<tr>
<th>X_n</th>
<th>C_n</th>
<th>X_e</th>
<th>C_e</th>
<th>X_d</th>
<th>C_d</th>
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</thead>
<tbody>
<tr>
<td>86</td>
<td>82</td>
<td>08</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Starting estimate, \( \vec{t}_1 \),

accepted solution, \( \vec{t}_1 \),

\[
\begin{pmatrix}
81 \\
74 \\
18
\end{pmatrix}
\]

C. estimated vector of \( \vec{t}_3 \)

accepted solution, \( \vec{t}_3 \)

\[
\begin{pmatrix}
146 \\
61 \\
87
\end{pmatrix}
\]

D. vector \( \vec{v}_2 \), measured normal to \( \vec{t}_1 \) and \( \vec{t}_3 \)


E. eigenvalues determined by pre-multiplying eigenvectors \( \vec{t}_1, \vec{t}_2, \vec{t}_3 \) by matrix \( T \) (above)

\[
\begin{align*}
\lambda_1 &= 0.2855 \\
\lambda_2 &= 4.4270 \\
\lambda_3 &= 7.3330
\end{align*}
\]
Table 1-4 cont'd.

F. Calculation of zone of confidence - calculation of angle $\alpha$, at 0.1 significance level

Formula:

$$\sin^2 \alpha = \frac{\frac{T_1 - T}{(T_2 \cos^2 \beta + T_2 \sin^2 \beta)}}{\frac{T_1 - T_2}{T_2 \cos^2 \beta + T_2 \sin^2 \beta}}$$

In which:

$$z = T_1 - (\frac{E - \bar{S} \pm 2\bar{E}}{n - 2})$$

$T_2, T_3$ are listed above.

Values of $\alpha$ at specified angle $\beta$ (plotted on Fig. 1-5)

<table>
<thead>
<tr>
<th>$\beta$ (°)</th>
<th>$\alpha$ (°)</th>
<th>$\beta$ (°)</th>
<th>$\alpha$ (°)</th>
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<tr>
<td>30</td>
<td>15.1</td>
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<td>60</td>
<td>10.9</td>
<td>45</td>
<td>11.6</td>
</tr>
<tr>
<td>90</td>
<td>10.5</td>
<td>20</td>
<td>14.0</td>
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<tr>
<td>120</td>
<td>10.9</td>
<td>50</td>
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</tr>
<tr>
<td>160</td>
<td>13.0</td>
<td>110</td>
<td>10.6</td>
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</tbody>
</table>
Fig. I-5  Galabraes Quarry.

A stereographic projection showing: a) orientation of geopetal structures plotted as plunge directions, forming a girdle distribution along a great circle; b) poles of bedding clustered in the middle; c) mean pole of bedding and its surrounding cone of confidence; d) the pole of the geopetal structure distribution \( \hat{\mathbf{t}}_1 \) and its cone of confidence. Note that both the bedding and geopetal data are clustered. The original orientation of bedding has been restored by rotation of the geopetal pole back to horizontal about its strike.

Fig. I-6  South Quarry

A stereographic projection showing a plot of geopetal structure plunges, the orientation of bedding pole (taken from orientated block) and the restored orientation of bedding after rotation about strike of the geopetal structure.
6. Correction for tectonic dip

Correction for tectonic dip was made by rotation of the geopetal structure back to horizontal about the strike of the geopetal. The original orientation of bedding was found to be 16° 081, as shown in Fig. I-5.

South Quarry

1. Measurements.

Data were taken from the flank beds. The exposure itself does not reveal a sufficient number of geopetal structures to provide the necessary data for analysis. In this case a large (45 cm x 45 cm x 45 cm) block was carefully orientated in the field, prior to removal from the outcrop. The slab was serially sectioned vertically in several directions and the geopetal orientation data was measured on the slab surfaces. As in the previous study, only large shell infillings were measured. Bedding was carefully measured and found to be orientated at 16° 256. The geopetal orientation data are listed in Table I-7.

2. Determination of mean geopetal structure orientation

The same statistical analyses were applied to these data as to those described above; in this case the calculations were performed using BINGO. The results of these calculations are shown in Fig. I-6, plotted as $\bar{\xi}_1$ the center of the great circle along which the geopetal plunges are distributed. Note again that geopetal and bedding data are clustered into distinct areas.

3. Correction for tectonic dip

The original orientation of bedding was again determined by moving the geopetal pole back to horizontal by rotation along its strike. In this case the geopetal pole ($\bar{\xi}_1$) was found to be 21° 280. Rotation
back to the horizontal restored bedding to an original depositional orientation of 10 : 144 (Fig. I-6).
<p>| | | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>26 : 348</td>
<td>00 : 180</td>
<td>22 : 348</td>
</tr>
<tr>
<td>04 : 280</td>
<td>24 : 284</td>
<td>10 : 196</td>
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<td>16 : 191</td>
<td>08 : 191</td>
<td>07 : 284</td>
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<td>12 : 327</td>
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<td>04 : 168</td>
<td>25 : 246</td>
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<tr>
<td>18 : 272</td>
<td>24 : 284</td>
<td>37 : 316</td>
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<tr>
<td>07 : 191</td>
<td>14 : 350</td>
<td>08 : 327</td>
</tr>
<tr>
<td>09 : 003</td>
<td>09 : 003</td>
<td>18 : 246</td>
</tr>
</tbody>
</table>

Orientations are listed as dips (two figures) and dip directions (three figures, measured in degrees from magnetic north). They were taken from serial sections of a large block in a bed orientated at 16 : 256. Sample taken from flank beds, mid South Quarry.
APPENDIX J

ORIENTATION OF CRINOIDS IN SUBFACIES C, THE BUILD-UP

The orientation of 88 crinoid stems between 10-65 cm in length were measured from the underside of a bedding surface occurring 260 cm above the base of the build-up facies, i.e. the quarry floor at the southern wall of the Petershill Reservoir. The bedding surface was photographed with a 35 mm Leica orientated on a tripod parallel to the surface, approximately 170 cm away from it. This method was employed because the surface was inaccessible by any other means.

The orientation of crinoid stems was then measured from 25 x 36 cm photographs of the bedding surface. Following Schwarzacher (1963) three types of orientations were plotted: a) "V" and "T" orientations, interpreted as residual orientations or arrangements of stems that had come to rest after rolling a short distance; b) straight stems in possible rolling orientations; c) imbricate "toppled", radial or curving arrangements of stems likely to represent a single crinoid. Imbricate stems show a marked decrease in stem diameter in the direction of toppling.

Results of this study are shown in Figs. 11-9 (text), Table J-1, Table J-2, Fig. J-3 and Fig. J-4.
Table J-1  Azimuth Orientation of V and T stem arrangements

<p>| | | | |</p>
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<td></td>
<td></td>
<td>320</td>
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</tr>
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</table>

Data are listed as azimuths measured in degrees from N. These data are plotted in Fig. 11-9. They do not show a statistically significant preferred orientation.

Table J-2  Orientation, measured in degrees from north of elongate crinoid stems longer than 10 cm.

<p>| | | | | |</p>
<table>
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<td></td>
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<td>170</td>
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</tbody>
</table>

n = 54
R = 0.799  Rayleigh test mean resultant length

Stems show a significant orientation at 0.1 level. Data are shown plotted in Fig. 11-9.
Fig. J-3   Imbricate crinoid stem arrangements.

Stems shown here are an addition to those shown in Fig. 11-9 (text). Each arrangement shown at approximately 1/10th original size. They are described as follows: F) imbricate toppled arrangement decreasing in length toward 345° (arrow); G) imbricate toppled array, no inferrable current direction; H) radial array, no inferrable current direction; I) slightly curved imbricate array; J) imbricate, toppled array, (?) stems decreasing in length toward 210° (arrow); K) radial array, no inferrable direction, stems reach up to 3 cm diameter.
Fig. J-4  Combined data from different stem arrangements.

Superimposition of various types of orientations suggests a northeastward current, although the degree of preferred orientation is not pronounced. This suggests that stem accumulations are poorly sorted and formed in situ.
Palaeogeographical Reconstruction

Positive area or Barrier created by lavas

Nearshore zone

Offshore zone

BASINAL AREA

limit of lavas

lava platform
PETERSHILL FORMATION — cross section

south

Petershill Reservoir

Sunnyside

black micaceous shales and siltstones

massive mod.-well sorted unit A transition to ARRIC

mod.-well sorted cream pl. facies

<table>
<thead>
<tr>
<th>HETEROGENEOUS</th>
<th>MAJOR FACIES</th>
</tr>
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<tbody>
<tr>
<td>CARBONATE</td>
<td>LIMESTONE</td>
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</tbody>
</table>

RESERVOIR MBR.

BASALT LAVA

0 125 m

0 1 2

large scale cross-stratified siltstones

large scale cross-stratified sandstone subfacies

basal level

Knock Hill

SILVERMINE MEMBER

black micaceous siltstones coarsening upwards

BASAL SANDSTONE FACIES

CRINOIDAL PACKSTONE FACIES

SLIGHTLY ARGILLACEOUS LIMESTONE FACIES

CARBONACEOUS SHALE FACIES

MIXED SANDSTONES AND TUFFS

HETEROGENEOUS SUBFACIES

PACKSTONE FACIES

ARGILLACEOUS CARBONATE FACIES

REMEMBER

fossiferous calc. marls

siltifers calc. marls

siltifers calc. marls

argill bmps grading up into argillaceous lmps

tl carlb sh

argill bmps

tl carlb sh