HEAVY MINERAL ANALYSES AND FACIES INTERPRETATIONS OF PART OF THE CALCIFEROUS SANDSTONE MEASURES, PITTENWEEM, E. FIFE, SCOTLAND.

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Being a thesis submitted for the degree of M.Sc. November, 1987.

I, Alasdair E. Robertson hereby certify that this thesis has been composed by myself, that it is a record of my own work, and that it has not been accepted in partial or complete fulfilment of any other degree or professional qualification.

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And I refuse to believe in some of the things that are said to be here, let alone those that are not.

Roy Harper, 1984.

ABSTRACT.

A vertical section of fluvio - deltaic sediments of Dinantian age is exposed along the coast in Fife. These sediments form a series of cycles and cycle types evolving by progradation into a shallow bay area at the eastern end of the Midland Valley. Analysis of the heavy fraction indicates provenance from a variety of rock types comprising the Caledonian Massif. Although certain suites can be identified it is impossible to determine absolutely the origin of the sediment due to transport and deposition effects.

The analysis of the delta cycle patterns shows an increased importance of marine influences towards the top of the section resulting in limestone formation. The measured section shows five distinctive environments of deposition - swamp, splay, channel, overbank interdistributary and lagoon each with their own distinctive types of sediment, structure and sedimentation pattern. The overlying form is of a birdfoot lobate type delta similar to that of the Guadalupe Delta of Texas.

ACKNOWLEDGEMENTS.

I wish to acknowledege the assistance given to me by my colleagues in the Geology Department. In particular I would like to thank Professor E.K. Walton for suggesting the project, J. Allen for assistance with plates and figures, A. Calder and A. Reid for X-ray work, D. Herd for probe analyses and A. Mackie for thin sections and mounting of heavy minerals. The assistance of H. Weir is gratefully recognised for his assistance with the graphics program 'GEOLOG'. My thanks are also extended to my graduate contemporaries P. Leighton, P. Holden, L. Evans, R. Greenwood, J. Reavy, A. Marshall, R. Curry, M. Gillespie, C. Morrison, M. Errington, B. Paterson and also to years of undergraduates for their encouragement and discussions (not necessarily geological), over the odd pint in 'The Crit'. Thanks.

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1 INTRODUCTION.

1.1 INTRODUCTION AND PREVIOUS WORK.

A Calciferous Sandstone succession of Visean age is exposed in Fife along the coast, from St. Andrews in the north to Elie in the south (Fig. 1.1.). About 1230 m. of gently folded sedimentary rocks are visible, but inland a thick mantling of drift material makes correlation of the succession difficult even though there are abundant fossils at some levels, (Kirkby in Geikie, 1902).

These Visean strata assigned to the Calciferous Sandstone Measures, have been described in the Fife region by Geikie (1902), and the Pittenweem marine Band is postulated by Currie (1954) as being of Cracoean (B) age, but the only recent studies of the Pittenweem section are those of Greensmith (1961a, 1961b, 1965), Forsyth and Chisholm (1977) and Belt (1975, 1979, 1981).

In E. Fife the succession was subdivided by Forsyth and Chisholm (1977), and interpreted as follows :-

	Lower Limestone Group (deltaic)
	Pathhead Beds 311m. (deltaic)
	Sandy Craig Beds 550+m. (fluvial)
Calciferous Sandstone	Pittenweem Beds 220+m. (deltaic)
Measures	Anstruther Beds 800+m. (deltaic)
	Fife Ness Beds 240 - 270m. (fluvio - deltaic)
Upper O.R.S.	Balcomie Beds (fluvial with cornstones)

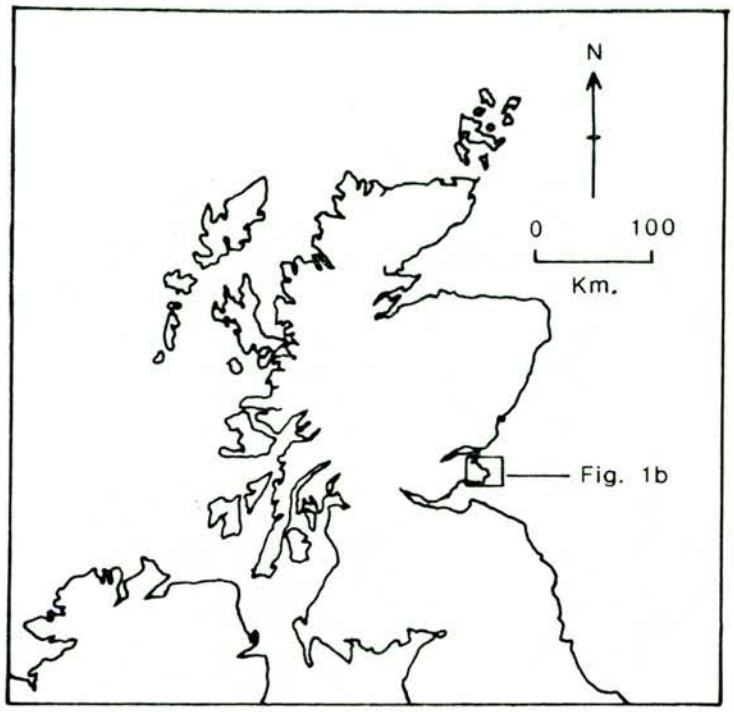

Fig. 1a. Location map of studied area.

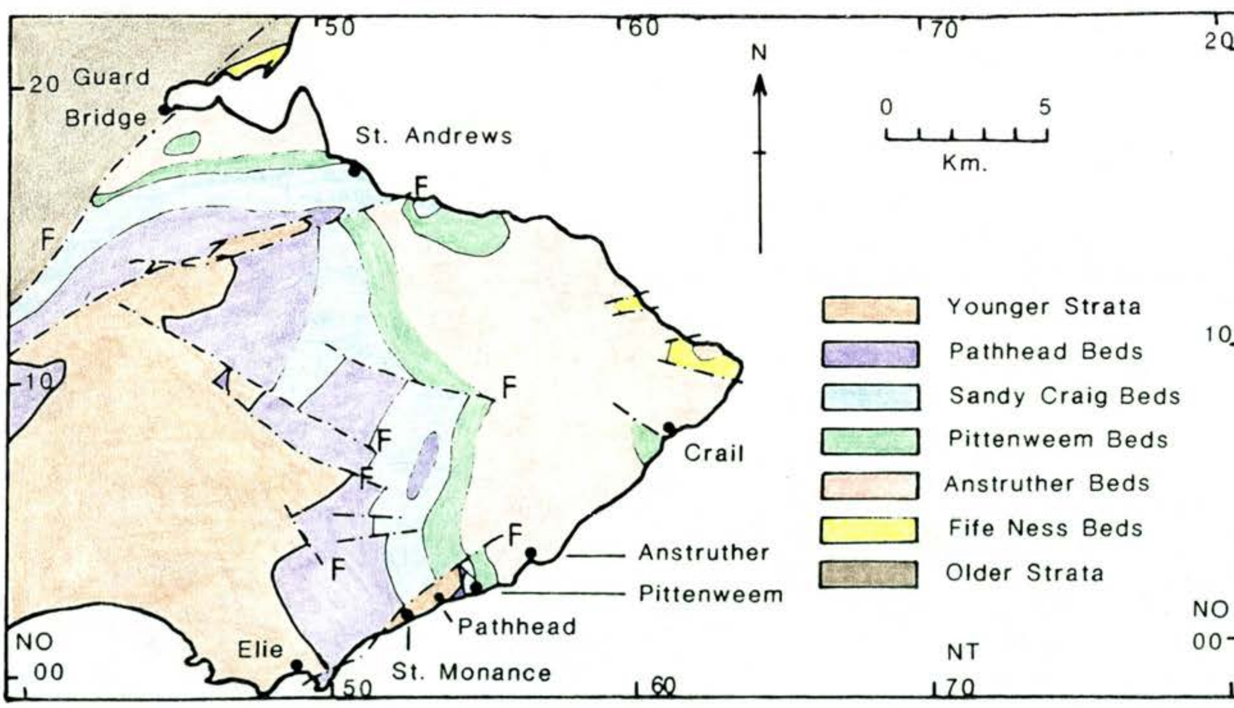

Fig. 1b. Generalised geological map of E. Fife showing divisions within the Calciferous Sandstone Measures.

For the Pathhead beds at Pittenweem (Forsyth and Chisholm, 1977) :-

"The lowest 161 m. consist of alternations of mudstone, siltstone and sandstone with many rootbeds and a few thin coals. About 110 m. up the section lies the West Braes Marine Band [N.O. 54190226] with a rather sparse fauna of Molluscs and Lingula in mudstone. The highest 150 m. consists of mainly mudstones containing marine bands and of thick sandstones.

The Ardross Limestones lie among marine mudstones in the upper part of the studied succession [N.O. 54120226], they are both dolomitised crinoidal beds about 30 cm. thick and are about 17 m. apart."

Greensmith, (1961b) studied cross - bedding in the sandstones of the Calciferous Sandstone Measures and deduced a S.W. trend for sediment transportation. In a petrographic study of Calciferous Sandstone sedimentation (1965), he subscribed to the palaeogeographic ideas of deposition on the western flanks of a major Carboniferous deltaic complex extending north - south along the North Sea depression. Greensmith also drew analogies to modern delta complexes noting their interdigitation, recognizing the following facies - on delta, delta front platform, delta slope and offshore. In 1966 Greensmith elaborated on the deltaic facies description and reconsidered his previous study concluding that previous inferences regarding the deltaic origin of the Calciferous Sandstone Sequence were valid and that the closest modern lithological analogy is with the Rhone delta of S. E. France.

Belt (1973), assigned cycles to a birdfoot style delta but in a more elaborate statistical analysis of cyclothem patterns in 1975 interpreted the delta as an elongate Guadalupian type which evolved eventually into a wave dominated Rhone type. In more recent studies and reinterpretations he suggests a Nile type delta with modifications, prograding into a shallow sea (1975, 1979).

1.2 AIMS OF THE STUDY.

This study is concerned with facies interpretation of the part of the Pathhead Beds in a vertical succession of 163 m. on the coast at Pittenweem. The measured succession starts at the top of the Sandy Craig Beds at Pittenweem bathing pool [N.O. 54350224], and ends at the top of the cycle containing the Lower Ardross Limestone [N.O. 54120226], the precursor of marine influences within the Pathhead Beds. The numbering of the beds will be as in Belt (1975) for correlation purposes. Petrographic analysis (Appendix 2) of the sediments, coupled heavy mineral analysis (Appendices 3 and 4) and X.R.D. analysis is used in an attempt to determine provenance of the sediment. S.E.M. studies were undertaken to interpret any diagenetic features of the samples.

Samples were collected through the vertical succession from the major sandstones comprising the major forms of deposit (e.g. channel, levee) and the rest of the units were measured for stratigraphic logging. Samples were collected from the centre of each unit as being representative of the lithological unit. The exceptions to this are the units composed of mega-scale features where samples were collected at the top and base of the units as well. The stratigraphy of the succession is illustrated in Chapter 2.

2 LITHOFACIES.

2.1 LITHOFACIES INTRODUCTION.

Lithofacies analysis is used to interpret the sedimentary units found in the succession (Fig. 2) by their gross characteristics. Groups of mappable units of differing characteristics (Collinson, 1968, Fielding, 1984, 1986), can then be used in supporting a cyclical depositional model for the sediments. These cycles (Fig. 3) are a mixture of eight lithofacies, composed of sandstones, siltstones, claystones, coals and carbonates, as will be discussed below, and which can be linked to five environments of deposition (Fig. 4, p. 22). However these postulated lithofacies (2.2) merely indicate the nature of the sedimentation processes present, an interpretation of these lithofacies and then of depositional facies is given in Chapter 2.3 and 2.4. The form of the cycle (2.6.1), is treated separately from thickness (2.6.2), because controls on cycle type and thickness although similar are not the same. Both reflect sedimentation, compaction and subsidence but the last is perhaps the most important for thickness.

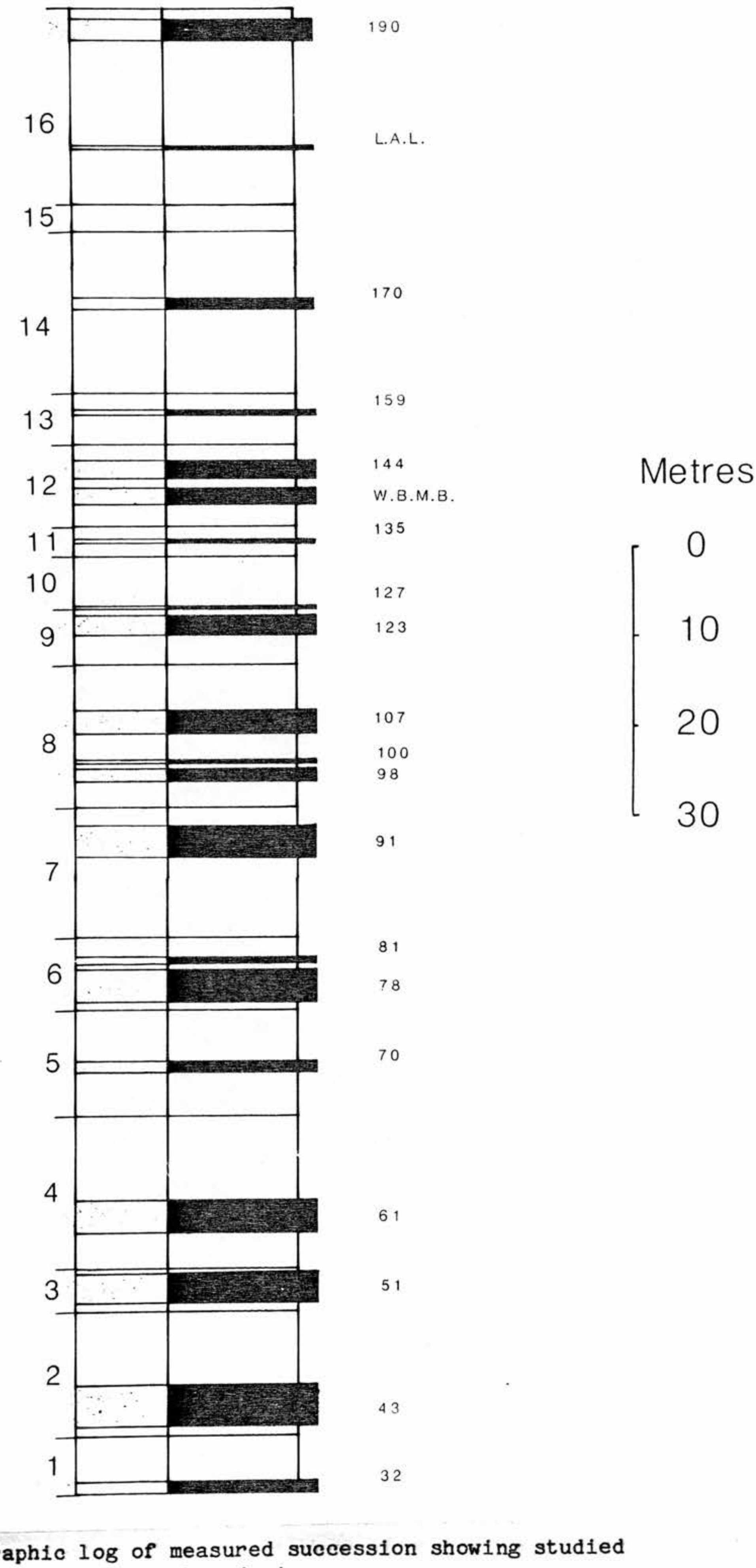

Fig. 2. Graphic log of measured succession showing studied units and cycle boundaries.

Key for Graphic Logs

1. Shales
2. Shale with silt and sand streaks
3. V. f. laminated Siltstones and Sandstones
4. Laminated and cross - laminated Siltstones and Sandstones
5. Small Scale Sandstone Bodies
6. Large Scale Sandstone Bodies
7. Coal and Rooted Seat - earth
8. Carbonates

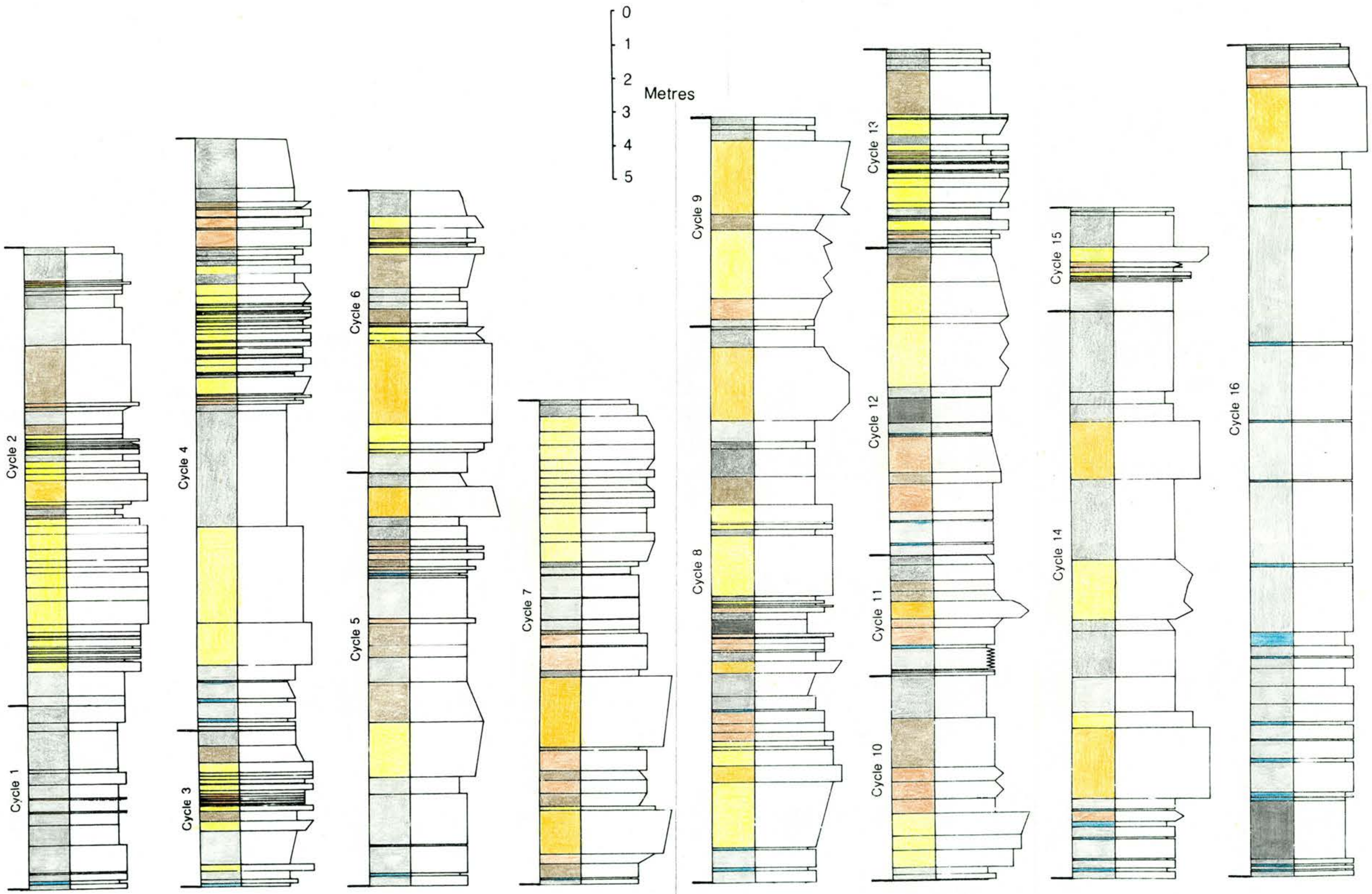

Fig. 3. Graphic log of measured cycles - continuous succession (1 - 16).

2.2 LITHOFACIES.

1. Shales.

These thin units of very fine grained, dark material are found in the succession in units of cm. scale, up to 30 cm. thick, composed of thin laminae of mm. scale. They contain a marine fauna (West Braes Marine Band, and associated with the Lower Ardross Limestone), or ironstone nodules.

2. Shale with silt and sand streaks (Shale >50%).

These units are of the order of 10 - 20 cm. thick with subordinate laminae of silt or sand grade material 1 - 2 mm. thick. These units contain coarser sediment as streaked lenses (de Raaf, et al., 1977), (Plates 1 and 2). The internal morphology of these lenses shows both asymmetrical and symmetrical ripples with undulatory boundaries top and bottom.

These units with thin subordinate sand and silt laminae form two types in the succession, those with associated dolostones and those without. They are thought to have formed from sediment settling out of suspension in an overbank or interdistributary environment with little coarse terrigenous input except for intermittent material influx. The subordinate laminae of siltstone appear to fine upwards indicative of a waning current while for the bulk of the unit there is no internal pattern at all. Those units occurring with dolostone horizons are possibly formed from evaporating pools with marine influences, while those without are formed away from marine

Plate 1. Bed 46. Lithofacies 2. Shale with silt and sand streaks. Silt lens shows lamination due to asymmetrical ripples (upper left).

Plate 2. Bed 100. Lithofacies 2. Shale with silt and sand streaks. Laminae forming wave ripples in lenses.


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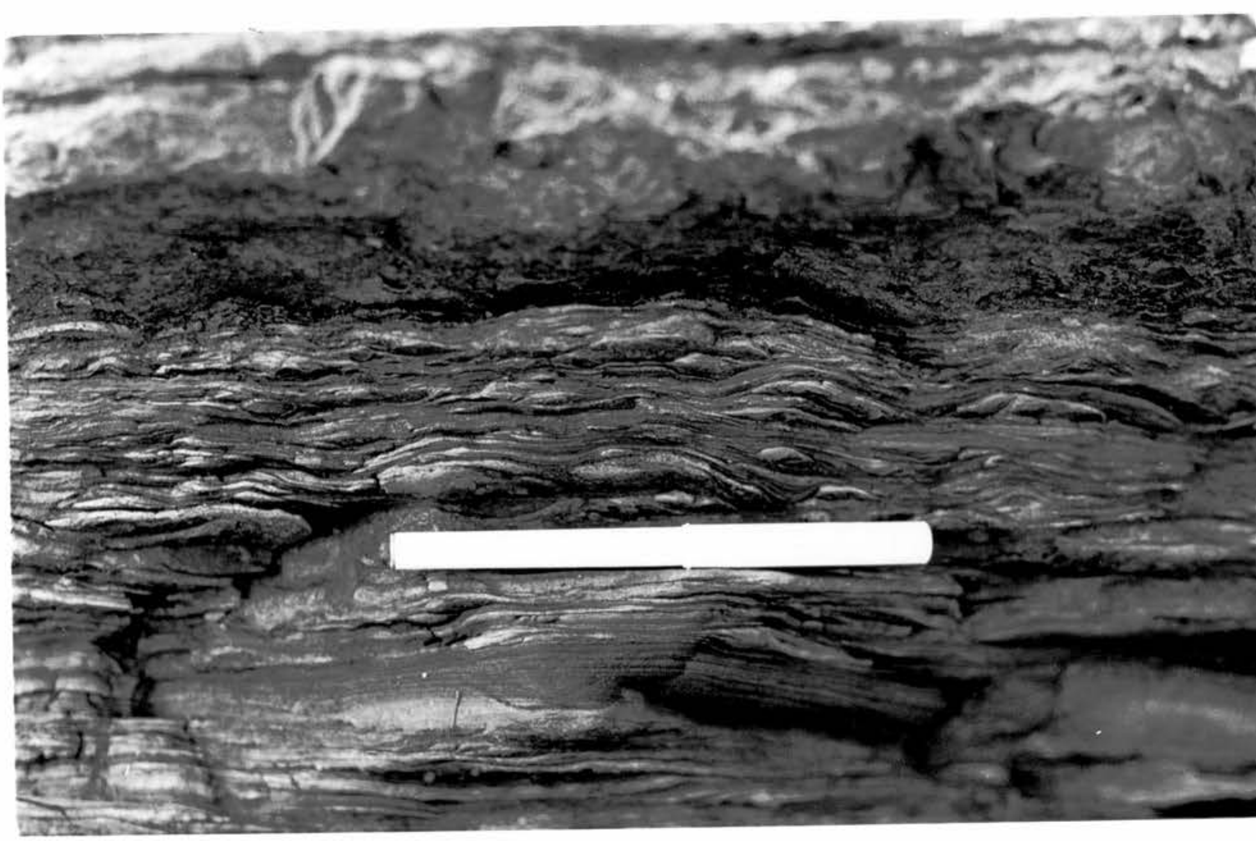


influences.

3. Very fine laminated Siltstones and Sandstones (Shale <50%).

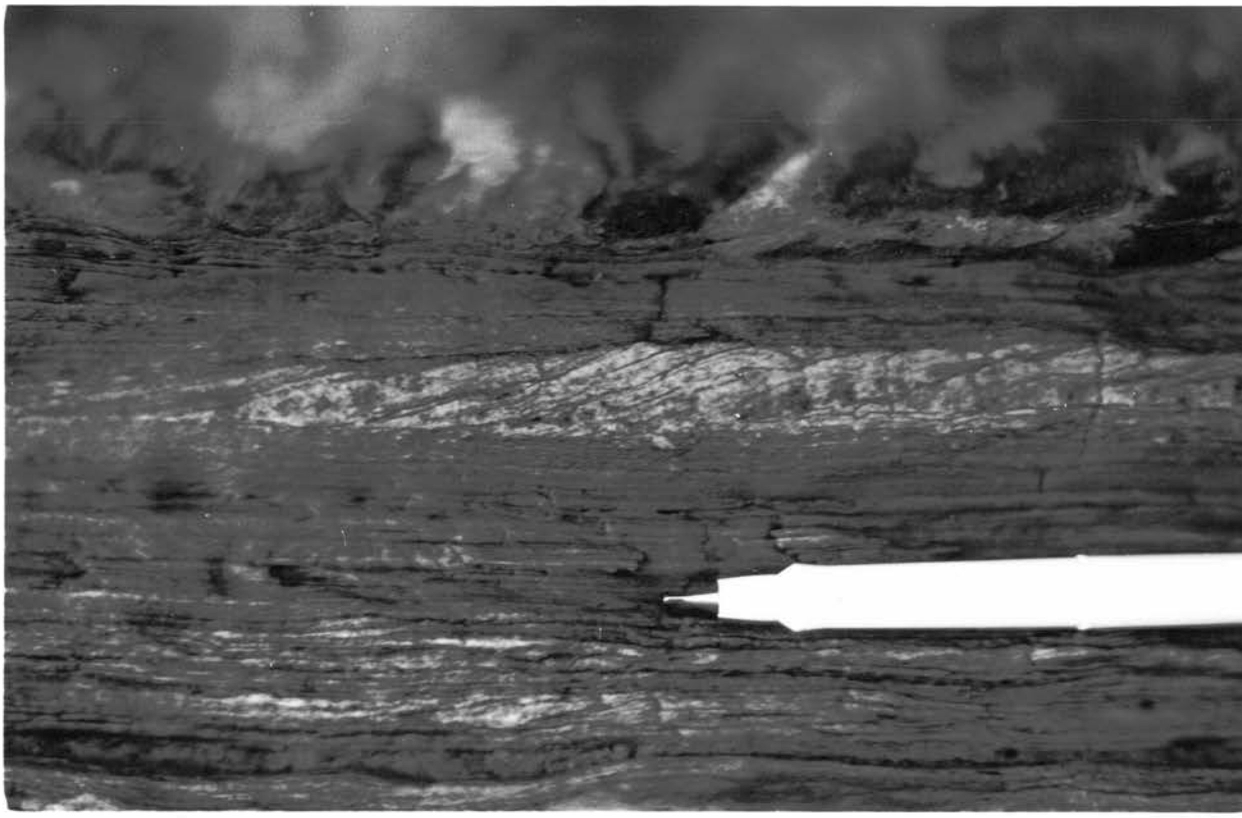
Occurring as parallel beds throughout the succession and comprising fine to very fine siltstone (0.01cm. - 0.001cm.), very fine sandstone and subordinate shale laminae forming sub-horizontal laminae (cm. scale) rich in flat lying micas. These rocks are planar bedded in units of the order of 2 cm. occasionally extending to 4 cm. thick (Plate 3). The thin laminae (shale, silt and sand) exhibit bioturbation - contorted bedding visible through some horizons. This facies grades into lithofacies 4, with local swelling and pinching visible, the internal lamination can increase to form poorly developed ripple cross lamination (Bed 87). These poorly developed current ripple cross laminations may exhibit erosion in that the crests have been partially removed. Also present within this unit are symmetrical wave ripples formed in very fine grained sediment by wind acting over water.

4. Laminated and Cross - Laminated Siltstones and Sandstones.

This lithofacies comprises siltstones, fine grained sandstones and shale splits similar to lithofacies 3 although coarser grained (0.01cm - 0.1cm) in units of dm. scale. A variety of coarsening and fining upwards sequences as well as current ripples, cross bedding and flat lamination is contained. Also present are synsedimentary deformation structures including load casts (Bed 70), dewatering features (Bed 127, Plate 4) and contorted bedding (Bed 61, Plate 5). These units comprise ripple swellings forming flat lenses of cm.

Plate 3. Bed 61. Lithofacies 3. V. thin laminated siltstones and sandstones (shale <50 %). Silt horizon in middle shows asymmetrical ripple lamination.

Plate 4. Bed 127. Lithofacies 4. Dewatering structure before consolidation, in sandstone.



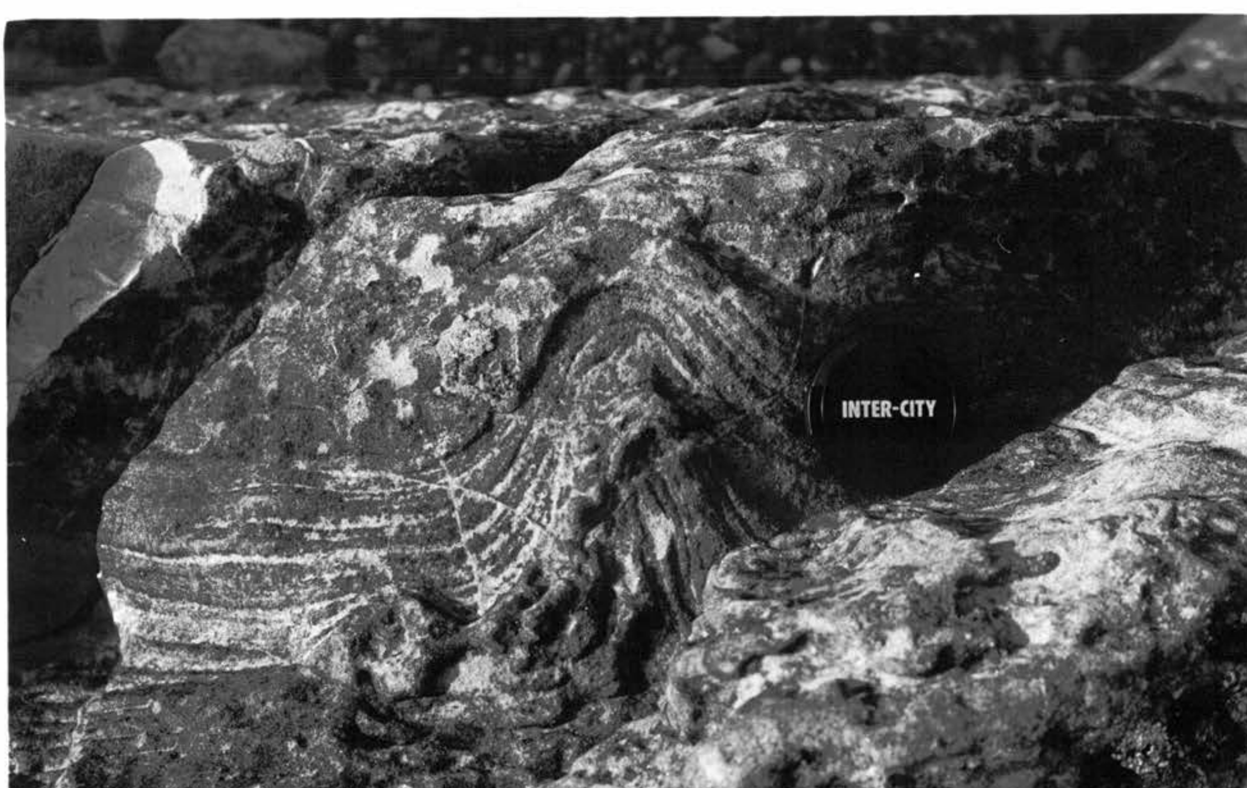

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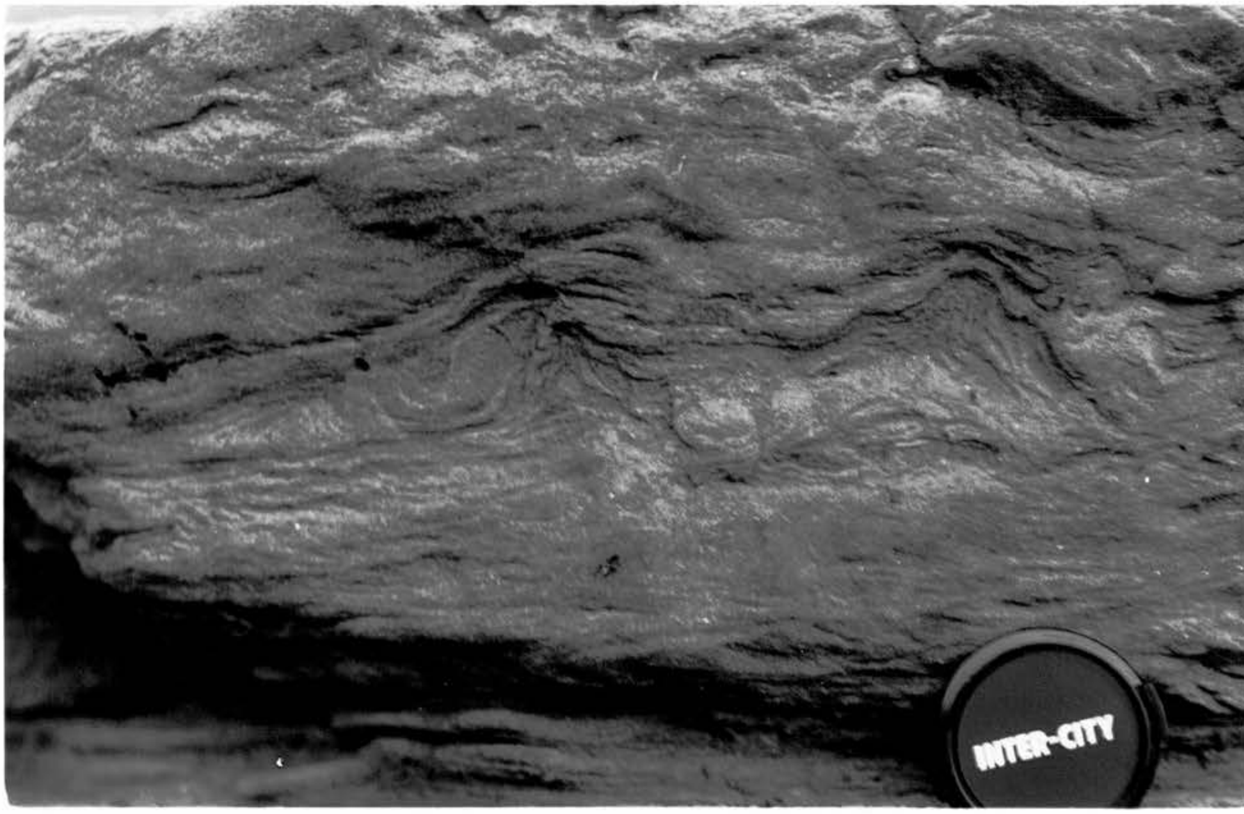
Plate 5. Bed 61. Lithofacies 4. Contorted bedding before consolidation, in sandstone.

Plate 6. Bed 107. Lithofacies 5. Variety of cross bedding due to current variability, picked out by minor trough bedding.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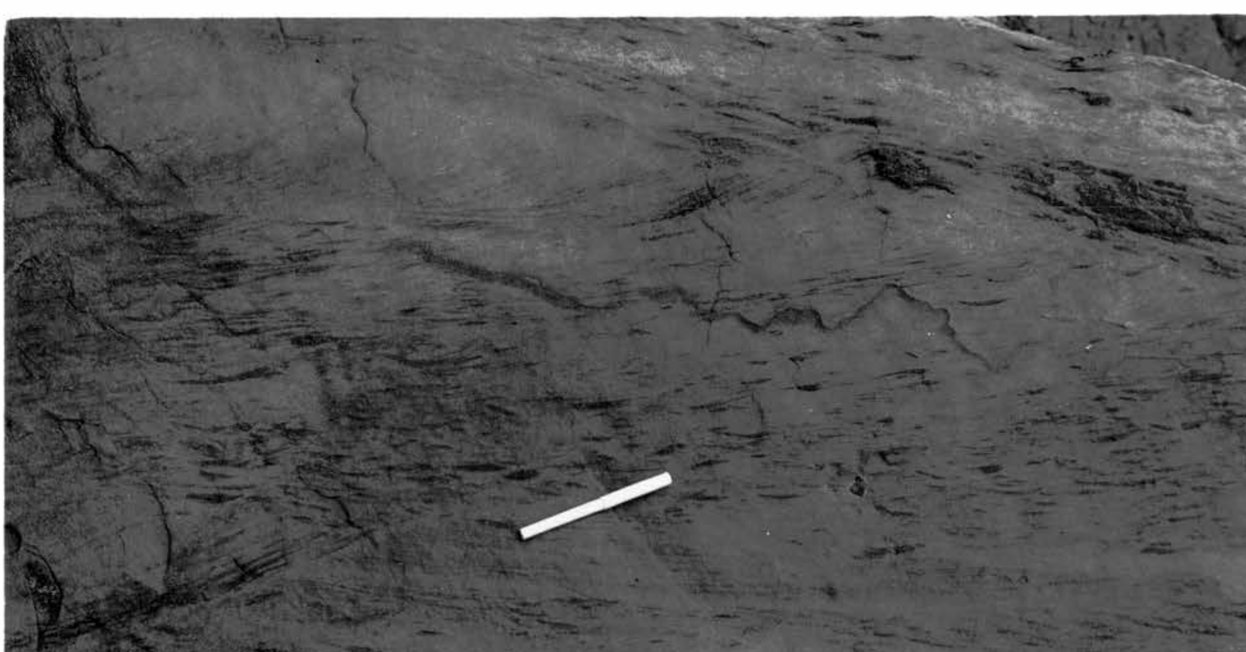


scale throughout the unit, these ripple 'lenses' are formed by current ripples and also by wave ripples formed by wind over standing water. These units also exhibit bioturbation, as well as showing abundant iron rich nodules in some units. Also present in this lithofacies are some lenticular bedded units of variable thickness (30cm. to 1.00 m.), the lenticularity possibly a result of ephemeral channels.

5. Small Scale Sandstone Bodies.

Within the succession sandstones are found of variable size, generally no thicker than 1.50m, composed of very fine to medium grained sediment (0.1cm. - 0.32cm.). These sandstone bodies are of two types :- 1) tabular cross bedded, 2) trough cross bedded.

1. The tabular cross bedded sands (Plate 6) are composed of medium grained sands in sets 5 - 15 cm. thick in bodies up to 1.00m. thick. These units also contain structureless horizons of the order of decimetres thick. The sets throughout the units are formed by the migration of ripples, and generally have flat bases and show flat upper boundaries, although internally ripples can occasionally be seen to climb at about 5 - 10 degrees (Bed 52). The higher angles of climb are linked to higher rates of sedimentation (Allen, 1970, 1971). Tabular cross bedding results from the migration of straight crested ripples of current form. Within the sets fining upward sequences can be seen on the current ripples.

2. The trough cross bedded bodies up to 1.00m thick are composed of sets 10 - 30 cm. thick of medium grained sand in which the trough cross bedding was formed by the migration of linguoid ripples, producing curved basal contacts to the sets. Within these occasional sets angles of climb of c. 5 - 10 degrees are visible in bands 1 - 2 cm. thick (Bed 61).

Also present are fining upward sequences of finer grained sandstones with thin carbonaceous partings, the sands contain ripple cross lamination and climbing ripple cross lamination (Bed 43). These fining upward sandstones contain thin partings of very fine grained sediment (shale) towards their tops.

Also present in this group of sediments are massively bedded sands made up of sub - units 10 - 30 cm. thick with erosive basal contacts, medium grain size and drifted plant remains. These deposits are characterised in section by some trough like scour surfaces (Bed 91). Drifted plant material is present and the size of this material combined with erosive basal sedimentary features, indicate high current velocities in channels. The sub - units may be internally contorted or not, although where un - contorted, ripple sets are usually visible. Coarsening upward sequences of mouth bar form are found within this lithotype in Cycles 2, 4 and 7, with climbing ripples (5 - 10 degrees). The coarsening upward sequences are a result of bar progradation.

6. Large Scale Sandstone Bodies.

These sand bodies form units generally over 1.00m. thick and are composed of series of sets 10 - 50 cm. thick. These units contain a variety of grain sizes from fine to coarse (0.10cm. - 0.50cm.) with well developed fining upward sequences visible in some units. Some of these units contain a variety of different ripple sizes (h = 0.5cm - 1.0cm), within them reflecting differing rates of deposition and / or current strength.

The bases of these units occasionally cut into underlying horizons forming grooves. These units are also found to contain variable amounts of drifted vegetation from finely comminuted material to impressions of larger fragments.

The few wave ripples in the finer grained horizons, visible within some of these units are thought to result from formation in an environment where winds affect standing bodies of water (possibly due to abandonment), while the current ripples were probably formed in the distributary channels themselves or as crevasse channels. At the base of one of these units is a megaripple (h = 30 cm., λ = 2.00 m.), composed of medium grained sand (Bed 135), in a channel base. This megaripple is surrounded by ripple sets c. 10 cm. thick, which are contorted and thin over the megaripple crest. There is also present in these sandstones with shale partings large scale epsilon cross bedding, indicating lateral infill to a channel. This feature is best seen in Bed 144, although it is also present to the west of the swimming pool (Cycles 6 and 9). Toward the top of some of these units can be seen very fine grained horizons of siltstone and claystone containing ripple cross lamination, primary current lineation and trough cross bedding (Bed 45) these small scale features are superimposed on some of the larger features.

7. Coal and Rooted Seat Earth.

Lumped together as indicated by Doveton (1971), almost all coals are associated with an underlying seat earth and have a distinct non - random series of formation. A clay unit which contains numerous rootlets and plant remains, the seat earth is generally massive in form although laminated more resistant limonitised horizons are present. Concretions of limonitised siderite are present sometimes filling larger root casts, but also as variously sized nodules not related to roots, forming from percolating fluids. The coals are thought to be largely of autochthonous origin with the deposits separated by thin laminae of clay and silt. The coals are dull, fissile and break into thin laminae. There is great variability in the form of the coals and the amount of clay present.

8. Carbonates.

The Lower Ardross Limestone, a biomicrite containing algae, productoids, *Lingula*, and crinoid remains in a unit up to 50 cm. thick, forms a distinct horizon in the succession. The form of this is indicative of relatively high energy fully marine conditions.

The dolostone units (2 - 5 cm. thick) which are dolomitised calci-lutites contain mainly dolomite with some ostracod fragments. They are found to occur in two distinct varieties, 1) laminated, with some grading of silt and sand sized ostracod particles (Bed 32), 2) nodular, forming as lengthened pods with no internal structures (Bed 100). These deposits are found interbedded with the thick shale deposits, the dolostones standing out as distinct ribs. Some dolostones exhibit mud cracks on their upper surfaces.

The formation of these dolostones is from evaporation of trapped pools (marine or freshwater) on the interdistributary plain or in lagoonal areas. These pools contain increased amounts of carbonate for the following reasons :-

a) breakdown of organisms bearing extracellular $CaCO_3$ giving off aragonitic needle mud,

b) precipitation of Mg calcite by blue green algal mats in freshwater environments,

c) diagenetic formation of high Mg calcite and protodolomite through preferential enrichment of $MgCO_3$ in residual water by evaporation,

The reduction in pool size causes primary carbonate precipitation subaqueosly near the shore regions where temperatures and salinities are higher. If exposed areas with primary carbonate present can force evaporative pumping, with dolomitisation of the sediment (Hsu and Siegenthaler, 1969). Alternatively, dolomitisation could have resulted from mixing of fresh and marine waters (Bodiozamani, 1973). However, as some of these dolostones exhibit mud cracks on their upper surfaces, the evaporative process is considered more likely. These deposits are of the order of 10's of square metres possibly reflecting pool sizes.

2.2.1 Palaeontological Content Of The Succession.

The faunal assemblage present in the succession is similar to that found in equivalent measures in many other parts of the Midland Valley, although individual beds cannot be correlated for any distance on palaeontological evidence alone. Although the succession is a series of cyclically deposited coal bearing sediments similar to those of the Carboniferous Limestone Groups, there are differences. The Fife units appear to have a much more rapid lateral variation than most of the Carboniferous, and only marine bands can be traced with any certainty (Forsyth and Chisholm, 1977). Some of the black shales in E. Fife contain abundant ostracods, as do the non - marine dolostones, however, in the rest of the Carboniferous ostracods are rare or absent (Wilson, 1962).

The distribution of the non - marine faunas in the section differs from the bulk of the Calciferous Sandstone Measures in that the non - marine bivalve Naiadites obesus is missing and largely replaced by the bivalve Curvirimula scotica, a similar feature has been noted by Wilson (1962), in the distribution of the non - marine bivalve in the Lower Carboniferous of the Lothians.

The West Braes Marine Band (Bed 142) is characterised by the presence of Lingula squamiformis, productoids and Modiolus. The Ardross Limestone is characterised by Hexaphyllia, Fenestella, bryozoans and Lithophaga lingualis. The assemblages in the Pathhead Beds become richer in variety of species, and the character of the fauna changes, the lower bands are essentially molluscan dominated, while articulate brachiopods rare or absent in the lower part, form a significant portion of the Ardross Limestone.

Within the succession trace fossils are frequently noted in a variety of forms, the most abundant of these are Teichichnus, Monocraterion, and Chondrites. Teichichnus is associated with both marine and freshwater conditions and comprises tubes (up to 10 cm. in length), of very fine sediment, in varying orientations. These tubes appear on the surface of bedding planes and are composed of coarser grained material than the surrounding sediment, they are interpreted as being feeding traces. Chondrites, are also interpreted as feeding traces, they appear as dendritic trails over the bedding surfaces. These traces are linked to fully marine conditions. Monocraterion, on the other hand is a dwelling trace and occurs as tubes perpendicular to bedding and is composed of a series of rings.

2.3 ENVIRONMENTAL INTERPRETATION OF LITHOFACIES.

From the lithofacies descriptions above an environmental interpretation (Fig. 4) is proposed along the lines of a deltaic complex.

The shale (lithofacies 1) occurs in units with little internal structure and is postulated as forming out of suspension in an marine type environment (West Braes Marine Band, Bed 142) with no coarse terrigenous input.

From the visible types of internal structure present in lithofacies 2, it is postulated that they formed in one of a variety of environments, either in shoaling bay areas forming flats, retained water on interdistributary areas, or as a result of overbank flooding.

The occurrence of symmetrical wave ripples (de Raaf, et. al., 1977), is restricted to where shallow water waves develop an oscillation at the bed implying the silt and sand laminae were deposited distally to crevasses or channel mouths and Reworked by waves. Few are purely asymmetrical, most show foreset laminae dominantly in one direction.

As shales of lithofacies 2 occur both with and without dolostones, they are likely to have been derived from two different environments. Those without dolostones are possibly derived from interdistributary areas, whilst the presence of dolostones with shale units could be explained by evaporation on flats of pools containing

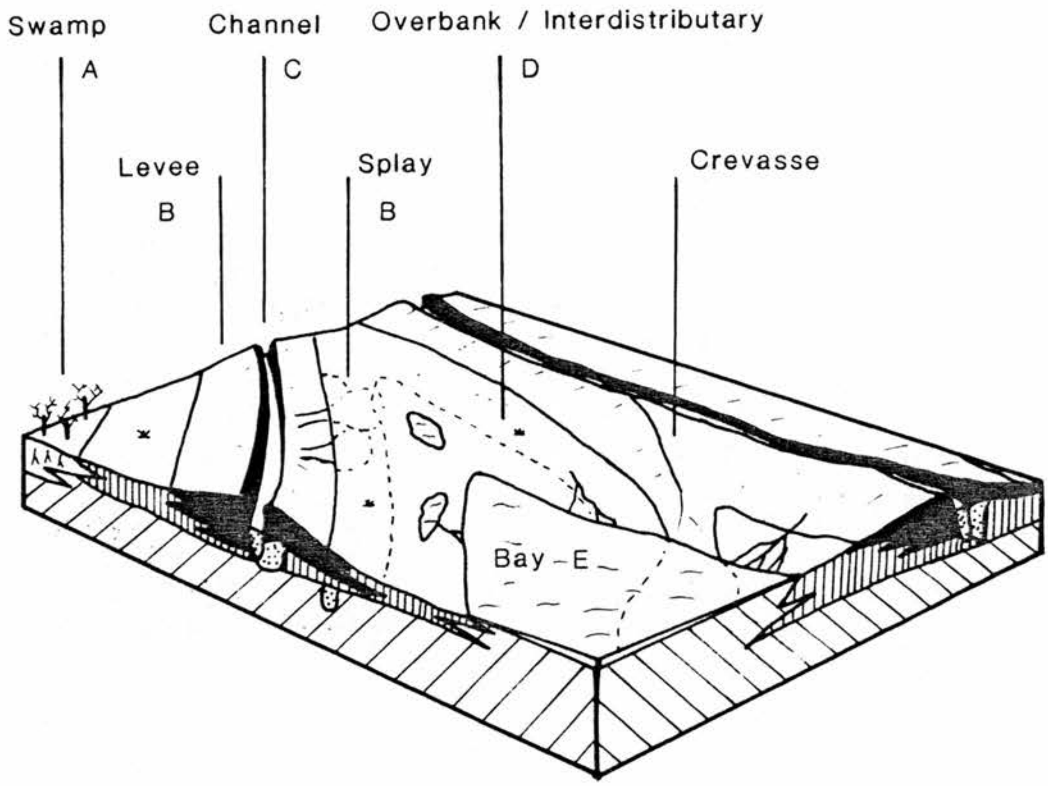


Fig. 4.1 Schematic block diagram showing position of environments of deposition.

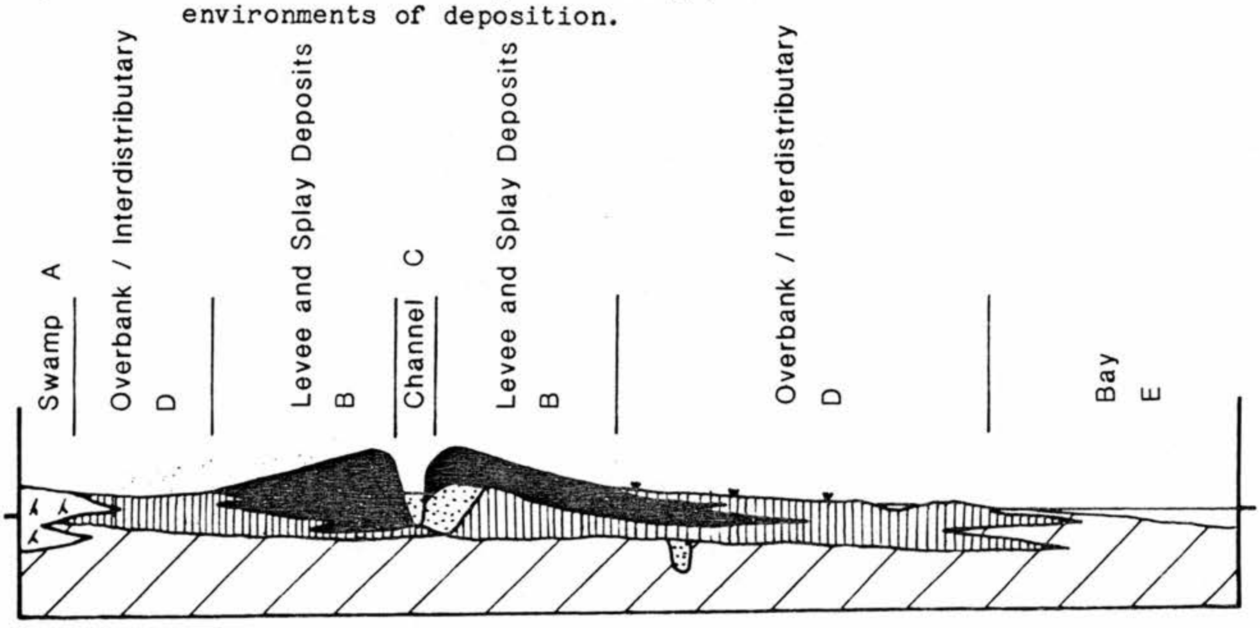


Fig. 4.2 Generalised cross section showing interrelations of depositional facies.

primary carbonate (evaporative pumping - Hsu and Siegenthaler, 1969).

The thin units of fine grained deposits of lithofacies 3 forming generally horizontal laminae tend to indicate that the unit formed in an environment similar to that of lithofacies 2 although with a greater percentage of coarse material and therefore slightly more proximal to crevasses. The presence on rare units of feeding traces (Chondrites Bed 130), suggests that on occasion the area was near marine influences. The presence of poorly developed current ripple cross - lamination would imply a current distal to channel margins.

The units of lithofacies 4 with current ripples and fining - upward sequences present are interpreted as levee sedimentation or proximal crevasse channels. Within these units the flat laminated coarsening upwards horizons are taken as indicative of levee formation. The coarser grained layers are deposited by sheet flow of sediment laden waters over major channel banks during flood events, (within these crevasse channel units the ripple trends are at variance with those of the main channel (Bed 127, ripple crests 025 degrees, channel 030 degrees, Fig 5). The lack of associated seat earths within this lithotype indicate that the flat laminated levees were generally submerged although some of the sand units contain rootlets indicating vegetation growth.

The lenticular channel units (eg. Bed 78) represent intermittent channels during exceptional floods with finer grained sediment splits settling out of suspension during quiet periods. Laterally these units become less erosive and thinner as they pass down current. Wave ripples present in the finer grained horizons are interpreted as

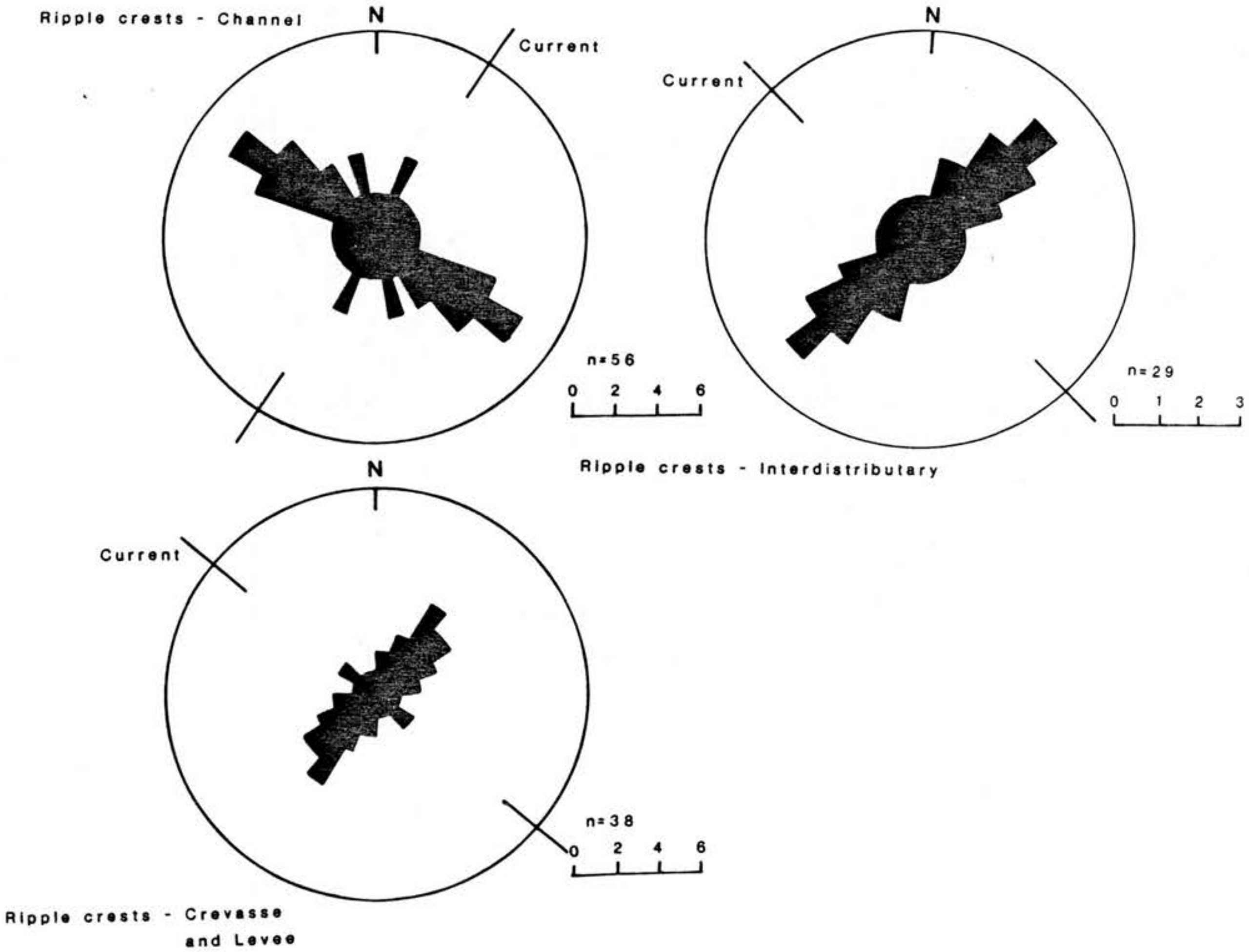


Fig. 5. Rose diagram of current indicators within the succession for channels, interdistributary, levee and splay deposits.

forming on the flooded parts of the interdistributary area.

The small scale sandstone bodies of lithofacies 5 with erosive bases are interpreted as forming in channels which would have been initiated from crevasse breaching. These channels would have transported sediment across the interdistributary areas. The flows would become less powerful as they passed outward across the interdistributary area eventually forming sheet like deposits of lithofacies 2 and 3. For the contorted sub - units the interpretation is of deformation by dewatering on disturbance of the unconsolidated sediment (Greensmith, 1965). Lithofacies 5 also contain a deposit with coarsening upward sequences (Cycles 2, 4 and 7, Beds 43, 61 and 91), internally these coarsening upwards sequences, show climbing ripples indicative of an advancing sequence in a mouth bar.

The large scale bodies of lithofacies 6 are interpreted as being formed in major distributary channels. The massive deposits are interpreted as being the result of high energy flows. The occurrence of finer grained horizons towards the top of the units can be explained by abandonment. The epsilon cross bedded units (best seen in Bed 144, also Cycles 6 and 9), is interpreted as lateral infill to a channel.

The coal seams are interpreted as largely autochthonous deposits on peat swamps by the presence of rootlets in the ubiquitous seat earths.

For the dolostone (lithofacies 8), the interpretations listed in Chapter 2.2 indicate formation in either drying out shallow marine or freshwater pools on flats. Continued evaporation of a pool where carbonate precipitation has occurred leads to exposure of its margins. This exposed carbonate is dessicated and dolomitised as a result of which the top surfaces of some of these dolostones exhibit mud cracks.

The Lower Ardross Limestone (lithofacies 8) is interpreted by its faunal content as forming in fully marine conditions in shallow water.

2.4 DELTAIC FACIES INTERPRETATIONS.

The possible interpretation of lithofacies postulated in Chapter 2.2 leads to the concept of 5 possible environments of deltaic deposition in the succession, these are shown schematically in Fig. 4 (p. 22). In which the lithofacies fall into the following facies.

A. Swamp Facies.

The swamp facies comprises lithofacies 7 the coal and rooted seat earths with occasional thin sandstone. This facies is generally thin and flat lying. The coal is largely autochthonous with seat earth development on shallow submerged areas of low energy and low sedimentation rates. The presence of channel sandstone units within this facies is attributable to channel migration across the delta top (Cycle 14).

B. Levee and Splay Facies.

This facies is composed of ripple and planar laminated siltstones and sandstones with a variety of grain sizes from fine to medium. This facies is interpreted as linear structures parallel to distributary channel margins with minor fining upward sequences. Within this facies are erosively based sands interpreted as being derived from splay channels during floods.

For the levees with current ripples and flat lamination, coarser grained deposits are formed by sheetflow of sediment laden waters over channel margins during flood events, with finer material settling out of suspension during quiet periods. These finer grained horizons of lithofacies 3, distal to levee or splays could have been submerged on the interdistributary area. This facies supplies the coarse sediment that is reworked to be present in the shale, siltstone and sandstone units of the interdistributary area.

Away from channel margins this facies interfingers with that of the finer interdistributary area facies. Within these levee and splay units can be found weak ripple cross - lamination which imply a variety of current directions, although largely away from the main channel (Fig. 5).

C. Channel Facies.

Distributary channels form a distinct facies in the succession, composed of a variety of sized units and grain sizes. This facies is the most widespread vertically throughout the succession and is composed mainly of lithofacies 5 and 6 although lithofacies 4 can also be present. This facies is interpreted as the distributary and major crevasse (erosively based) channel system with ripple sets indicating current direction. Within these channel sands are thin finer grained deposits possibly representative of inactivity or ephemeral channels, thicker deposits are as a result of abandonment within channel belts. Mouth bar type deposits (Cycles 2, 4 and 7), are present within this facies with coarsening upward sequences and finer grained laminae indicative of a prograding system.

D. Overbank / Interdistributary Facies.

This facies comprises a suite of sediments (lithofacies 1, 2, 3, and 4) dominated by the shales of lithofacies 1 and 2 forming out of suspension away from the overbank flows of facies B. This facies can contain drifted coal deposits and is marked by its presence of burrowing organisms (Teichichnus, Monocraterion) displaying both horizontal and vertical traces. These sediments are most commonly flat laminated with occasional rippled sandy laminae. Nodules of siderite are present sometimes flattened as are the few plant fragments. This facies is laterally extensive and is of a sheet form passing up palaeocurrent into the coarser and rippled levee and splay deposits. Within this facies, which was likely submerged for part of its time are symmetric wave ripples (2.4), distal to channel margins.

From the fine grain size and the virtual lack of current generated structures, this facies is interpreted as having been deposited form suspension, the upward colour change in some horizons with an increase in grain size implies that sedimentation rates were at first very slow but increased with time. The sandstone laminae are interpreted as representing the distal deposits to overbank flow. Interdistributary lake and bay fills in modern delta plain settings are often largely composed of overbank flood type deposits, without any current activity (Donaldson et al, 1970, Elliot, 1974).

E. Lagoon Facies.

This facies is interpreted as being of an offshore type behind a barrier and is composed of lithofacies 1, 2 and 8. There are two main inferred environments of deposition - those that are periodically exposed (freshwater or brackish, 2 and 8), and those that remain submerged (fully marine, 1).

Lithofacies 1 is considered to be the marine end member, formed offshore (West Braes Marine Band). For lithofacies 2 with interbedded dolostones this is interpreted as being formed on flats with evaporating brackish pools (2.3), although coarser laminae are present from D.

This lagoon facies became fully marine, with the formation of the Lower Ardross Limestone (Cycle 16).

2.5 MARKOV ANALYSIS.

Markov Chain analysis (Miall, 1966) was applied to the succession in an attempt to check for repetitive processes. The first stage is the transition count matrix defining the actual number of lithological transitions which occur in the succession. Transitions are not taken between similar lithologies ie. shale / shale (i=j=0). The matrices for this analysis are included in Table 1, in which the I th column variable overlies the J th row variable (lithofacies 3 overlies lithofacies 5, 18 times). From this a transition probability matrix is derived. The assumption that some form of control is exerted on the pattern of sedimentation can be tested by the construction of an independent trials matrix, where the values calculated assume the vertical sequences were formed in a random fashion. From this the difference matrix with its positive non - zero values may indicate non - random processes ie. there is a memory in the sequence of sedimentation. The greater the values in this matrix up to 1.00 indicates a greater likelihood of memory in the sequence.

The chain (Fig. 6) drawn with differences greater than 0.06 shows two distinct parts, the interrelations between the carbonates, marine shales and the shale with streaked sand and silt, and the major part comprising the sandstones and the coal formation of the delta plain.

The link between these two parts is based around lithofacies 2, supporting both marine and freshwater formation.

TABLE 1.

Markov Analysis of Lithofacies.

Transition Count Matrix.

LITHOFACIES.

	1	2	3	4	5	6	7	8	Total
1	X	2	0	0	0	0	0	1	3
2	2	X	7	7	13	0	15	37	81
3	0	8	X	17	21	2	0	1	49
4	0	9	14	X	5	1	4	3	36
5	0	16	18	7	X	6	3	0	50
6	0	3	2	3	3	X	2	0	13
7	1	3	9	0	9	5	X	0	27
8	0	37	1	2	0	0	2	X	42

Independent Trials Matrix.

LITHOFACIES.

	1	2	3	4	5	6	7	8
1	X	.261	.171	.121	.171	.047	.087	.141
2	.014	X	.236	.164	.232	.064	.118	.191
3	.012	.305	X	.143	.202	.055	.103	.166
4	.011	.290	.196	X	.192	.053	.098	.158
5	.012	.307	.207	.143	X	.056	.104	.167
6	.010	.267	.181	.125	.177	X	.090	.146
7	.011	.281	.189	.131	.186	.057	X	.153
8	.011	.297	.201	.139	.197	.054	.100	X

Transition Probability Matrix.

LITHOFACIES.

	1	2	3	4	5	6	7	8
1	X	.666	0	0	0	0	0	.333
2	.025	X	.086	.086	.160	0	.185	.457
3	0	.163	X	.347	.428	.041	0	.020
4	0	.025	.388	X	.138	.027	.111	.083
5	0	.320	.360	.140	X	.120	.060	0
6	0	.231	.154	.231	.231	X	.154	0
7	.037	.111	.333	0	.333	.185	X	0
8	0	.881	.024	.048	0	0	.048	X

Difference Matrix.

LITHOFACIES.

	1	2	3	4	5	6	7	8
1	X	.405						.192
2		X					.067	.266
3			X	.204	.226			
4			.192	X				
5			.153		X	.064		
6				.106		X	.064	
7			.144		.147	.128	X	
8		.584						

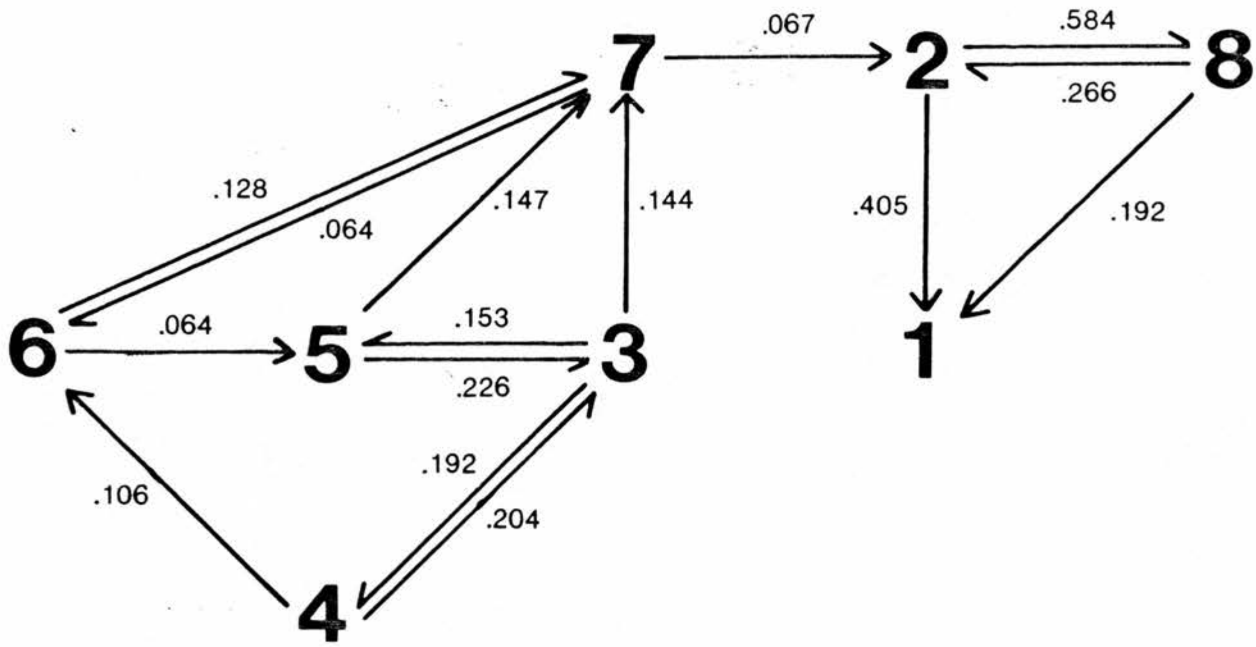


Fig. 6. Markov chain derived from analysis of 8 lithofacies, from the measured succession.

2.6 VERTICAL SEQUENCES AND COMPARISON WITH E.S. BELT.

The sequence of sediments in the measured section (Fig. 2, p. 7) can be thought of as cycles in that there is some repeated form to the sequence of lithofacies observed by the Markov analysis. In this work cycles are delimited when two criteria are satisfied; 1. the top of the in situ coal / seat earth unit with an overlying shale 2. the base of the lowest shale containing marine / brackish indicators, faunal or lithogenetic.

Belt (1975), formed 6 categories of cycle based on his transgressive, progradational and aggradational phases. This form of cycle analysis has been omitted as it appears unnecessarily complicated, and modes or environments can be inferred by much simpler processes (as above). Belts' analysis cannot categorise cycles precisely although no great differences regarding environment of deposition or cycle pattern can be ascertained using Belts' or this author's method of study.

2.6.1 Cycle Form.

Linking environments to the Markov analysis of lithofacies, the simplest ideal cycle follows the general environmental pattern E-D-C-B-A in which the sequence C-B-A is fining upward. The occurrence of a C (channel) unit may however if erosive have removed intervening units. The pattern is never fully developed, but frequently interrupted. The whole succession is shown in Fig. 3, with particular note of Cycles 1, 8 and 16.

Cycle 1, is of interest as it contains thick interdistributary and swamp facies in one unit without any intervening sandstone bodies. This cycle is interpreted as a swamp forming over an interdistributary area without the formation of channel sands from distributaries with a basal sequence of bay area shales and carbonates.

Cycle 8 (Fig. 7), containing repeated channel, levee and interdistributary sediments, has a coal without a seat earth in the centre of the cycle (1). This coal has been interpreted as being of drifted origin, distal to splay deposits 'B'. The cycle has been kept as one and not split at either the top of the drifted coal (1), or the base of the shale and dolostone (2), as the requirement for cycle boundaries explained earlier necessitates these two criteria to occur adjacent to each other.

Cycle 16, contains repeated bay and overbank / interdistributary deposits with marine horizons present in the bay deposits (Lower Ardross Limestone). This cycle is interpreted as the result of repeated submergence and exposure of an interdistributary plain leading to bay type sediment formation with no distributary channels formed until the top of the cycle where conventional 'simple' delta lobe formation continues from channel, through splay type deposits to seat - earth and coal formation.

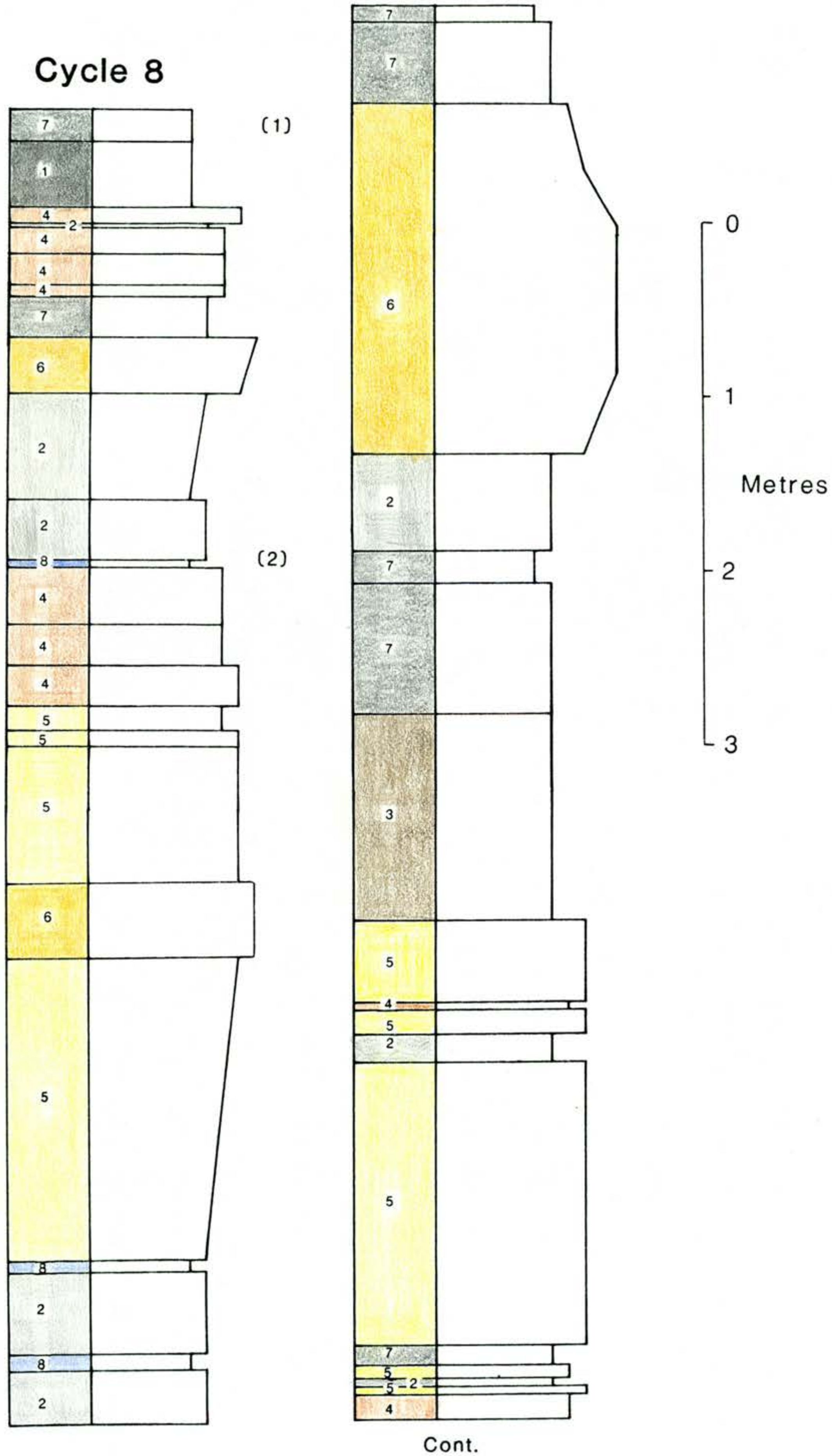


Fig. 7. Graphic log for cycle 8.

2.6.2 Cycle Thickness.

The thickness of the cycle can be useful as an indicator of the processes operating (Belt, 1979), with reference to autocyclic and allocyclic changes. Autocyclic changes are those brought about by the sedimentary system itself (eg. delta lobe switching), and allocyclic changes are caused by external factors (eustatic climatic or tectonic controls). Based on Read and Dean (1975), where there is a strong correlation between net subsidence and the number of autocycles, (Belt, 1979) graphed cumulative thickness against cycle number along lines proposed by Swarzarcher (1975), and detected allocyclic 'kinks'. Successional analysis (studying change in cycle form within a long statigraphic succession, 2.6.1), cannot differentiate between autocycles and allocycles, however a considerable difference in modal type could be interpreted as a change in process.

Within the succession the thickness of each unit represents the product of time and rate of deposition (in which the rate of deposition is controlled by the rate of sedimentation and effects of compaction). This is complicated by the fact that time is generally unknown as is the rate of deposition (Belt, 1981). However such an analysis requires an interval scale for time. Such an absolute scale is hardly ever available, so the analysis is based on steps which one has reason to believe are approximately equal - in this case cycles formed by repeated similar sedimentary processes with similar time scales. Once this time unit has been established, a cumulative plot of thickness vs. cycle number should plot as a straight line so long as the series is stationary (subsidence = deposition), and the time assumption is accepted.

As the cycle delimiter is taken as the coal, and assuming that the coal always forms at the same height above sea level, the amount of deposition must equal the amount of subsidence, (neither emergence nor transgression), thus straight lines occur in Fig. 8.

Variations in the gradient of the best fit lines (Fig. 9), are related to increases or decreases in deposition and / or subsidence rates Fig. 8, (more sediment accumulates in same time). The events in Fig. 8 (line 2), shows the effect (for one time unit), of significant increases or decreases in deposition and subsidence rates (allocyclic effects), before returning to normal autocyclic effects. Lines 1, 2 and 3 in Fig. 8, all have deposition and subsidence equal for each line, but at differing rates to each line.

Because the swamp phase contains seat earths and coals, and the remainder of the cycle contains varying proportions of shale and sand, decompaction of the cycles was considered necessary. The decompaction factors (based on Ferguson, 1963) were taken as follows :- lithofacies 1 - 8, 2 - 6, 3 - 4, 4 - 2, 5 - 1, 6 - 1, 7 - 10, 8 - 1.

Frequency histograms (Fig. 10), of the cycle phases are used to determine autocyclic from allocyclic phases. Allocycles are taken to be those which fall greater than one standard deviation from the mean. This analysis shows Cycle 14 swamp phase, and Cycle 16 main phase to likely be allocyclic.

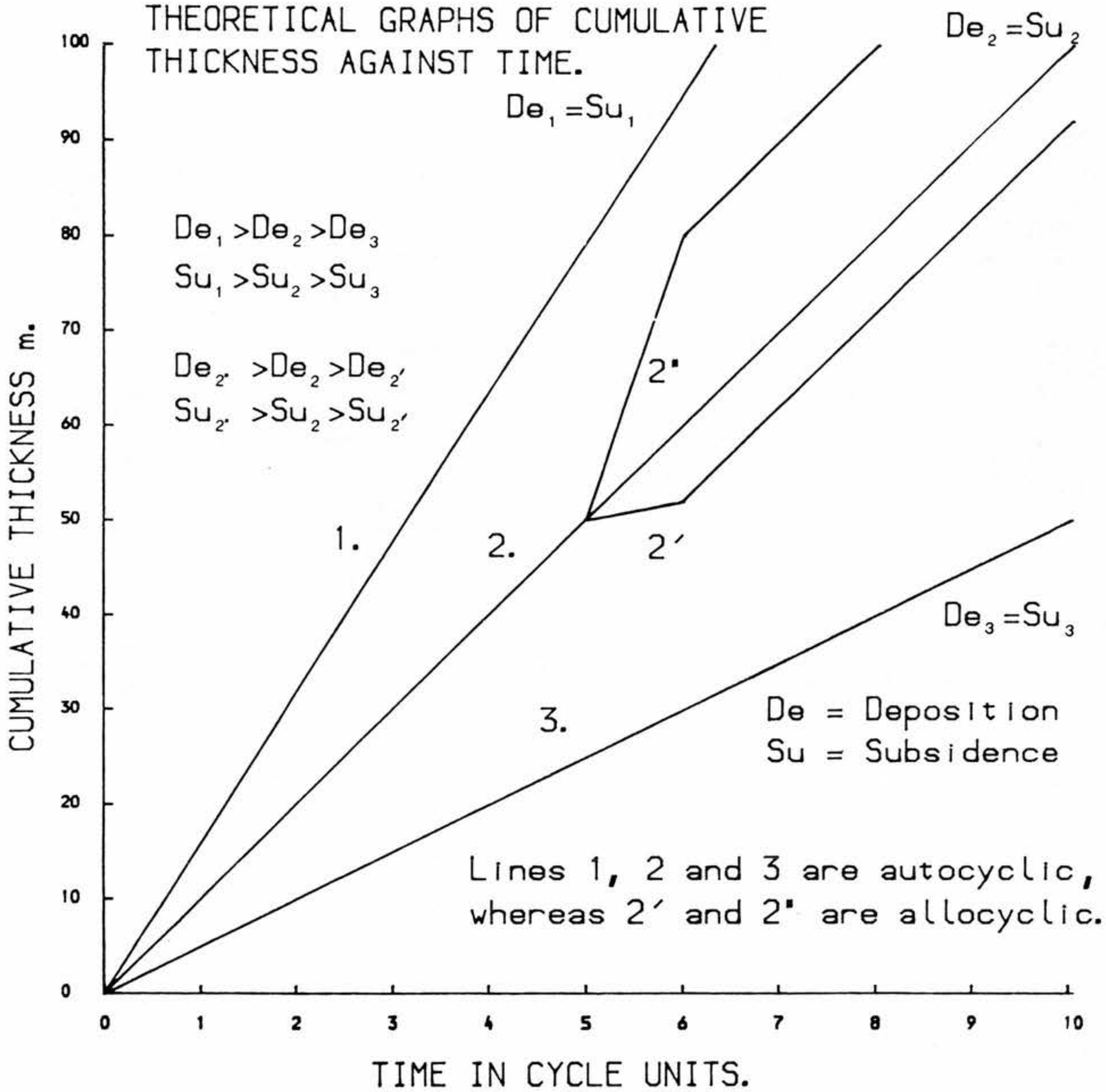


Fig. 8. Graph of cumulative thickness of sediments for a theoretical succession.

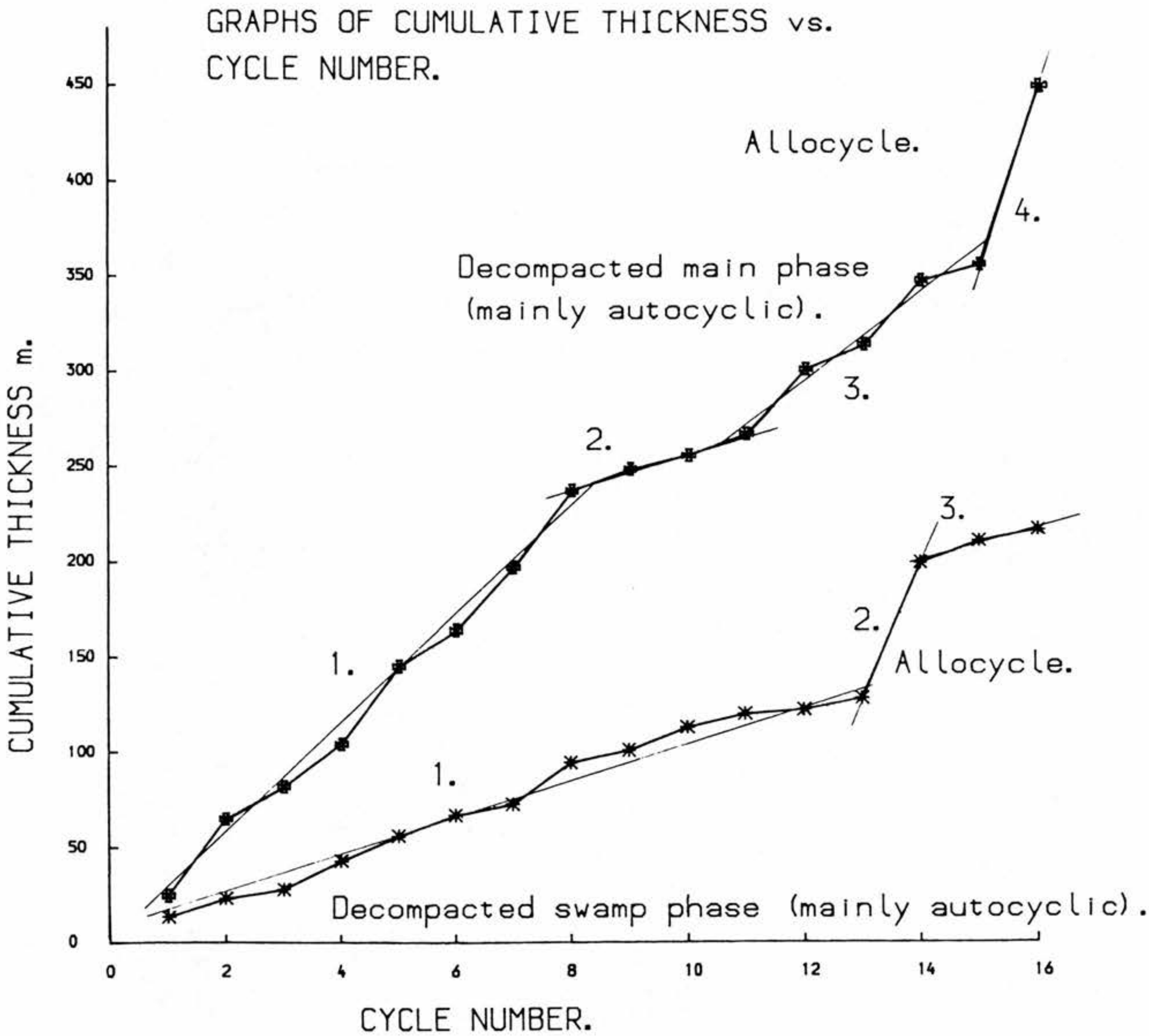
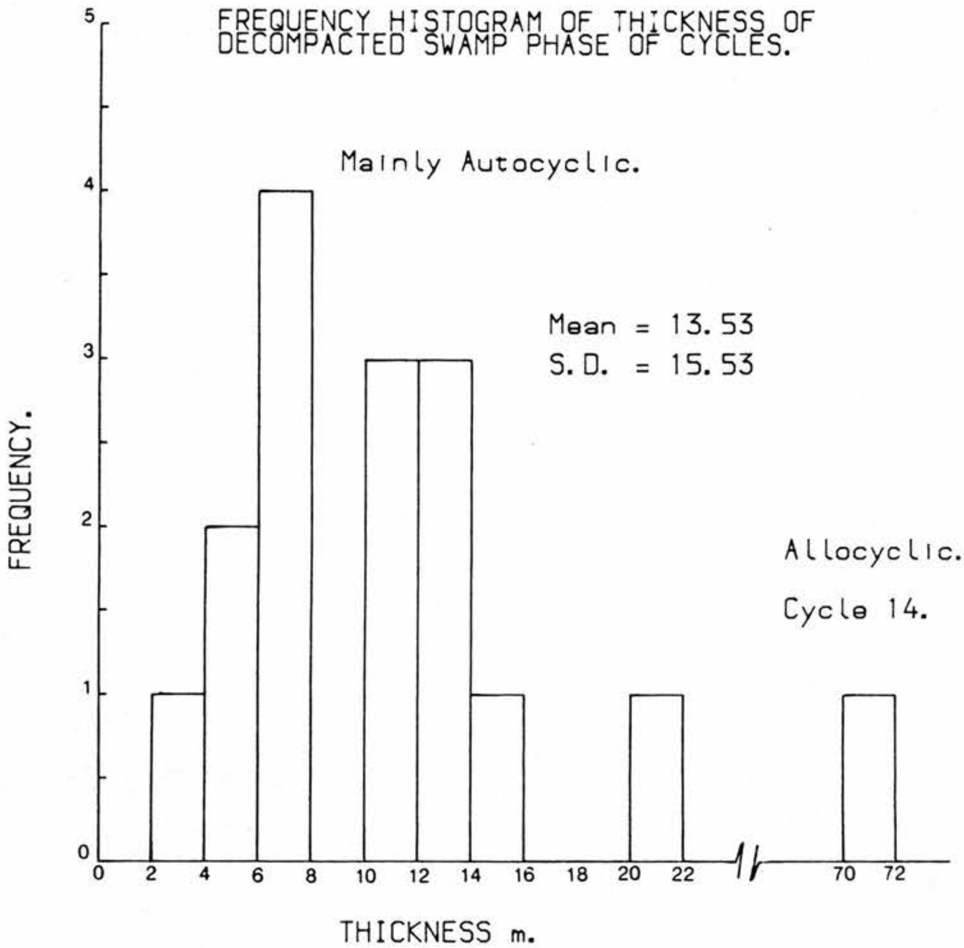


Fig. 9. Graph of the cumulative thickness of the decompacted swamp phase and decompacted main phase of the cycle versus cycle number.



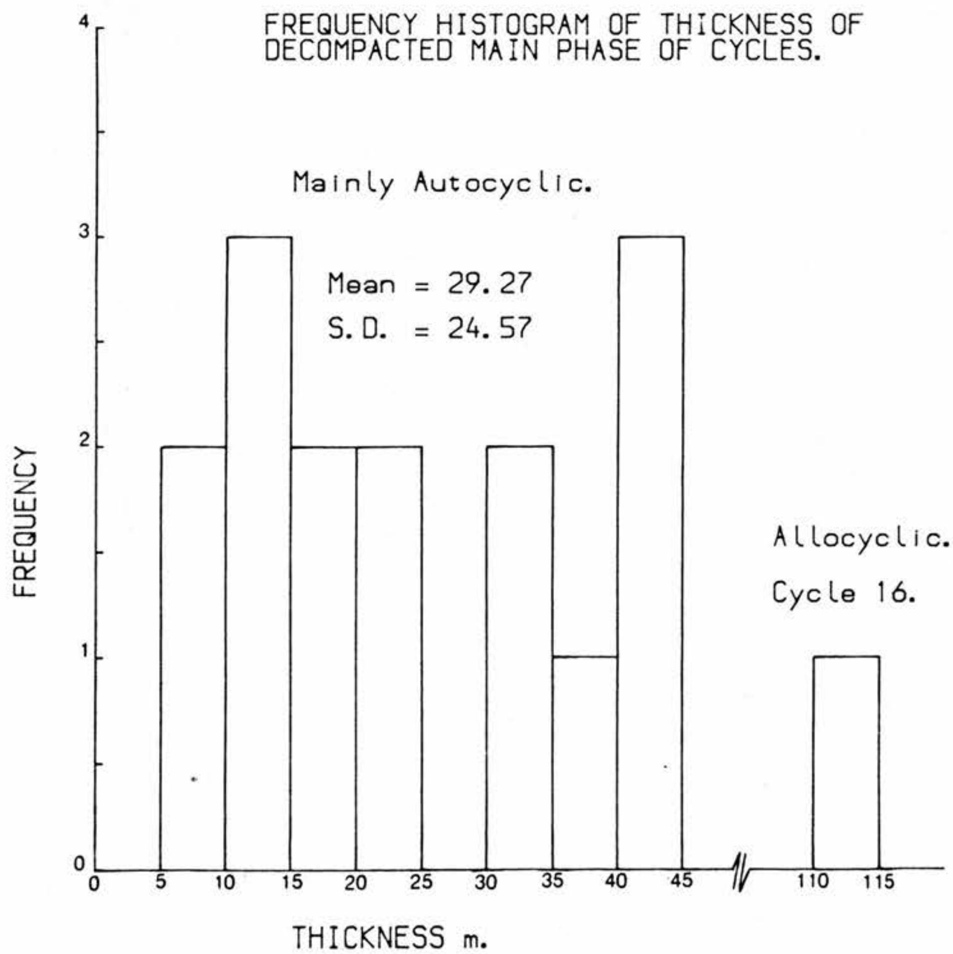


Fig. 10. Frequency histograms of the decompacted swamp

The cumulative thickness graphs (Fig. 9), reveal a series of best fit lines reflecting mainly autocyclic processes with similar deposition and subsidence rates. However Cycle 14 swamp phase and Cycle 16 main phase deviate from these straight lines and are thus inferred as being allocyclic.

The possible causes for allocyclicity could be local climatic variations, changes in basin subsidence rate, occasional tectonism in the Midland Valley or eustatic sea level changes. The problem for the allocycles is whether it is a local effect (Midland Valley tectonism) or global eustasy. This author prefers the local tectonic theory, as it is difficult to conceive a glacially induced sea entering the Midland Valley Rift and producing gradually thicker basin phases. The local tectonic model is a mixture of delta lobe construction, gradual basin subsidence and infrequent tectonism. It has therefore been deemed sensible to attribute these cycles to mainly autocyclic rather than allocyclic processes, (cf. Ramsbottom, 1979).

As cycles start and finish with a coal horizon, the thickness must equal the rate of sedimentation multiplied by time. The rate of sedimentation is linked to the rate of deposition and the rate of subsidence.

For most of the cycles, autocyclic processes predominate indicating that deposition and subsidence rates kept in step, producing 'normal' thicknesses by delta lobe switching. Generally the swamp builds up in step with sea level producing coal horizons, although in Cycle 14 the subsidence rate must have slowed down considerably allowing thick coal and seat earth formation. The basin phase thickness is an approximation of sediment accumulated to sea level for each cycle (Klein, 1974). This could be an explanation for Cycle 16 with its thick basin phase as a result of widely variable rates of subsidence with increased rates of deposition. Such changes would allow thick accumulation of shale in a rapidly subsidising area.

2.7 COMPARISON WITH OTHER DELTAS.

The delta appears to be similar to that of the Guadalupe of Texas (Donaldson et al, 1970) in its sedimentation pattern and overall form, with largely non - marine waters (Fig. 11). The Guadalupe Delta represents part of a modern complex of lagoonal and deltaic sediments (sands, silts and clays), deposited along a shoreline dominated by barrier islands. The thickness of these units is comparable with those in E. Fife. The major difference however, is the presence of evaporite deposits within the Pittenweem section; to explain this, a parallel is drawn with the Burdekin River Delta of Australia (Coleman and Wright, 1975), (Fig. 11).

Although of a much larger scale than the Fife delta, the Burdekin contains a similar assemblage of lithotypes and occasional evaporite deposits. The Burdekin Delta (a wave dominated delta), contains many bifurcating channels debouching into a shallow shelf area behind the Great Barrier Reef. Overbank crevasse splays are common in the area above tidal influence (tides 2.2m.), and are particularly abundant just above the limit of tidal inundation. These deposits consist of fine to medium grained sands with thin clay stringers. The interdistributary area affected by tides consists of tidal flat deposits, mangrove, algae and evaporite deposits, exposed during low tide.

The Fife delta under study therefore, situated at the Eastern end of a shallow sheltered lagoon had shallow muddy margins which would have been exposed during low tide, allowing evaporation of pools to take place and hence dolomite formation.

Key to stratigraphic section of Burdekin Delta (after Coleman and Wright, 1975).

Unit 7 Clay, silt and sand layers; well sorted and display small scale bidirectional cross stratification; organic remains common in clays; root and animal burrowing common in clays and silts; most sands have scoured base; thin zones of algal lamination.

Unit 6 Clean well-sorted sand layers; grain size increases upward; large scale cross bedding common; small slump structures common within cross beds; occasionally rooted near top.

Clean well-sorted sand displaying low-angle parallel layers; occasional heavy mineral layers.

Unit 5 Alternating clay, silt and sand stringers; small scoured base channel sands common; organic remains common; root and animal burrows abundant; thin stringers of evaporite deposits; algal laminations common; sand stringers display highly angular grains.

Unit 4 Silty sand with occasional clay stringers; small scale climbing ripples abundant; few contorted structures; high mica content; root burrowing common near top of unit.

Unit 3 Well-sorted sands with silt stringers; cross stratification abundant; bidirectional cross stratification common; scour-fill structure present; possible scoured base channels locally; generally coarsens upwards.

Unit 2 Alternating sand, silt and shale stringers, shale content decreases upward; sand:silt content increases upward; small-scale cross stratification; local shell concentrations.

Unit 1 Marine shale; thin bedded; zones of intense burrowing; scattered macro- and micro-fauna.

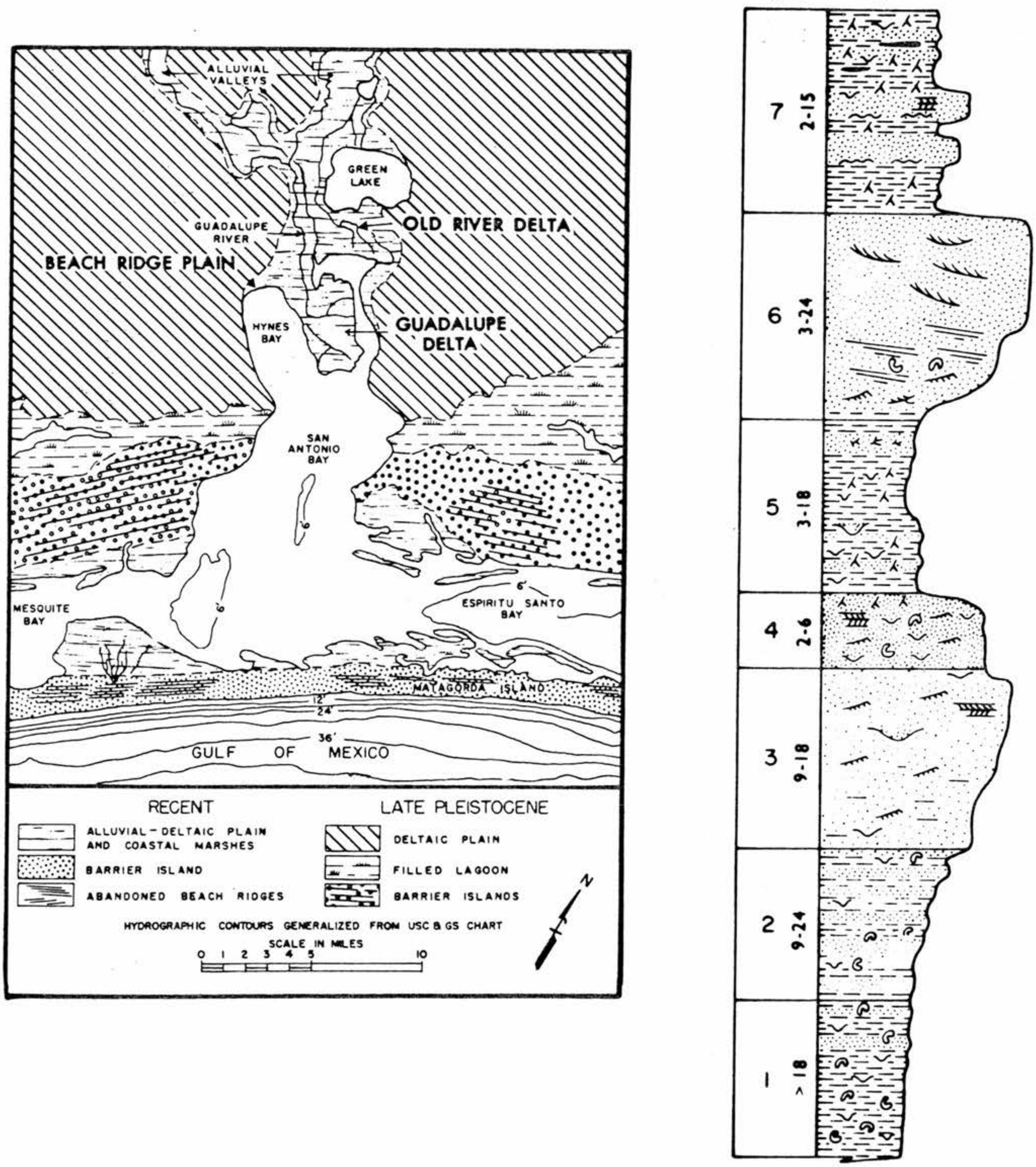


Fig. 11. Setting of the Guadalupe Delta (after LeBlanc and Hodgson, 1959), and composite stratigraphic section of the Burdekin Delta (after Coleman and Wright, 1975).

Belt (1975, 1979), suggested a shallow water wave dominated destructive Nile or Rhone type deltaic origin for these sediments using lithogenetic units (units which form distinct groups by textural, biological and physical characteristics). The Pittenweem section does not fit a Nile or Rhone model (Coleman and Wright, 1975), because of differences in size and amount of sediment transport, so a Guadalupe model is considered a closer comparison. Moreover, the Nile Delta has no beach spits or barrier islands whereas the Rhone has, as has the Guadalupe and the inferred Pittenweem delta.

No evidence of barrier islands have been located within the Fife section, although with limited visible tidal effects, it is suggested that such a barrier formed offshore at the margins of lagoons.

2.8 EVOLUTION OF THE DELTA.

For each cycle (Fig. 3, p. 8) the uppermost portion (Belts' aggradational phase) containing the sands, seatearths and coals, formed in the delta plain there are two types of patterns of sedimentation dependent on whether or not this phase contains a channel sand unit. The base of this portion is drawn at the top of the last levee or interdistributary unit in the body of the cycle. The two types of pattern with possible interpretations for their formation are as follows:-

X) Comprising nine cycles, and containing seatearths and coals without any intervening channel sandstones,

Y) Comprising seven cycles which contain channel sands at the base of the phase or within it.

This leads to five phases in the evolution of the delta :-

Phase 1	comprises	Cycle	1, 2, 3, 4	Pattern X
Phase 2	"	"	5, 6, 7, 8, 9	Pattern Y
Phase 3	"	"	10, 11, 12, 13	Pattern X
Phase 4	"	"	14, 15	Pattern Y
Phase 5	"	"	16	Pattern X

For pattern X the interdistributary area did not develop a channel sandstone preceding swamp formation, but in pattern Y the swamp formation was preceded or interrupted by a migrating channel system. Alternatively these differences (X and Y), in the uppermost portion of the cycle could be due to oscillations in the form of the delta related to distance away from the sand supply. No obvious differences in sand : shale ratio between patterns X and Y can be found, both systems appear to be relatively close to a sand supply except that pattern Y may by chance contain a channel sand unit.

The delta probably evolved by a series of progradational phases into a shallow calm bay (Fig. 12) sheltered by an offshore bar, with phases of basin subsidence and also marine incursion (Belt, 1979). There are indications in the distributary channel deposits of current flowing from the N.E. to S.W. (ripple crests c. 130 degrees), and these swing round (within the finer deposits), indicating preferred flow to the S.E and E. (ripple crests c. 30 - 60 degrees) possibly indicative of the basin to the E (Fig. 13).

The delta was largely constructional into a slowly subsiding basin with generally brackish to fresh water in the bay area (shales and cementstones). The main autocyclic processes are delta lobe switching where the delta front itself and the delta lobes simply filled up to sea level and developed root horizons and in some cases coal.

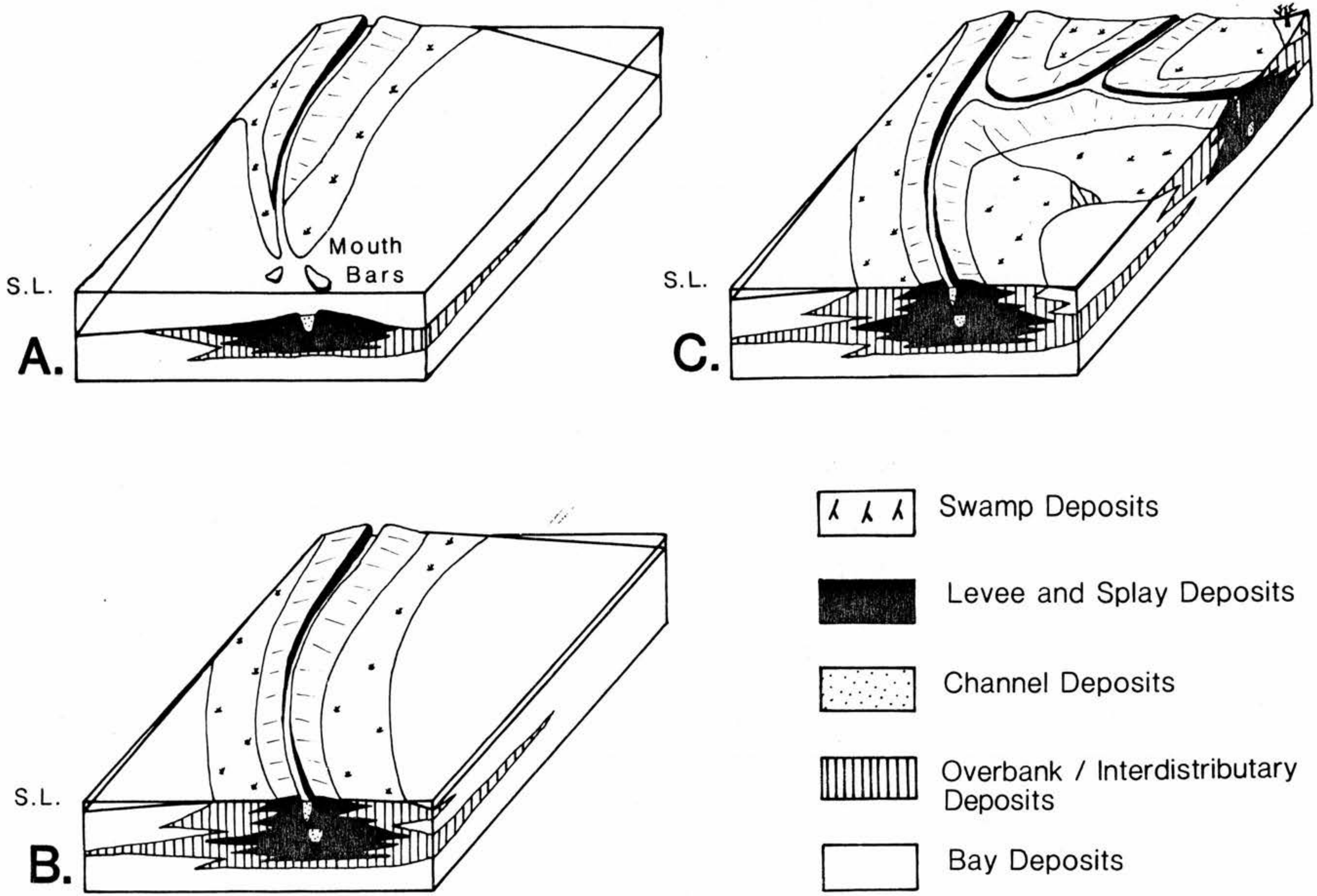


Fig. 12. Schematic diagram showing possible evolution of the proposed delta into a bay environment.

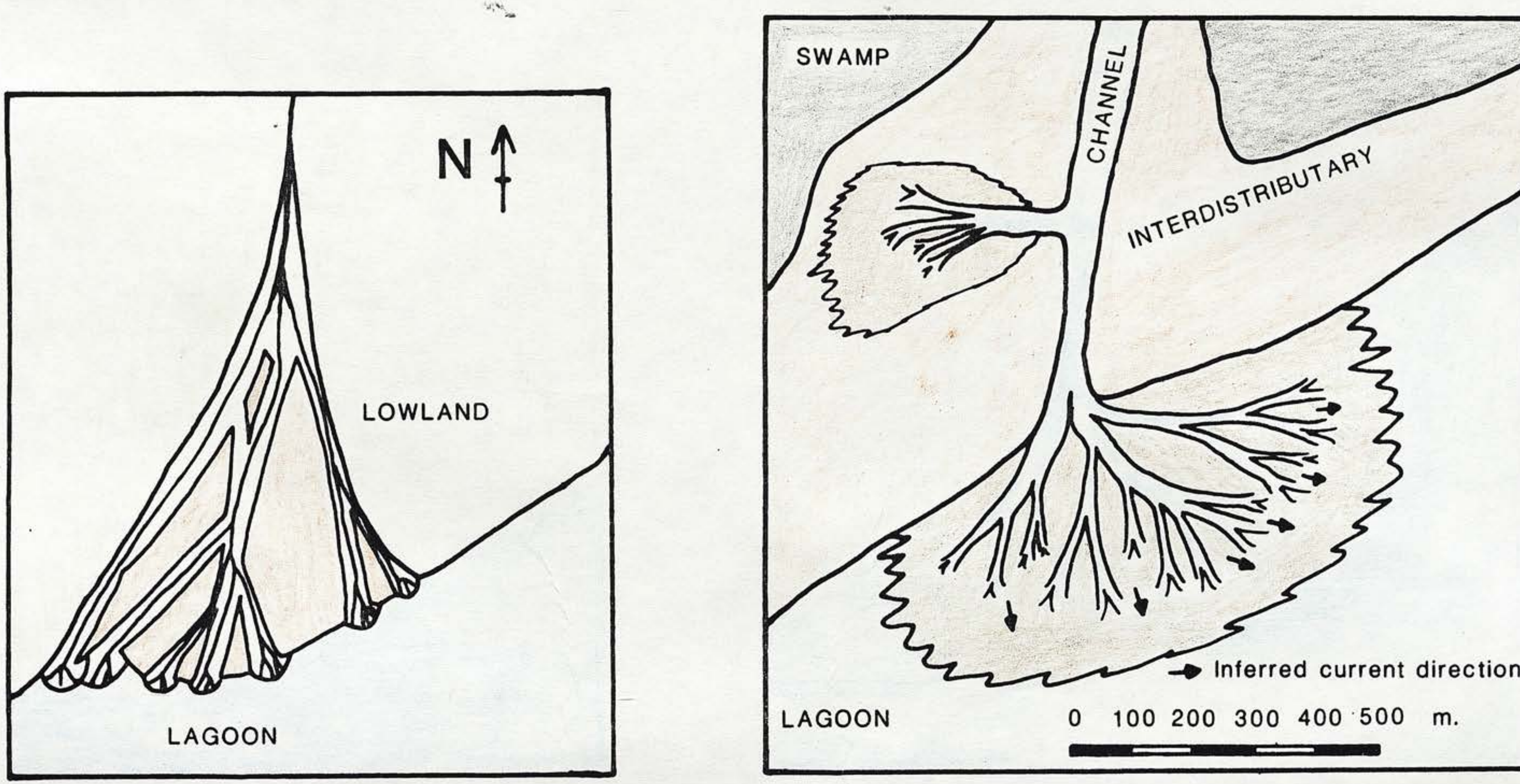


Fig. 13. Siting of the delta within Fife and its possible setting at Pittenweem.

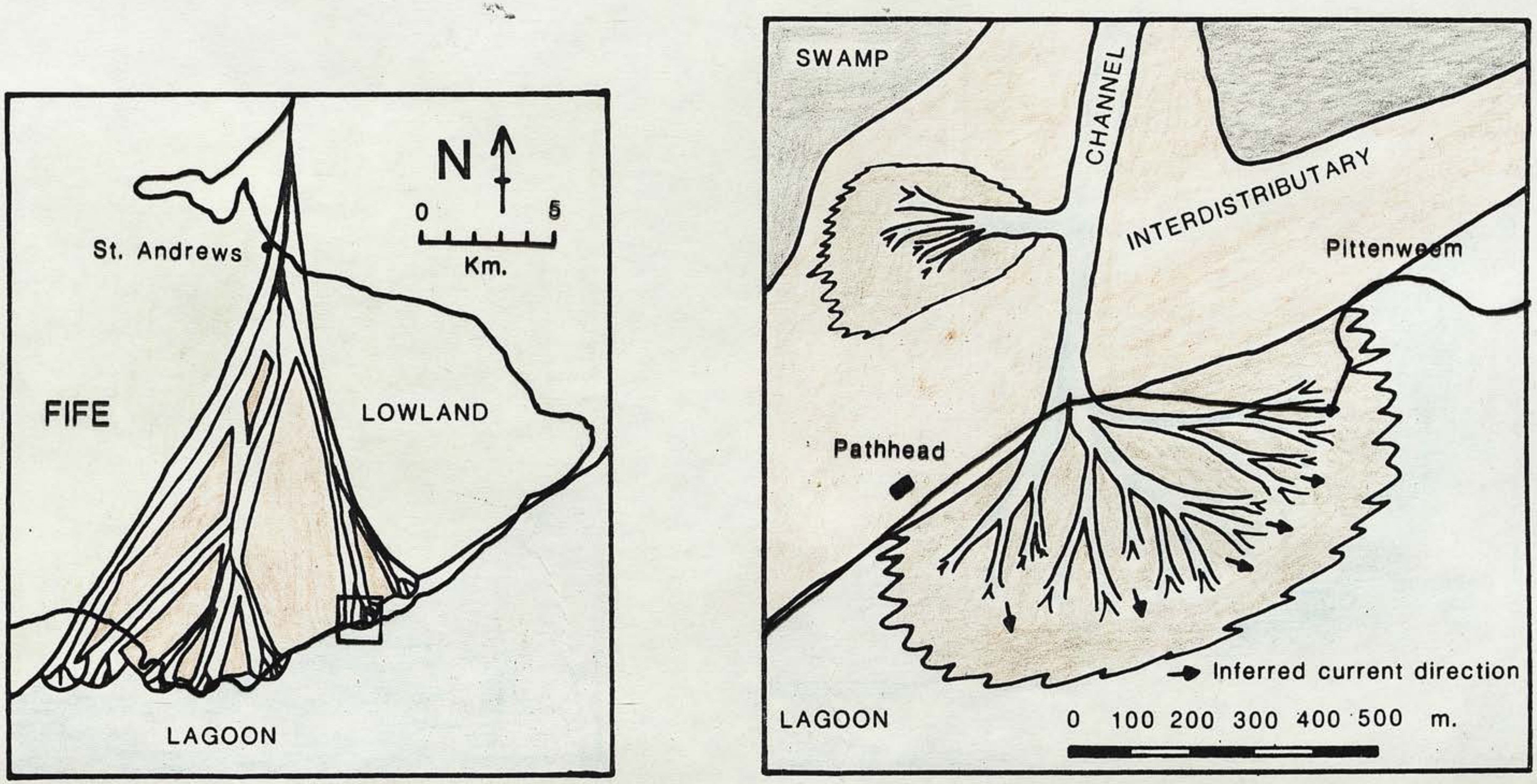


Fig. 13. Siting of the delta within Fife and its possible setting at Pittenweem.

For the bulk of the sediment a continuous stable rate of sedimentation 10 m. per cycle is mainly autocyclic although allocyclic factors are present in Cycles 14 and 16.

The rate of subsidence is inferred as being fairly constant although minor changes are possible. Marine incursions were limited at the base of the section, although by the Lower Ardross Limestone the area became more affected by marine conditions and continued to be so into the St. Monance section (Lower Limestone Group, Al - Rubaii, 1986).

3 SANDSTONE PETROGRAPHY.

3.1 INTRODUCTION.

The sandstones and siltstones of the Calciferous succession are predominantly quartzose sandstones and siltstones or proto-quartzite (Pettijohn, 1975) and are generally well sorted. Occasionally they fall into the sub-greywacke class. The following analysis is based on ten samples studied in thin section and under the S.E.M. Heavy mineral separates were taken and the mineralogy, the assemblages and their indications as to provenance are described in Chapter 4.

The dominant minerals are quartz, muscovite and feldspar, although dark brown or black carbonaceous matter from drifted plant debris forms an important component in some horizons as discrete patches or distinct laminae.

3.2 PETROGRAPHY.

3.2.1 Quartz Petrography.

Quartz forms 65 - 85 % by volume and two distinct varieties can be identified; non - undulatory and undulatory. Optically non - undulatory quartz habits predominate, in which the ratio of non - undulatory to undulatory grains is variable between 3:1 and 5:1. Within the samples mono and polycrystalline grains are present, polycrystalline grains are those grains which contain more than three sub grains. The amount of polycrystalline quartz varies from 10 - 40 % and is controlled by size, as the grains breakdown they will tend to become monocrystalline. Within these polycrystalline grains sutured boundaries predominate (pressure solution or straining of host). Monocrystalline quartz is variable throughout the section, generally angular to sub - rounded with both undulatory and non - undulatory forms.

The percentage of polycrystalline quartz in a sandstone can be taken as a rough indication of the amount and type of transport that the grains have undergone. Polycrystalline grains should be more abundant in immature sandstones than mature orthoquartzites (Blatt and Christie, 1963).

Non - undulatory forms generally predominate (extinguish < than 1 degree of rotation, (Blatt and Christie, 1963), forming 65 - 90 percent of the monocrystalline quartz. Undulatory quartz forms (extinguish > 1 degree of rotation), vary in their occurrence throughout the succession, and do not appear to be linked in any way to grain size or shape. It has been suggested (Blatt and Christie, 1963), that immature sandstones characteristically contain low percentages of undulatory quartz, although this amount of undulatory quartz is dependent on the source rocks and the abrasion history. Large amounts of non - undulatory quartz could imply large distances of transport or reworking, as undulatory quartz would be expected to abrade rapidly. Alternatively, the abundance of non - undulatory quartz could be a source effect, non - undulatory quartz is likely indicative of volcanic or extrusive igneous rocks, whereas undulatory quartz is possibly metamorphic (Conolly, 1965).

Basu et. al. (1975), in studies of undulosity and polycrystallinity of quartz showed that groups can be plotted on the basis of undulosity (greater or less than five percent), and the form of the polycrystalline grains, this produces three fields corresponding to granitic / granulitic source, medium to high grade metamorphism and low grade metamorphism. This plot uses the percentage of polycrystalline quartz in the whole sample, and the percentage on non - undulatory and undulatory quartz in the monocrystalline grains (M). The bulk of the observed samples are of the medium to high grade metamorphic type, with the exception of Beds 78 and 190 (Fig. 14), which are of the granitic / granulitic type and Bed 29 which is possibly plutonic.

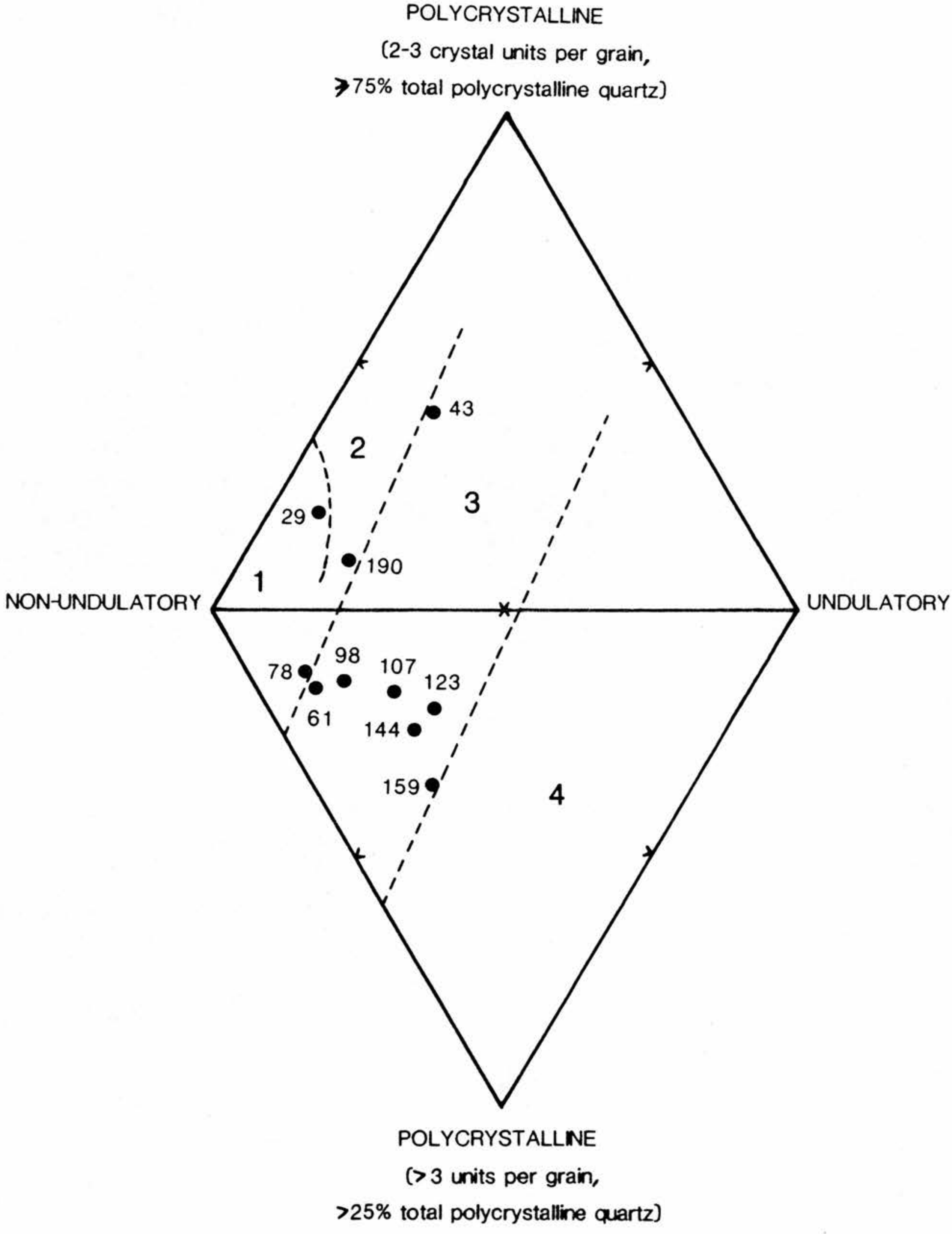


Fig. 14. Triangular plot of quartz sources (after Basu et al., 1975).

The presence of inclusions of three types, 'regular', 'acicular' and 'irregular' (Mackie, 1899, Keller and Littlefield, 1950), may help in the interpretation of the provenance, because although no one type is diagnostic it appears that the predominance of 'acicular' and 'irregular' forms favour an igneous rock origin. However Muir (1963), states that irregular inclusions denote an igneous source only where they are abundant. The abundance of 'regular' inclusions suggest a quartz bearing schist or metamorphic source rock. 'Globular' inclusions are gas or liquid filled and form as bands commonly parallel to crystal faces, growth zones or shear zones. 'Globular' inclusions are more abundant in igneous quartz than metamorphic quartz.

Throughout the studied samples there is a general domination of 'regular' inclusions although never in any great abundance, with 'irregular' as well as 'globular' inclusions also present. 'Acicular' inclusions are rarely present, and so these samples are generally assumed to be of medium to high grade metamorphic with some igneous derivation. However, Beds 29 and 190 with their 'acicular' inclusions show the importance of an igneous source. Detailed petrographic descriptions for these samples can be found in Appendix 2 (p. 138).

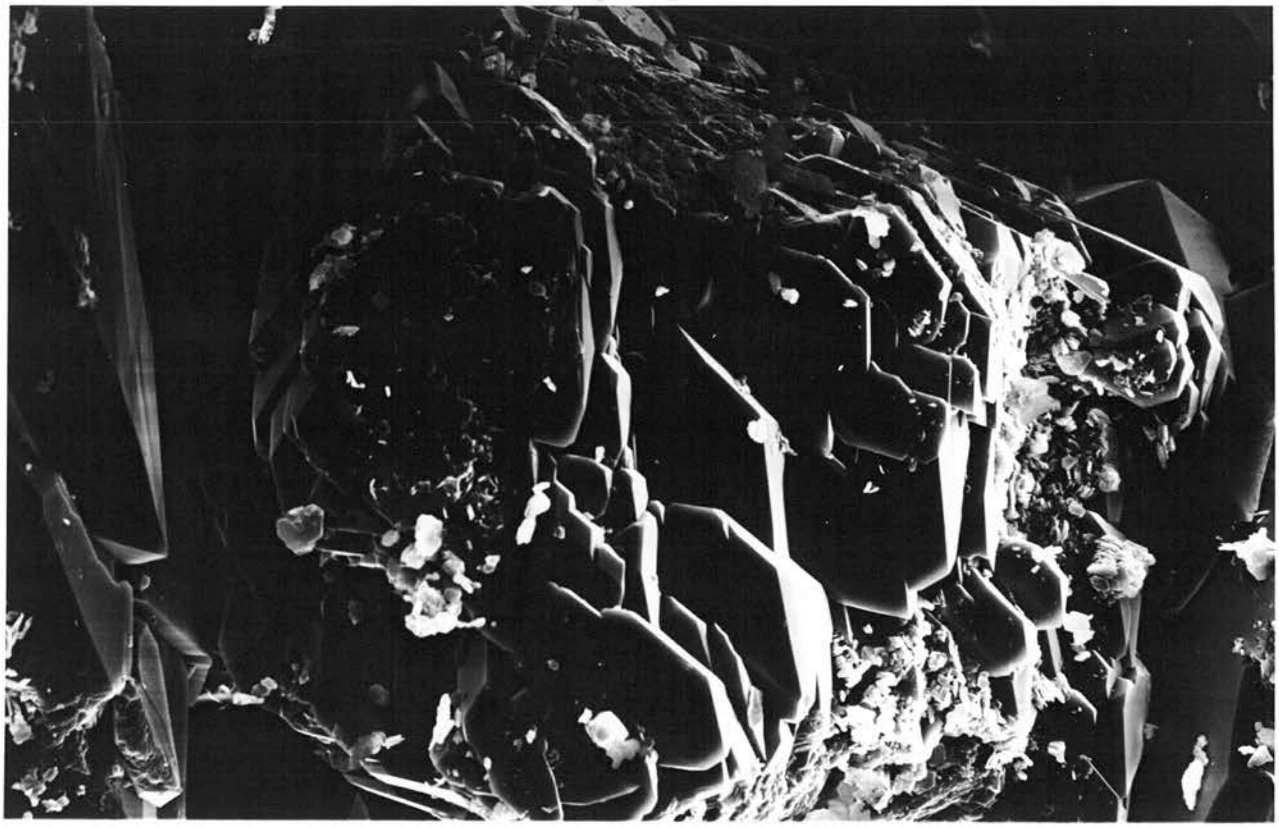
The samples are generally well sorted with respect to grain size with the bulk of the grains sub - angular, although both angular and rounded forms are present. The presence of the more rounded grains is suggestive of recycling by fluvial means, although it is also possibly an aeolian effect; these rounded grains are devoid of overgrowths.

Overgrowths are visible under the S.E.M. as well formed faces (Plate 7), initiated by formation of crystallites by pore fluids. Overgrowths are largely restricted to non - undulatory grains, altering them to angular or sub - angular in form (Plates 7 and 8). Secondary growth although appreciable in some cases has also been halted elsewhere by the presence of a clay matrix - incomplete overgrowths. In some cases dissolution of the grain on its rim is possibly associated with abundant interstitial clay (Muir, 1963) (top left Plate 8). The presence of authigenic overgrowths makes determination of the original grain shape difficult. Overgrowths can be identified in thin section by their lack of inclusions and impurities internally, because although they are in optical continuity with the host, 'dust lines' are frequently trapped around the original grain margin. Crystal faces tend to be produced by overgrowths, particularly where there is sufficient pore space to do so, Throughout the succession, long contacts even forming triple junctions are visible indicative of overgrowths. The majority of contacts in the succession are grain : grain (packing proximity 63 % - 80 %), these high figures are due to overgrowths (10 % - 30 % in samples), the number of original grain : original grain contacts varies between 33 and 61 % within samples.

Excessive packing of the sediment will lead to some dissolution (pressure solution, the Riecke Principle, Pittman, 1972), of the minerals forming suture contacts, but just a few are visible within the succession (Bed 29 high grain : grain contact ratio).

Plate 7. Quartz grain showing well formed faces due to overgrowths.

Plate 8. Quartz grain showing well formed faces due to overgrowths, and minor kaolinite.



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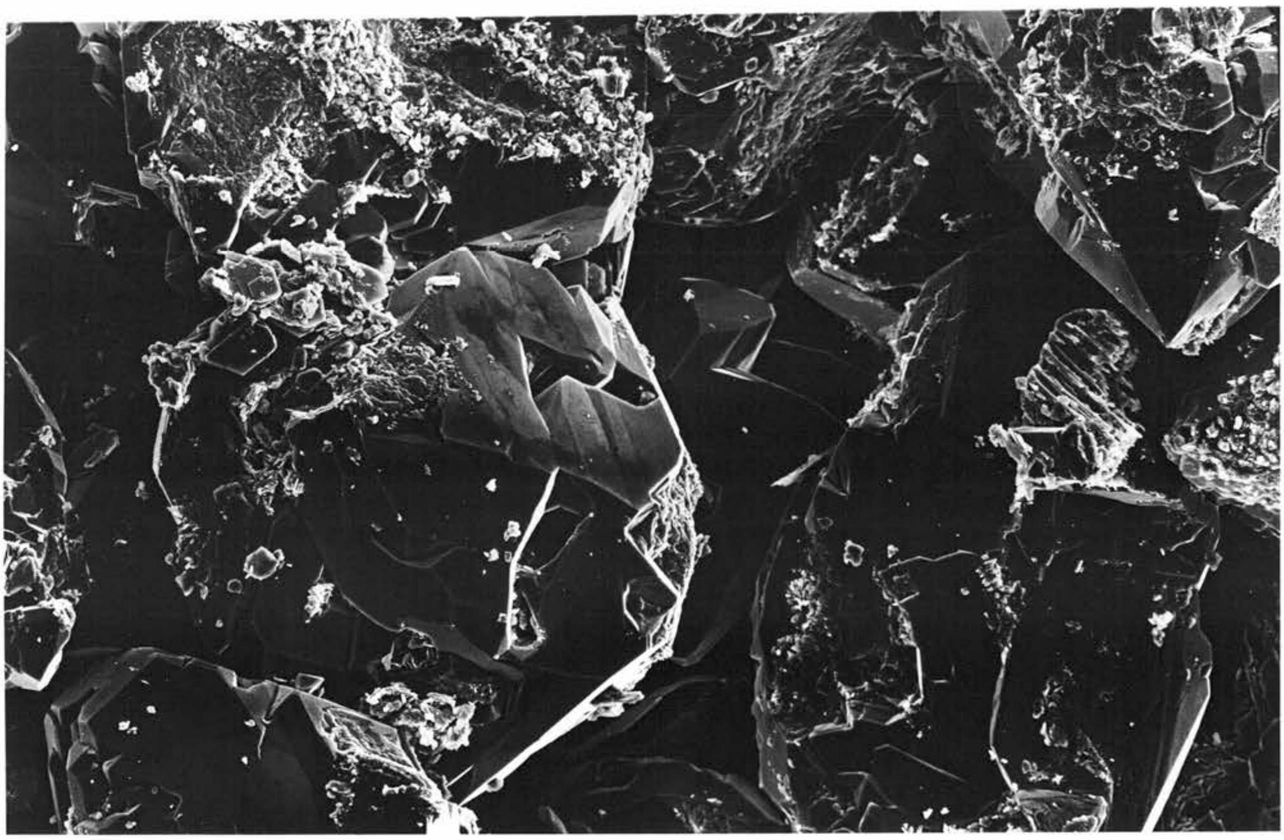

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Pettijohn (1975), calculated sizes of particles which will lodge in or migrate through pore spaces. For rhombohedral close packing, these limits are 0.154 D and 0.414 D (where D = mean diameter of grains). In this for closest packing grains between the two limits are occupying voids and were deposited contemporaneously. Grains with diameters less than the lower limit will pass through the throats of the pore spaces. This feature is especially noticeable in Bed 29 with two distinct size populations > 1.0 cm. and .1 - .2 cm. where the finer grains are likely to have been washed in. For the other samples most contain roughly similar grain sized clasts and are likely deposited contemporaneously with rhombohedral close packing.

3.2.2 Feldspar and Other Components.

The feldspar content does not exceed 3 % (modal analysis, table 2) and is mainly oligoclase - andesine with minor microcline. The grains generally appear fresh and angular and are usually smaller than the median diameter of the rock as a whole. Partial alteration to kaolinite (Plates 9 and 10) is infrequent. The low feldspar content does not imply a low feldspar content in the source as there are indications that most of the grains have been destroyed or altered, and show dissolution features along cleavage planes (Plates 9 and 10). No useful conclusions can be drawn from its occurrence in the succession, as regards facies or its stratigraphic position. However, as oligoclase - andesine predominates over microcline and is generally more susceptible to chemical weathering, it is likely to have

Bed No.	29	43	61	78	98	107	123	144	159	190
Grain size	1 - 3 cm 0.1 - 0.2 cm	c. 0.1 cm	0.1 - 0.2 cm	0.1 - 0.2 cm	0.1 - 0.25 cm	c. 0.1 cm	0.1 - 0.2 cm	0.1 - 0.25 cm.	0.1 - 0.3 cm.	c. 0.1 cm.
Quartz mono - poly - non - und. und.	80 % 20 % 90 % 10 %	60 % 40 % 70 % 30 %	85 % 15 % 88 % 12 %	90 % 10 % 86 % 14 %	85 % 15 % 82 % 18 %	83 % 17 % 72 % 28 %	80 % 20 % 65 % 35 %	75 % 25 % 70 % 30 %	65 % 35 % 70 % 30 %	90 % 10 % 80 % 20 %
Inclusions	Irregular and acicular 15 %	Few acicular	Few regular, irregular and acicular.	Acicular and globules	Irregular and regular	Irregular and regular	Few acicular 5 %	None observed	Abundant regular	Few acicular
Feldspar	< 1 %	c. 3 %	c. 1 %	2 %	c. 1 %	Trace	Trace	Trace	2 %	Trace
Mica	c. 3 %	4 %	2 %	2 %	Trace	Trace	Trace	Trace	5 %	Trace
Others	None	Pyrite cubes	Lithic clasts small grain size - volcanic.	Volcanic lithic clasts	Limonite, hematite	Kaolinite, hematite	Pyrite, illite kaolinite	Kaolinite	Volcanic lithic clasts	Rootlets, hematite
Sorting	Poor	Good	Good	Good	Poor	Good	Good	Poor	Poor	Good
Grain/grain contacts	80 % 90 % qtz/qtz 61 % original	70 % 85 % qtz/qtz 41 % original	63 % 78 % qtz/qtz 36 % original	73 % 73 % qtz/qtz 45 % original	71 % 70 % qtz/qtz 40 % original	70 % 80 % qtz/qtz 47 % original	70 % 85 % qtz/qtz 50 % original	66 % 70 % qtz/qtz 37 % original	76 % 78 % qtz/qtz 53 % original	72 % 85 % qtz/qtz 55 % original
Cement	Quartz and kaolinite	Quartz and kaolinite	Quartz, hematite and kaolinite	Quartz, hematite kaolinite	Hematite, kaolinite	Hematite, kaolinite	Pyrite, illite kaolinite	Quartz, hematite, kaolinite	Quartz, hematite, kaolinite	Kaolinite, hematite
Porosity	15 %	15 - 20 % rare intra - granular	c 10 %	10 %	5 %	5 %	10 %	5 %	5 - 10 %	c. 5 %
Authigenic quartz	Overgrowths and cement	Overgrowths and cement	Few overgrowths and cement	Few overgrowths and cement	Overgrowths	Few overgrowths	Few overgrowths	Few overgrowths	Overgrowths and cement	Few overgrowths

Table 2 Summary of Petrography

Plate 9. Bed 29. Intrastratal solution pitting along cleavage on feldspars.

Plate 10. Bed 29. Intrastratal solution pitting along cleavage on feldspars, with kaolinite formation.

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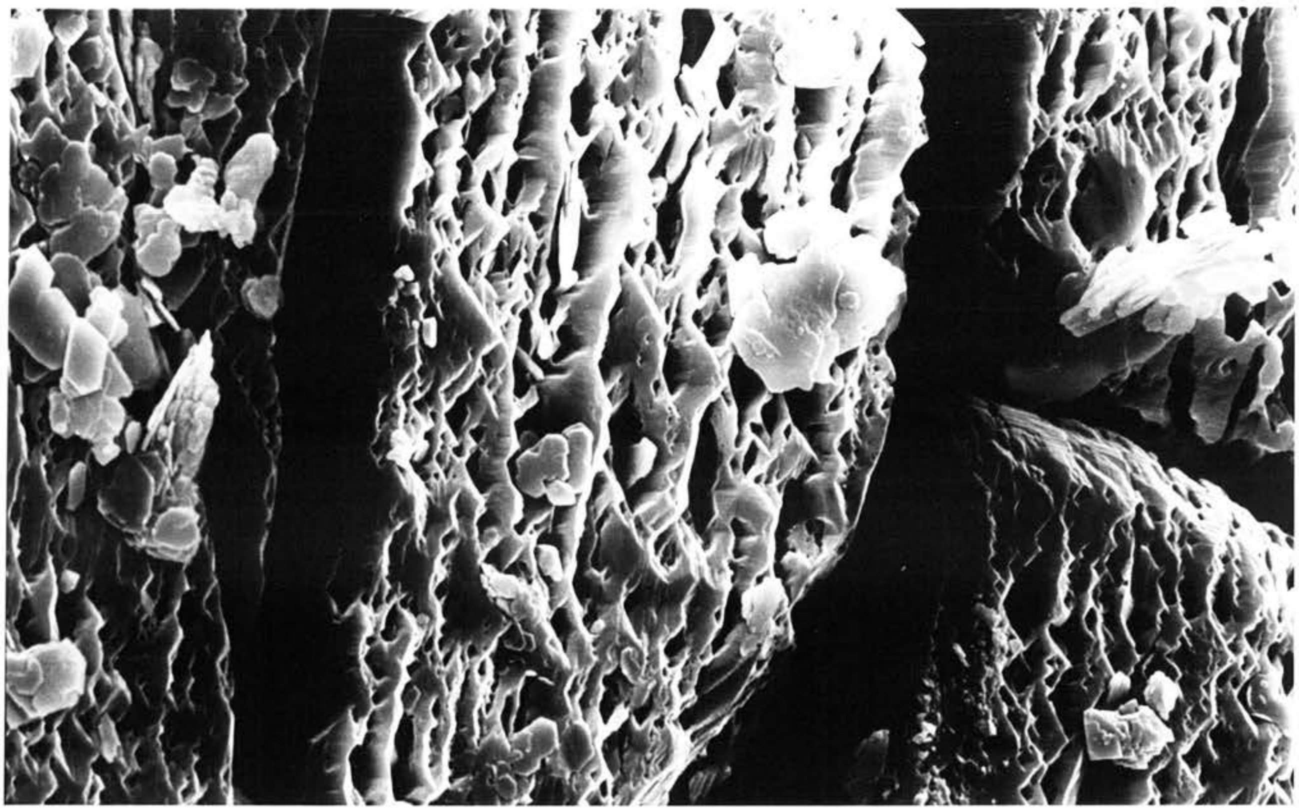

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predominated in the source material, which was possibly metamorphic or plutonic igneous.

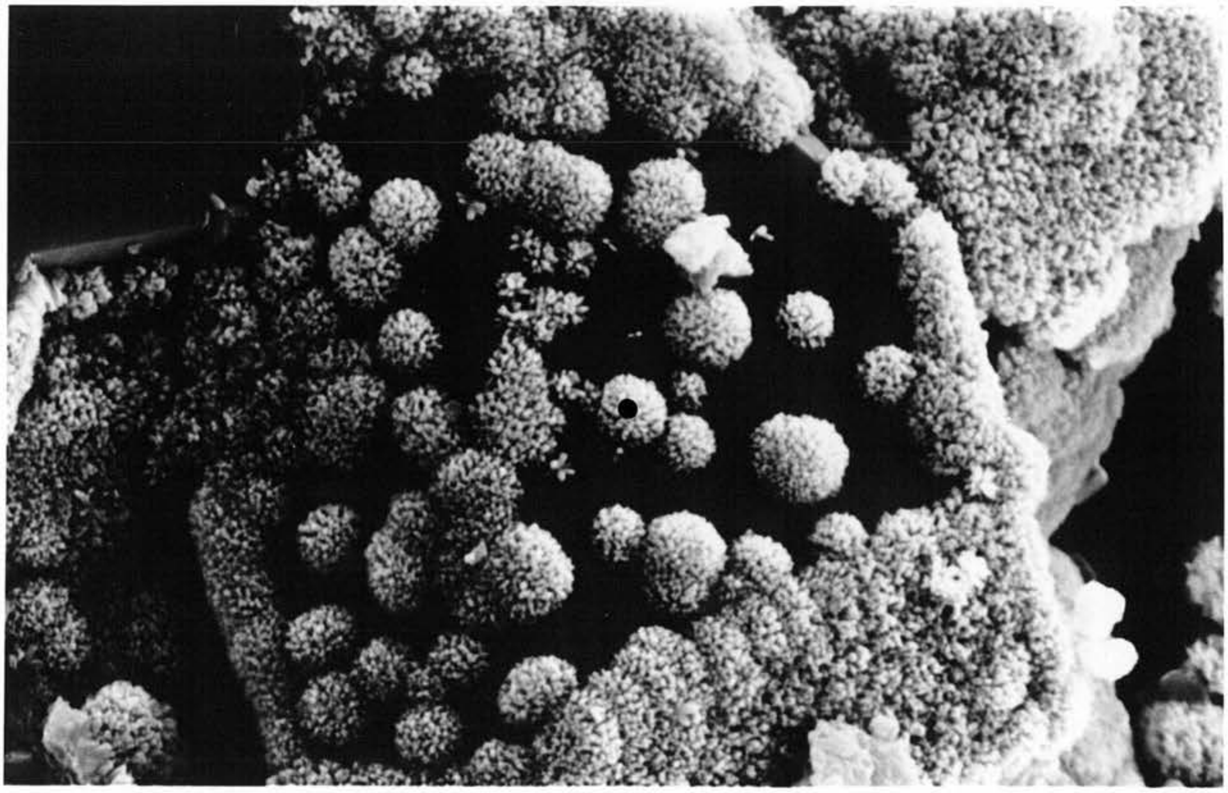
Clastic mica, up to 10 % in some laminae is present throughout the succession and is often found to be distorted and wrapped around grains due to compaction of the sediment. The largely muscovite mica is present as long flakes, whilst in some horizons it is corroded to form clay minerals. Small laths of white mica are present wherever there is a clay matrix.

Little carbonate has been observed in the samples. There is a thin rim of $CaCO_3$ on some grains.

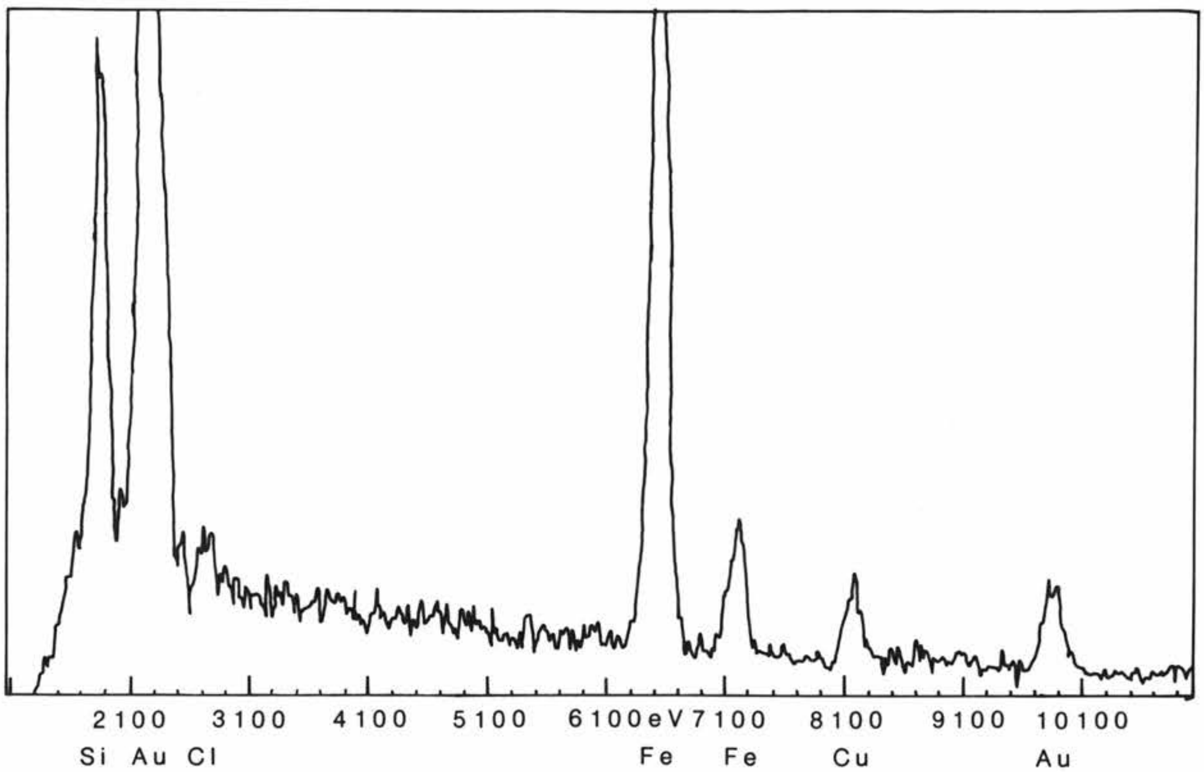
The common matrix for the clastic grains is made up of quartz, hematite or limonite, and argillaceous material. The argillaceous matrix contains biotite, kaolinite and small flakes of muscovite.

Hematite occurs in veins, fine grained in pockets and cross cutting patches which optically postdate the authigenic quartz overgrowths. Within the overgrowths rims of hematite are present, mantling the original grain, suggestive of relative ages. It can also be seen as small hemispherical masses (composed of blades), mantling quartz grains (Plate 11). The dating of this material is impossible petrographically though stratigraphic considerations suggested to Geikie (1902), that it could be Permo - Triassic. Siderite is also present within the succession, and hematised siderite nodules are present within the coal and seat earth facies.

Plate 11. Bed 61. Hemispherical masses of hematite blades,
(E.D.S. trace for hemispherical mass under dot,
(Cu and Au as a result of coating)).



1.0

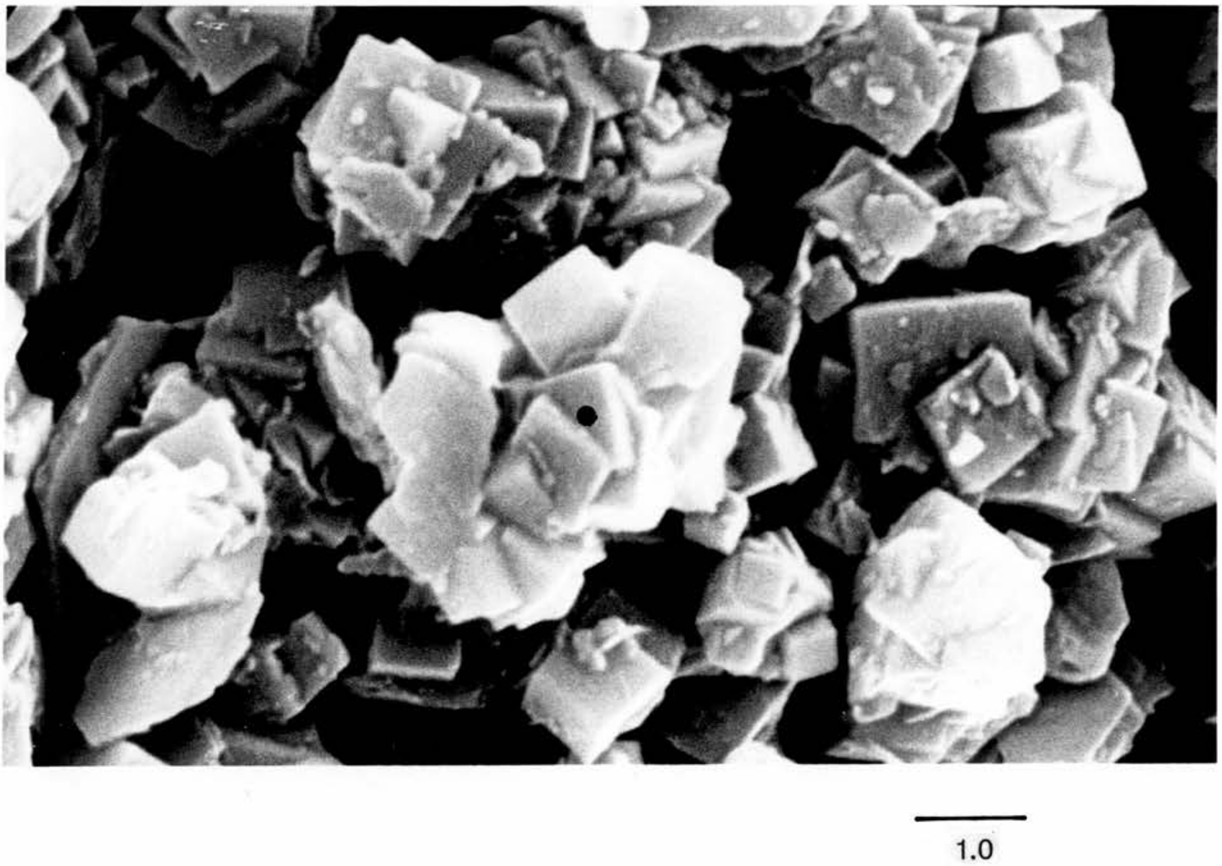

2100 3100 4100 5100 6100 eV 7100 8100 9100 10100
Si Au Cl Fe Fe Cu Au

Pyrite forms as a pore filling authigenic mineral which reduces the porosity intergranularly in the sediment but leaves a residual porosity around its cubic habit (Plates 12 and 14). It is formed during reducing conditions of high iron content pore waters. Where it occurs the hematite mantling the quartz grains within the overgrowths is earlier than the pyrite formation.

Small kaolinite pockets have been recognised from S.E.M. studies and are present in all the sandstones and siltstones, micro-granular accretion is more usual than vermiform structure. As the kaolinite abuts authigenic quartz and fresh feldspar and is moulded around cavities it is thought to be a late authigenic feature. In Plate 13 kaolinite stacks can be seen in pits on quartz overgrowths. These stacks could be later than the pitting, alternatively they could be early and inhibiting overgrowth formation (Muir, 1963) or overlapping in time with the overgrowth. Kaolinite flakes can be seen in most samples lying on quartz surfaces (Plate 15). Euhedral kaolinite must be authigenic ; an additional indication is that individual booklets are too large to pass through pore throats as detrital particles (Pettijohn, 1975). The kaolinite may form from the alteration of feldspar, and can be seen on such feldspar grains, (Plates 9 and 10).

The heavy mineral association consists of grains from 14 varieties of mineral (both detrital and authigenic) in differing concentrations (4.4). The form of these minerals is generally well rounded to sub - angular indicative of abrasion and transport, with the well formed grains possibly authigenic, and the better rounded forms polycyclic (4.4).

Plate 12. Bed 123. Small pyrite cubes (< .1u) mantling quartz grains (E.D.S trace of pyrite under dot (Cu and Au from coating)).



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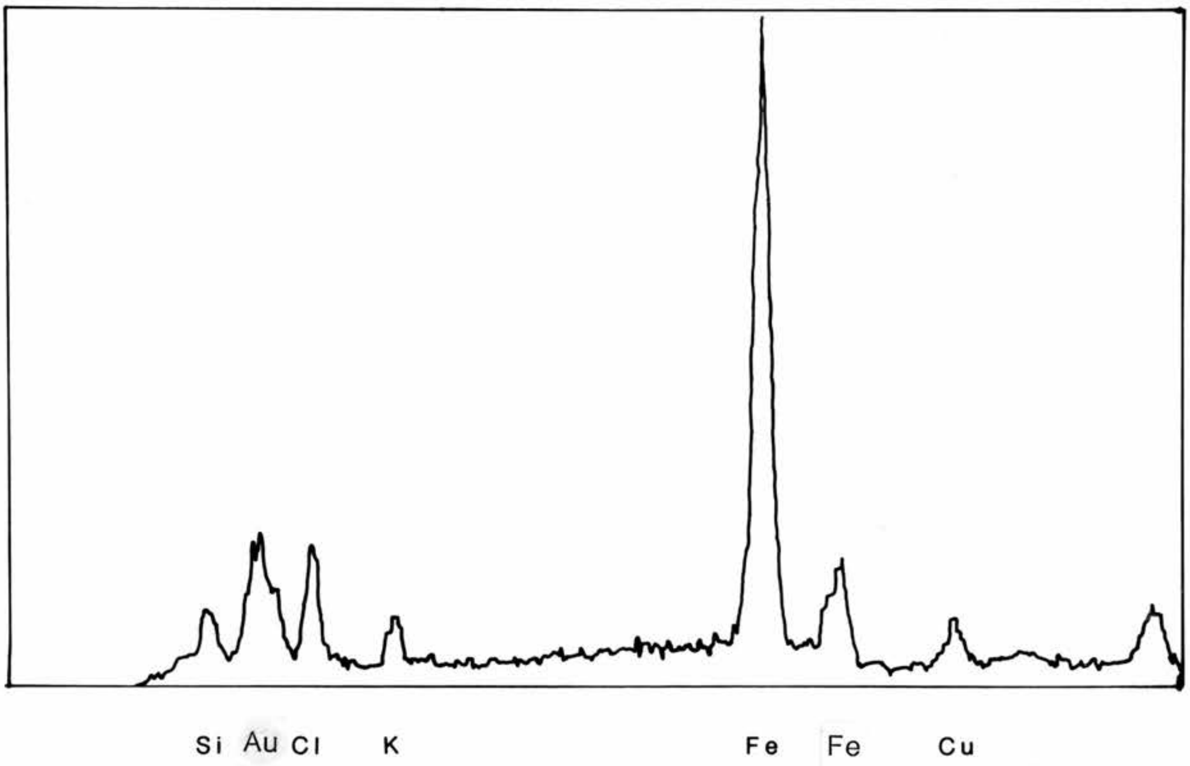
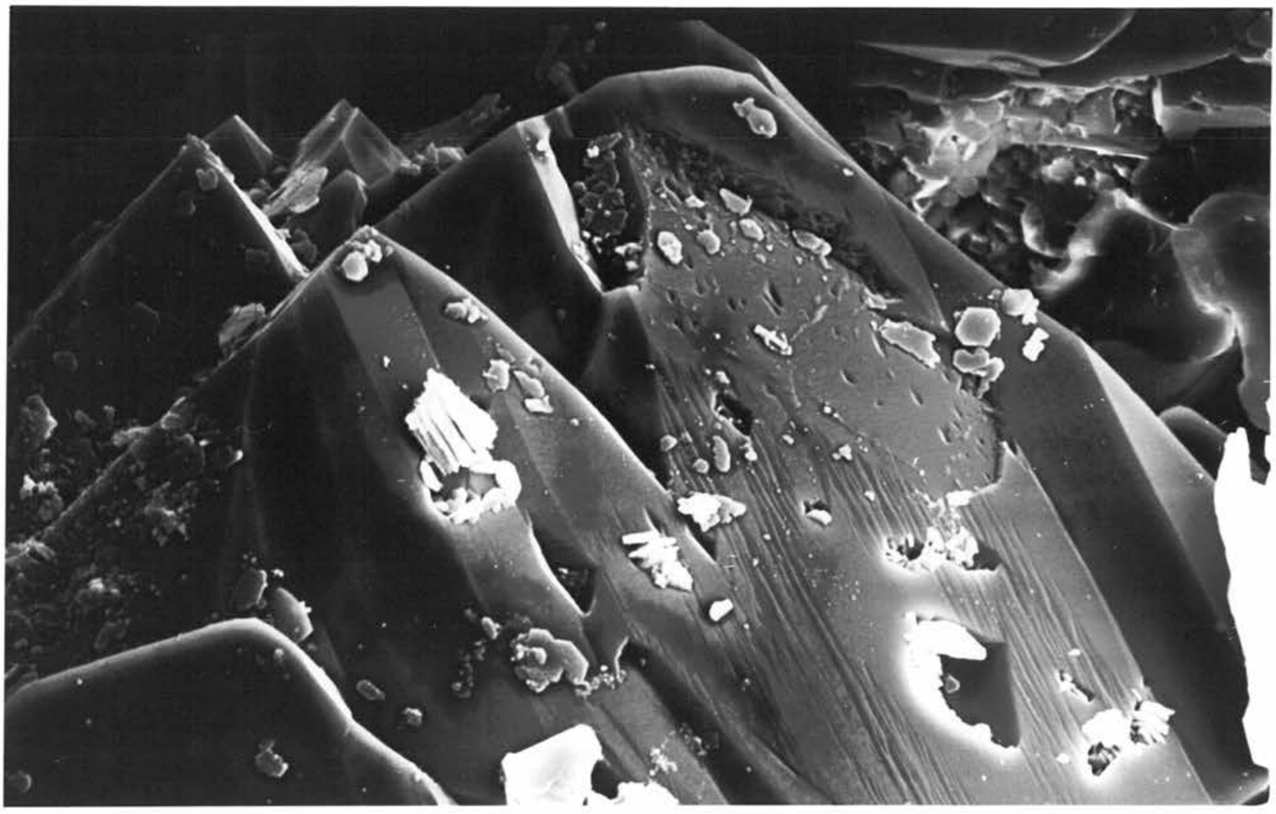


Si
Au
Cl
K
Fe
Fe
Cu

Plate 13. Bed 78. Quartz surface showing impact marks, some of which contain secondary kaolinite stacks. The well formed faces are overgrowths.

Plate 14. Bed 123. Cubic form of pyrite forming cement and mantling quartz grains.



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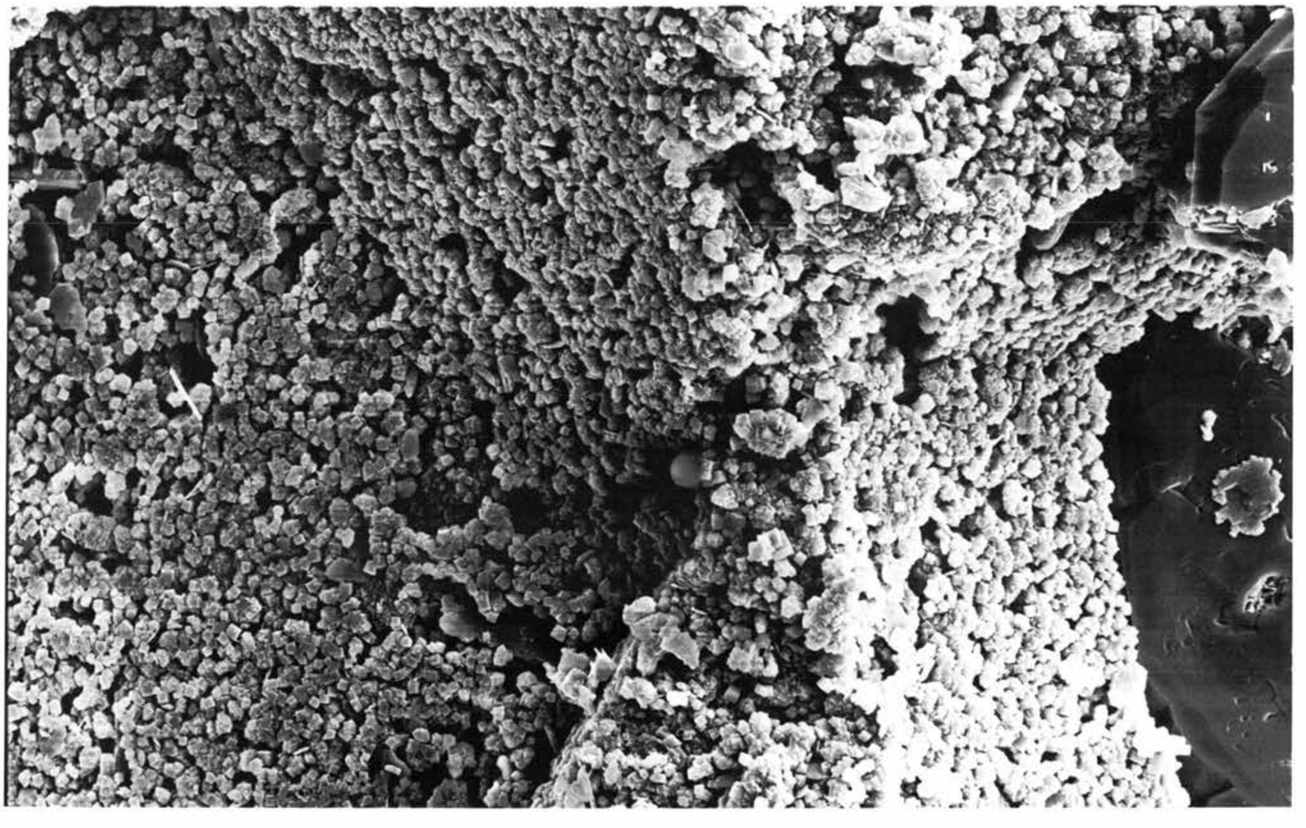

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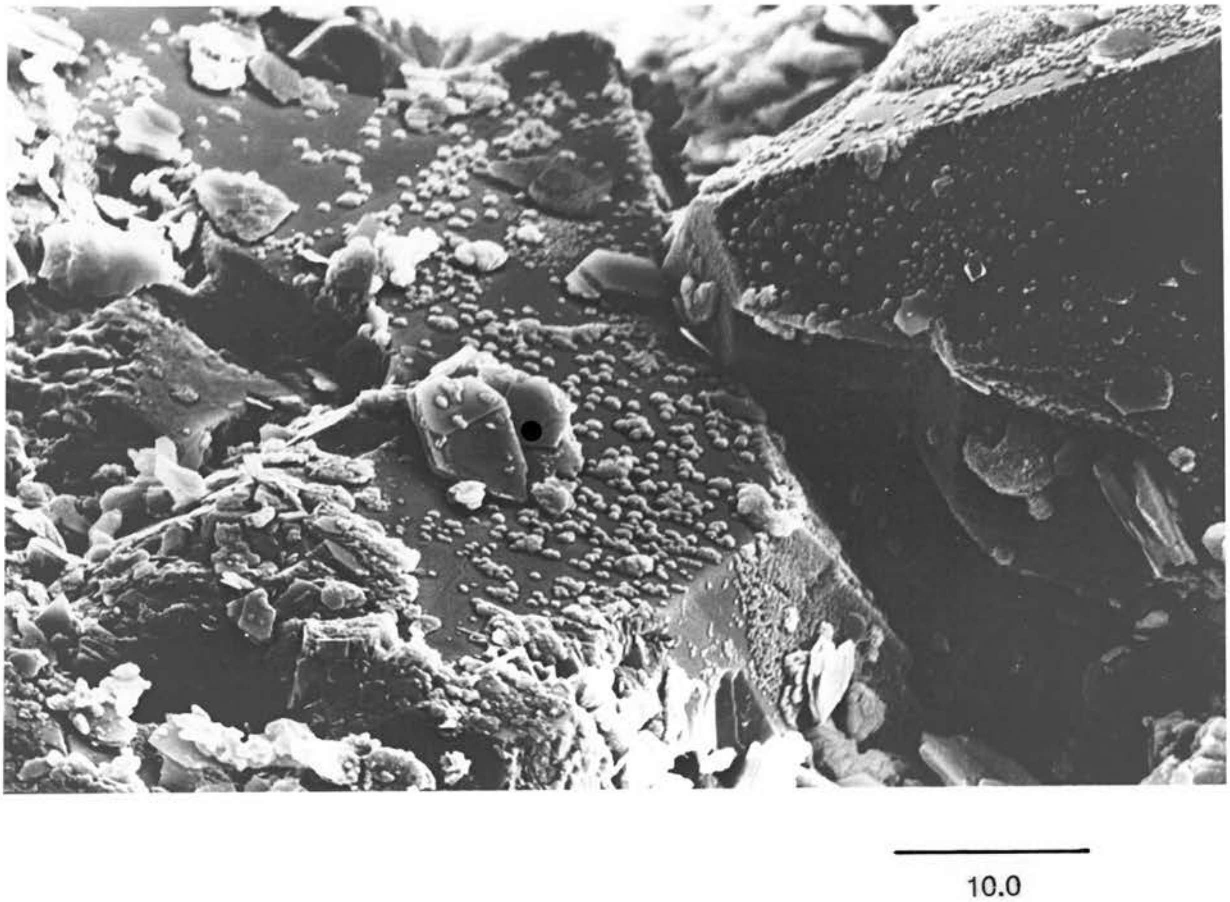
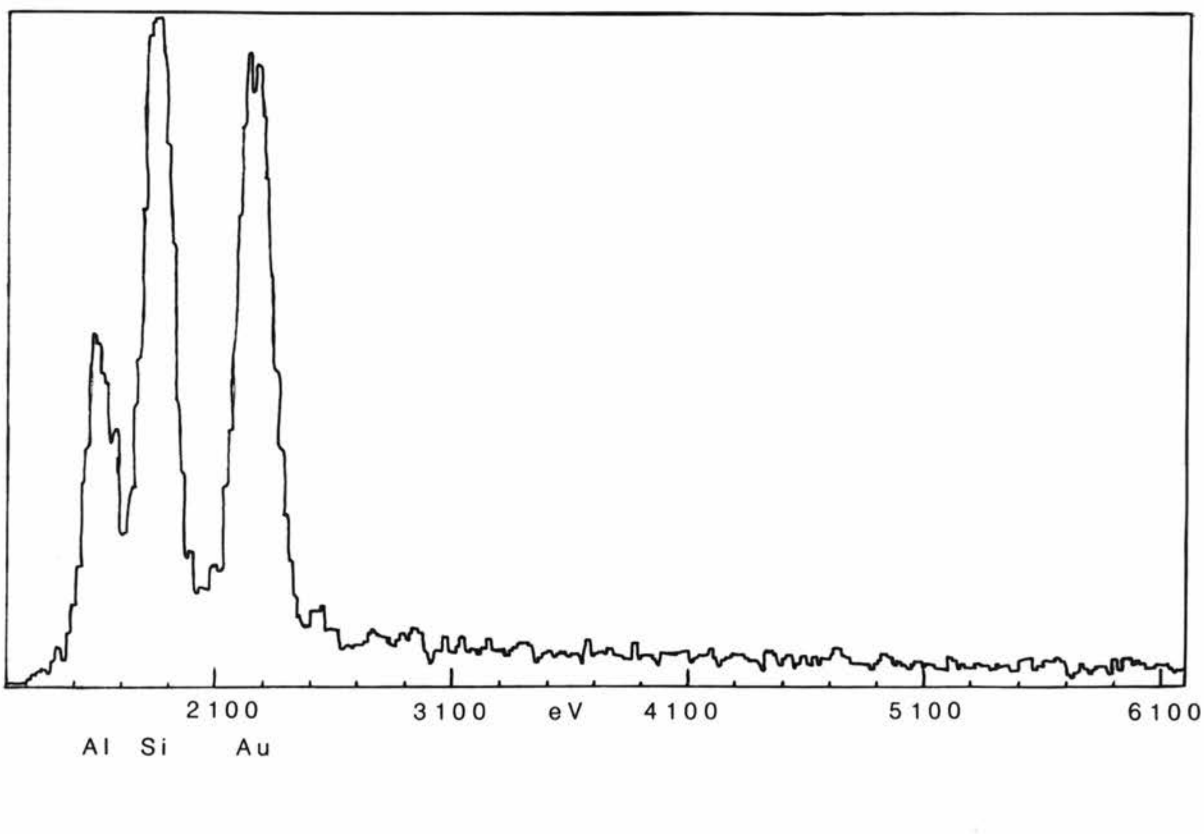
Plate 15. Bed 144. Quartz surface showing kaolinite flakes and minor hematite masses (E.D.S. shows presence of kaolinite and quartz (Cu and Au from coating)).


10.0


2100
3100
eV
4100
5100
6100
Al
Si
Au

Modal analysis (Appendix 6) of the heavy minerals through the succession suggests there is only a slight change in petrology of the source area from igneous to regional metamorphic (see Chapters 4.2 and 5.2).

3.3 DIAGENETIC PROCESSES.

3.3.1 Introduction.

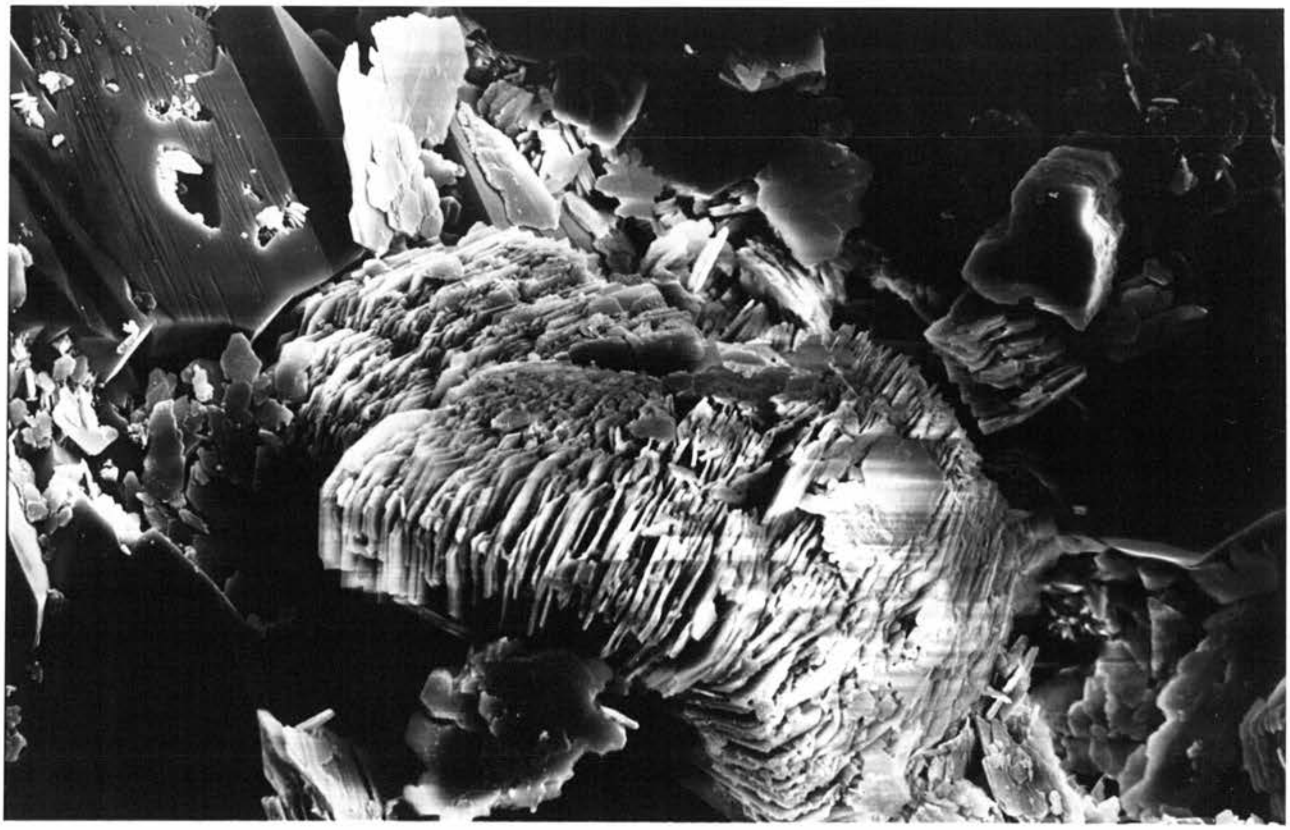
These processes occurred at a variety of times after deposition, and within the succession can be either constructive or destructive. Constructive processes include, cementation by overgrowths and authigenesis, while destructive processes are largely restricted to intrastratal solution. The processes are reviewed here as acting on the four mineral phases (quartz, feldspar, clay and iron minerals) and authigenesis.

3.3.1.1 Quartz.

Within the succession quartz overgrowths are considered to be the first diagenetic effect and it occurred at shallow depth. These overgrowths can be restricted by the occurrence of abundant kaolinite (top left Plate 16), or corroded by it (top left Plate 8). Silica is transported in natural estuarine waters hydrosilicic acid H_4SiO_4, in concentrations of 20 ppm. This silica will be precipitated where these solutions pass into lower pH marine environments forming overgrowths (Blatt et al, 1972).

Plate 16. Bed 78. Kaolinite stack present adjacent to quartz and also as void filling. Upper left shows quartz grain with impact marks filled by kaolinite.

Plate 17. Bed 78. Quartz surface (hummocky), showing chemical etch pits on crystallites which in some cases have become connected.



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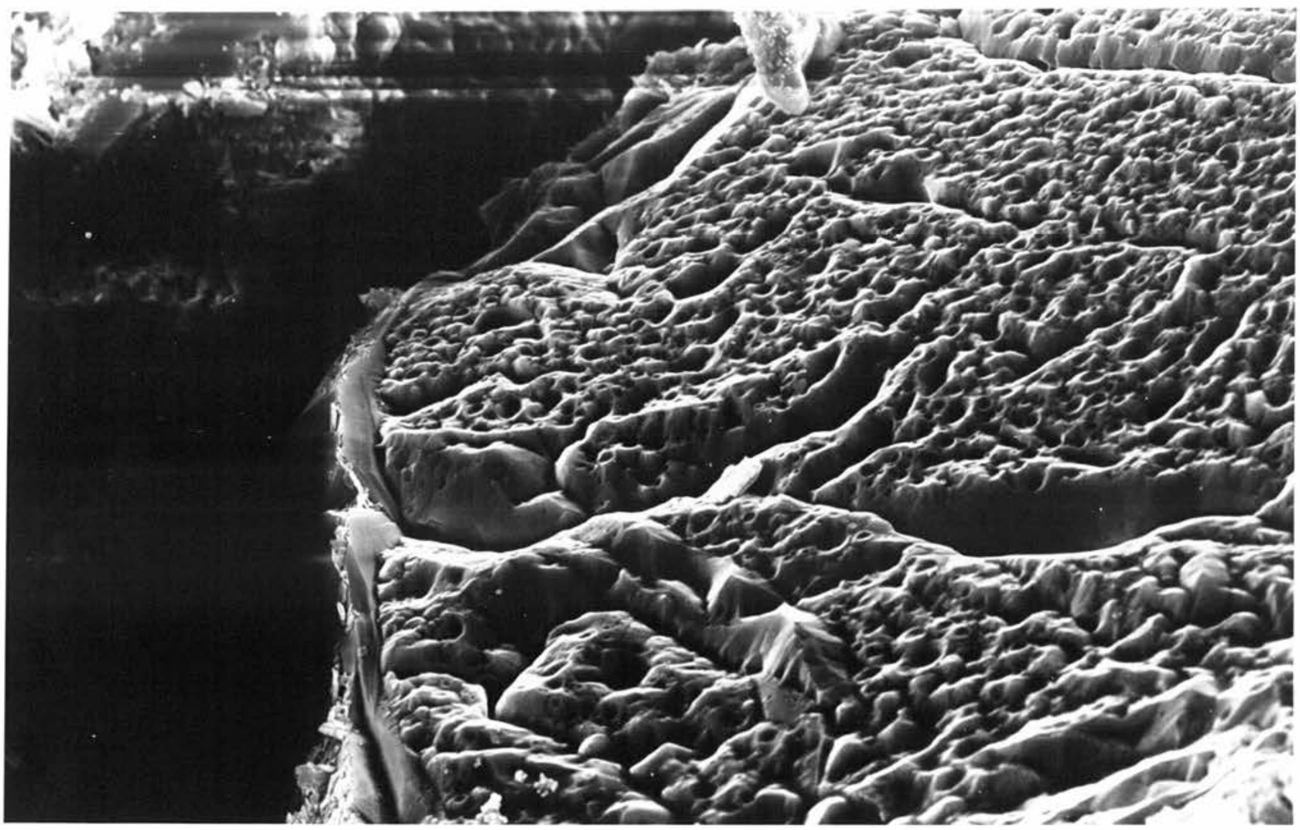

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Plate 17, shows crystallites forming as the first stage of overgrowths, although their apices have been dissolved away by high pH solutions.

3.3.1.2 Feldspar.

Diagenetic effects on feldspar are restricted within the succession to destructive dissolution effects. These dissolution effects visible along cleavage (Plates 9 and 10) forming skeletal grains, also result in the formation of kaolinite, possibly in acidic environments. This reaction (2), also provides free silica which could have been used for overgrowths.

1) $CaAl_2Si_2O_8 + 2\ H^+ + H_2O \longrightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+}$

2) $2(Na,K)AlSi_3O_8 + 2\ H^+ + H_2O \longrightarrow Al_2Si_2O_5(OH)_4 + 4\ SiO_2 + 2(Na,K)^+$

3.3.1.3 Clay Minerals.

The diagenetic clay minerals by their form and size, form from both the precipitation of pore fluids, and also by the destruction of detrital feldspar and mica (Eqns. 1 and 2).

The limited occurrence of illite is suggested as being related to feldspar decomposition and mica alteration.

3.3.1.4 Iron Minerals.

Within the succession are a variety of iron minerals, the most important of which are hematite, pyrite and siderite. These minerals form a proportion of the cementing material as well as being important in their own right.

Iron is present in these sediments from the breakdown of host rocks, or by the reduction of hornblende, biotite or chlorite during transport or after burial. Within the sedimentary pile, hematite (Plate 11), forms as a coating to the clasts from the breakdown of the transported iron compounds.

3) $6\ FeSO_4 + 3\ O = 2\ Fe_2(SO_4)_3 + Fe_2O_3$ (Hematite)

4) $2\ Fe(OH)_3 \longrightarrow 3\ H_2O + Fe_2O_3$ (Hematite)

Pyrite (Plate 12), is linked to formation below the zone of oxygenated pore water, where anaerobic reduction of the sulphate present in sea water occurs. This forms H_2S, which reacts with iron present to form FeS.

Siderite will form where a very low dissolved sulphide concentration is coupled with high dissolved carbonate, and near normal pH. This limits the occurrence of siderite to non - marine environments where abundant Fe^{2+} is present.

3.3.1.5 Authigenesis.

Wholly authigenic minerals are those which are formed at their place of occurrence, while regeneration of minerals also falls into this category, where a mineral is regenerated by growth around a host and in optical continuity with it (overgrowths). Quartz overgrowths have already been described.

Authigenic anatase is present as very small grains precipitated from titaniferous solutions, possibly after the decomposition of biotite. There does not however appear to be any authigenic rutile present although regeneration of some of the rutile grains could have occurred. This process is evidenced by the euhedral form to some of the grains.

Authigenic clays form from the breakdown of feldspar (Eqn. 1 and 2), and thence to illite with liberation of Si and K.

The iron minerals form from solution by a series of reactions (Eqns. 3 and 4), dependent on the conditions in the zone of deposition, and the composition of the pore waters.

3.3.2 Diagenetic History.

No absolute order can be identified for the diagenetic history of the rocks in the succession. However, a tentative sequence can be proposed based partly on thin-section and S.E.M. analysis, theoretical considerations and by comparison with the overlying Lower Limestone Group (Al-Rubaii, 1986).

1) Compaction of the sediments causing deformation of micas, occurs at shallow depth, with free access of pore fluids. At this stage percolating solutions would begin to deposit the first iron cements on the quartz clasts as hematite rims.

2) Dissolution of the feldspars occurs with formation of early kaolinite, as well as the alteration from mica to kaolinite via illite.

3) Overgrowth and kaolinite formation overlap evidenced by kaolinite within and inhibiting overgrowths. These two processes must have been stopped by a period of dissolution, forming etch pits on the quartz grains and overgrowths.

4) At some stage carbonate precipitation should have occurred, this is well developed within the Lower Limestone Group, but lacking in the Pathhead Beds, possibly due to recent dissolution within the present zone of weathering.

5) Later stages of diagenesis reflect pyrite formation and illite formation.

3.4 PETROGRAPHIC CONCLUSIONS.

Compositional variation throughout the succession is not marked. Most differences can be attributed to transportation and deposition associated with the different facies, for example channel sands are cleaner and better sorted than overbank deposits.

Source indicators such as undulose and non - undulose quartz, inclusions and mono - and polycrystallinity suggest that the bulk of the samples are from medium to high grade metamorphic sources Fig. 14. Some beds show more influence of high grade metamorphics (Beds 78 and 190), or plutonics (Bed 29).

This high grade metamorphic quartz could be from Dalradian or Old Red Sandstone contamination, with the rest being from medium - high grade with associated heavy minerals. However, these high grade metamorphic heavy minerals would likely disappear during transport. The question of provenance is discussed further in Chapter 4.

4 HEAVY MINERAL ANALYSIS.

4.1 INTRODUCTION.

Heavy mineral analysis is used in this study in an attempt to characterise the sediments under investigation, and to determine sediment provenance. Effects of later processes on the mineral assemblage may also be inferred. The method used for heavy mineral separation is described in Appendix 3, with a discussion of the accuracy of the technique in Appendix 4 (see also Morton, 1985a).

4.2 MINERALOGICAL VARIATION.

The sediments under study have been postulated as being derived from the Eastern Highlands (Greensmith, 1965, 1961b), a zone of Caledonian granitic emplacement and regional metamorphism (Chapter 5). Quartz petrography (Chapter 3), suggests both plutonic and metamorphic hosts. Denudation of these highlands in pre-Dinantian times led to an influx of sediment into a constructive, fluvially dominated delta (see Chapter 2.4). However, the minerals encountered today in the lithified sediments may not be as representative of the source for the following reasons:-

1. weathering both in the source area and alteration in the zone of deposition (4.2.1),

2. mechanical destruction during transportation (4.2.2),

3. selective sorting according to size, shape and density (granular variations) (4.2.3),

4. chemical destruction after deposition (diagenesis including intrastratal solution) (4.2.4).

4.2.1 Weathering.

The importance of weathering on modifying the heavy mineral assemblage has been investigated by many authors (Sindowski, 1949, Pettijohn, 1941). Weathering effects are shown by a decrease in the less stable components (augite, hornblende and epidote) and a corresponding relative increase in the stable components (kyanite, staurolite, tourmaline, rutile and zircon), (Van Andel, 1959). Although weathering may significantly modify mineral assemblages in humid areas of low relief with slow deposition rates, its influence on the composition of sediments is negligible in basins with rapid rates of erosion at source and rapid rates of deposition.

4.2.2 Mechanical Destruction.

Pettijohn (1975) has shown minerals to have differing susceptibilities to mechanical destruction, however there does not generally appear to be any appreciable wear on a sedimentary particle in a single cycle, and this would likely only be significant if sands are subjected to high energy especially aeolian conditions over a considerable length of time during transport phases. The effects of reworking will be cumulative and may lead to destruction of the less stable elements while those minerals with good cleavage would be expected to fracture rather than undergo attrition and rounding. The influence of cleavage is likely to lead to a concentration of minerals with excellent cleavage in the finer size fractions (Van Andel, 1959).

4.2.3 Granular Variations.

Granular variations are brought about by size, shape and density effects, in that these factors determine which minerals will be deposited together under given current conditions. These effects have been studied by Rubey, (1933), Maiklem, (1968) and Gibbs et al., (1971).

Sorting effects on an assemblage with a particular grain size distribution may increase or decrease density effects of the assemblage (Smithson, 1939).

Size effects.

The ideal settling equation for small spherical particles is Stokes' Law, however with larger particles complications arise. Gibbs et al. (1971), propose an empirical equation for fall velocity, based on spheres, this approximates Stokes Law for small grains, and Rubeys' (1933) impact law for larger grains.

$$V_s = \frac{-3\,n + \sqrt{9\,n^2 + g\,r^2 P_f\,(P_s - P_f)\,(0.015476 + 0.19841\,r)}}{P_f\,(0.011607 + 0.14881\,r)}$$

where n = viscoscity of fluid in poises,

g = acceleration due to gravity,

r = radius of sphere in cm.,

P_f = fluid density g / cm^3,

P_s = sphere density g / cm^3.

Generally small grains of high density settle with larger grains of low density for given current conditions. However, certain minerals tend to be restricted to crystals of a certain size eg. zircon and rutile are usually small (< 90 microns), hence current sorting cannot draw on a supply of minerals that is evenly distributed throughout the entire range of size grades but depends on the mineral availability. Large spherical particles will be deposited first from a moving body of water, with smaller or platy particles with smaller settling velocities staying in suspension for longer.

Shape effects.

Settling velocity will be affected by shape, platy particles will fall more slowly than spherical grains. Gibbs et al. (1971), propose the idea of nominal spheres, those theoretical grains having the same density and fall velocity as the platy grains, these spheres will be smaller than the platy grains and have lower settling velocities.

Maiklem (1968), states that spheres of similar bulk density settle with velocities 30 - 50 percent greater than plates of similar (sieve) size. The shape of the greatest cross sectional area most strongly affects settling behaviour. Therefore, in a given grain size, high sphericity particles will be transported more by traction and less by saltation. It appears that only in extreme cases does shape have any effect on the resultant assemblages (van Andel, 1959, Pettijohn, 1975).

Density effects.

The size frequency distributions (cumulative weight percent), of part of the mineral association are shown in Fig. 15 (Appendix 5). The percentage number (N) of grains of each type of heavy mineral in a size grade have been multiplied by their densities (D) divided by the sum of N * D for the minerals studied and multiplied by the total weight (W) of heavy minerals in that grade.

$$\frac{N_{Zi} * D_{Zi}}{\text{Sum } (N_{min} * D_{min})} * W180 = W_{Zi180}$$

Min. = Zi, Ru, To, Ga.

Thus total weights of each species in each grade are found and from this, distributions by size and density of the minerals can be found. These have been presented on graph paper (Fig. 15) for a selection of samples, (100 % is the total weight of mineral in the sample).

Weight of the heavy minerals has been used as opposed to number as, (in the case of zircon) this would show a false concentration towards the finer fractions. Although zircon is more abundant by number of grains (modal analyses Appendix 6), these fine fractions only comprise a small percentage of the sample.

The zircon cumulative curves all show a steepening towards the finer fractions, indicating a relative enrichment in these grades. The graphs for rutile (with the exception of Bed 107), are very close to straight lines indicating that the percentage by weight of rutile present is consistently normal in all the samples studied. For the

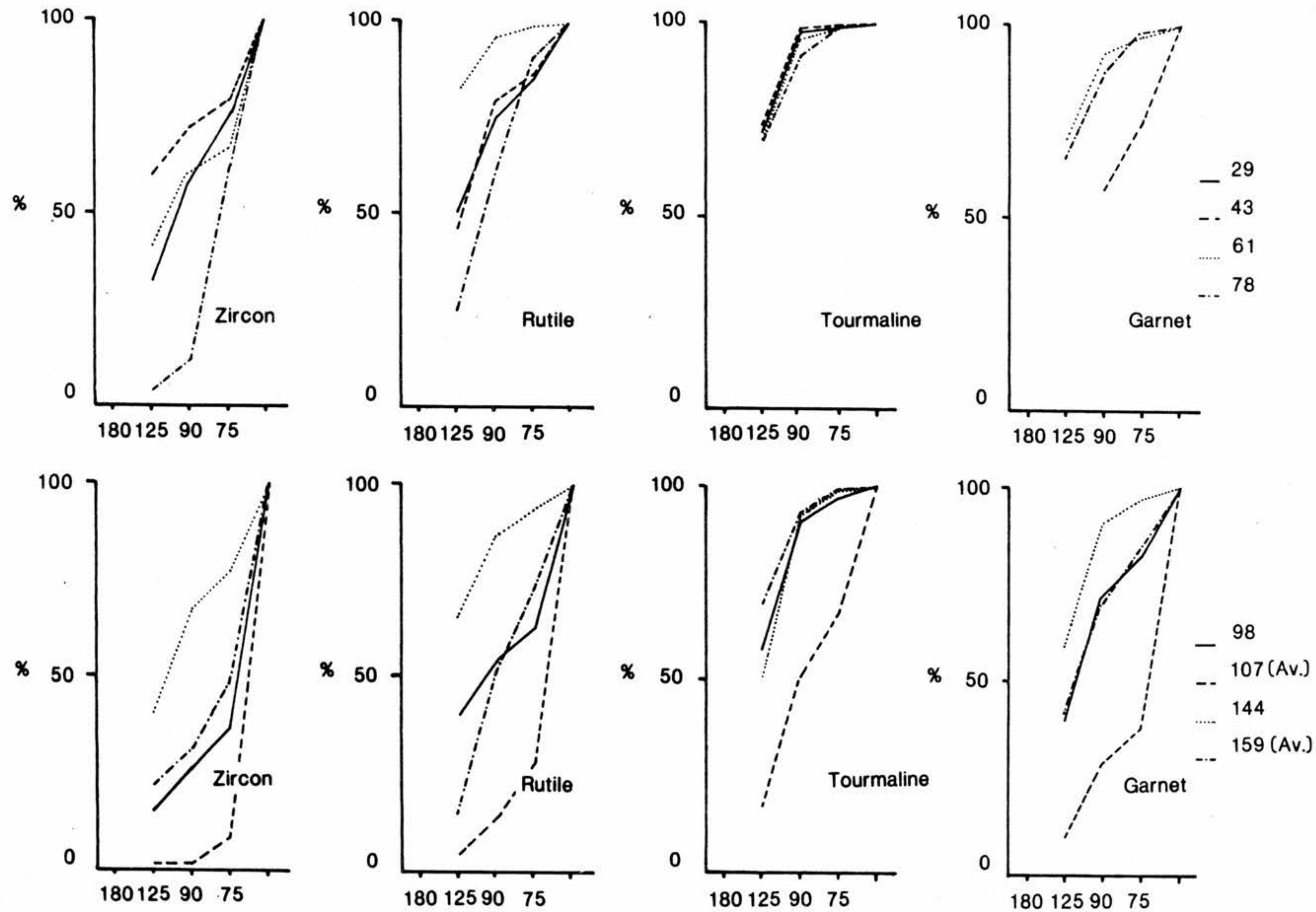


Fig. 15.1 Size frequency distribution of some heavy minerals in percentages by weight.

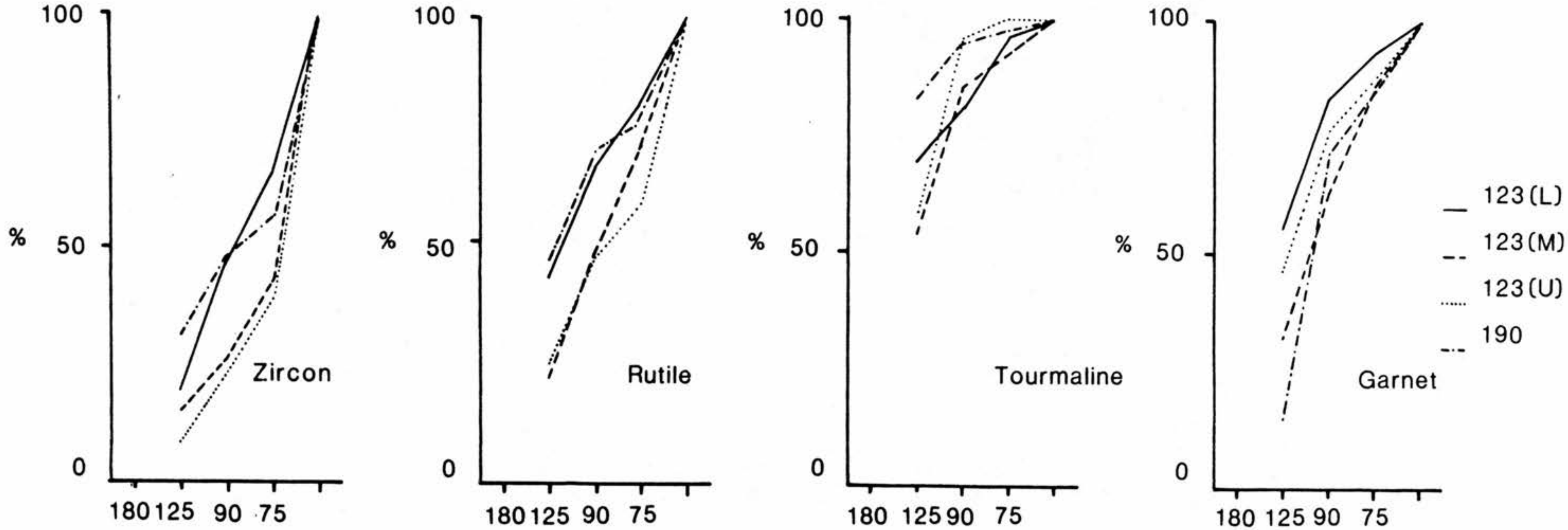


Fig. 15.2 Size frequency distribution of some heavy minerals in percentages by weight.

tourmaline curves there is a greater percentage by weight in the coarser grades than zircon but this declines rapidly towards the finer fractions for all the samples.

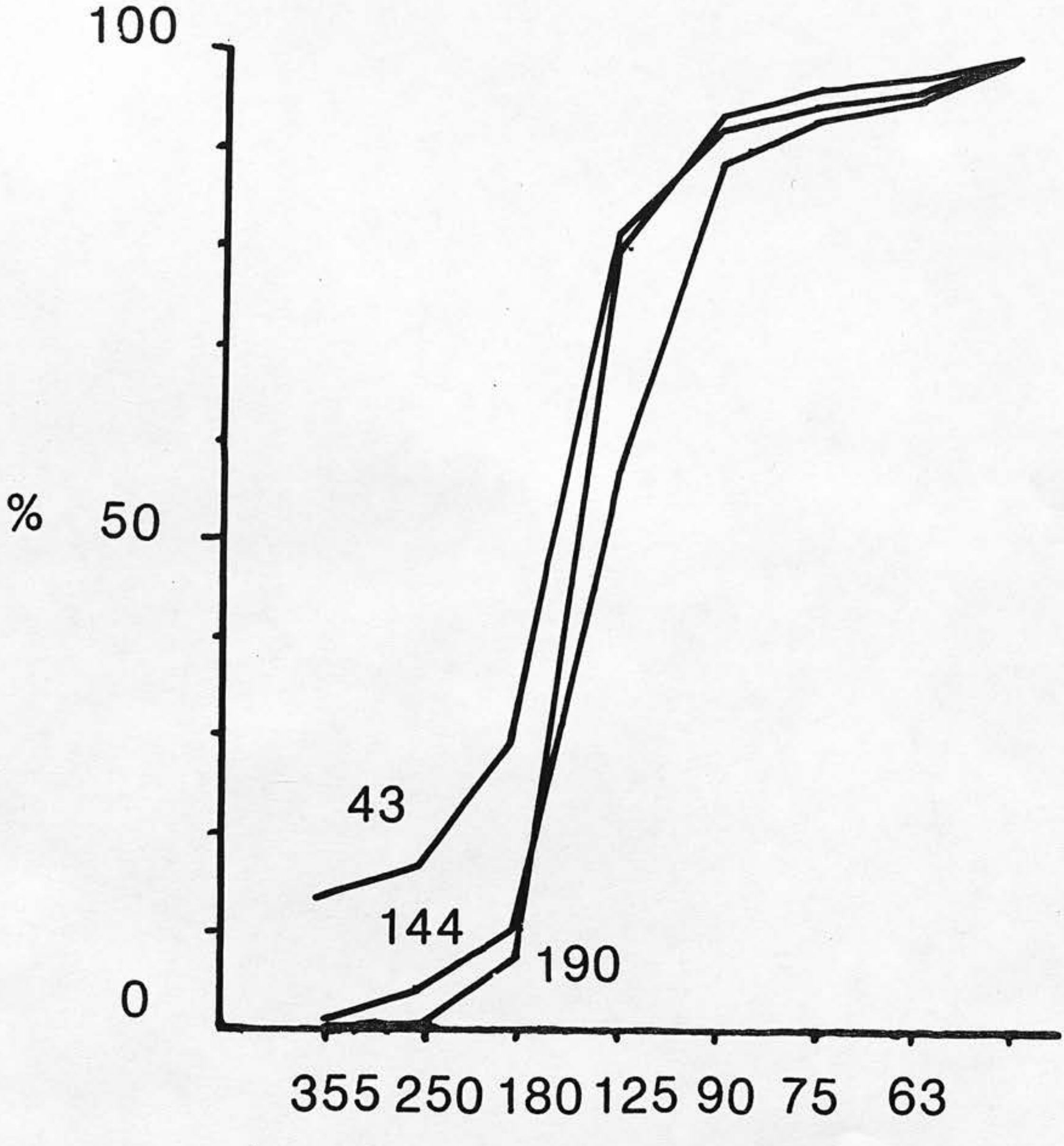
Figure 16 shows the similar distribution by weight of tourmaline (D = 3.2) to those of the light minerals while, the zircon distibution (higher density D = 4.6) is radically different, hence density effects play a major part in forming heavy mineral associations.

For garnet, the bulk of the weight distribution is in the coarser grades at the base of the succession (Beds 43, 61 and 78). Towards the top of the section (Beds 159 and 190), this effect becomes less noticeable and more garnet by weight is in the finer grades. This is possibly due to the effects of mechanical destruction or more likely source rocks variations.

Using the mineral weight percentage in Appendix 5, the median size for these minerals has been calculated (Fig. 17, Table 3). This shows a difference in distribution between zircon and tourmaline reflecting density controls (the less dense tourmaline is generally coarser, than the dense zircon which is usually fine). The rutile and garnet distributions are similar with similar densities.

Conclusions on granular variations.

These granular effects affect a mineral association in that if the source supplies an assemblage of mixed sizes and shapes, large grains may be absent in the deposit as they may have been removed earlier, alternatively there may be a total absence of the lighter or



ig. 16. Distribution by weight of zircon and tourmaline and light minerals for samples bed 43, 144 and 190.

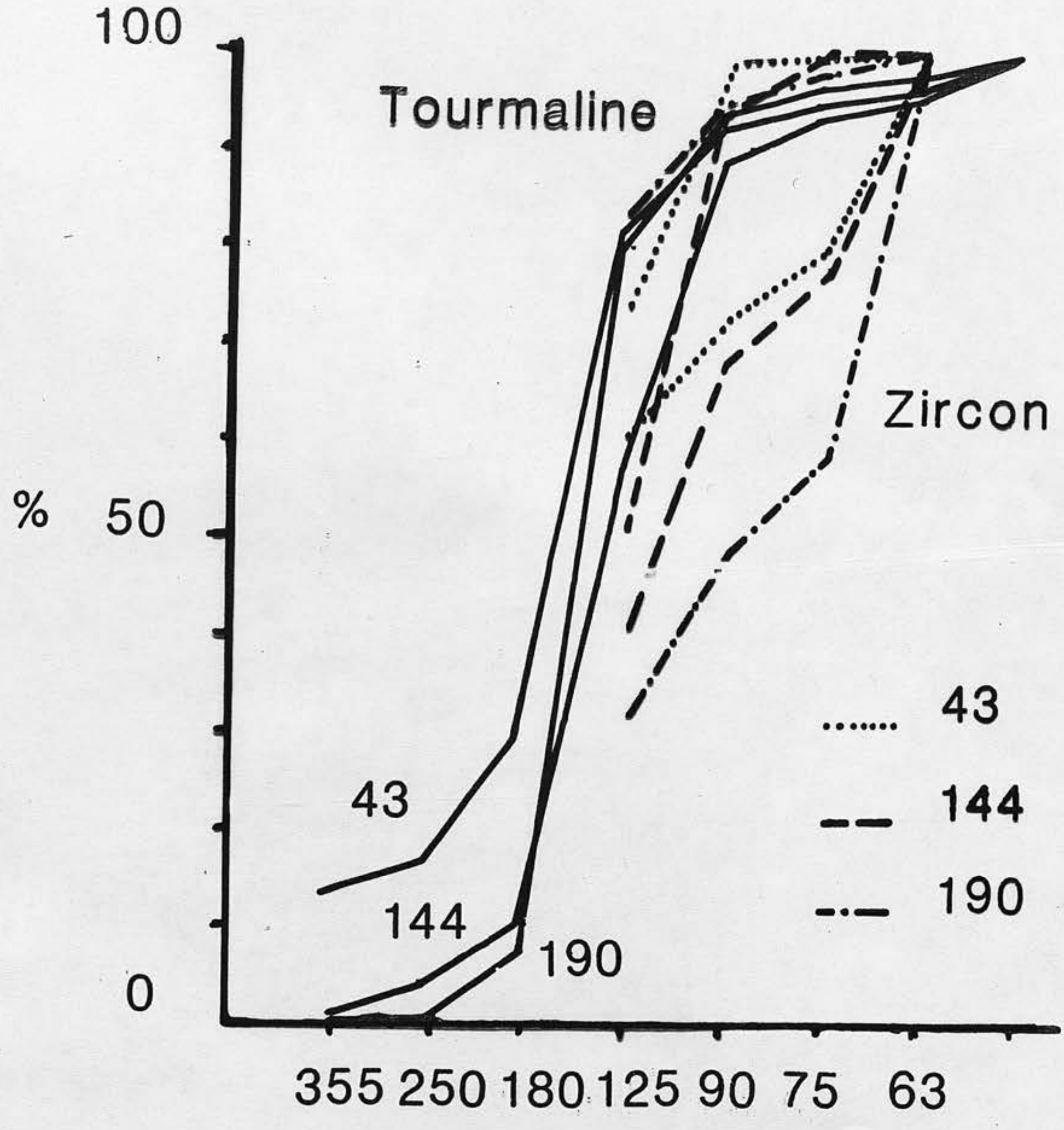


Fig. 16. Distribution by weight of zircon and tourmaline and light minerals for samples bed 43, 144 and 190.

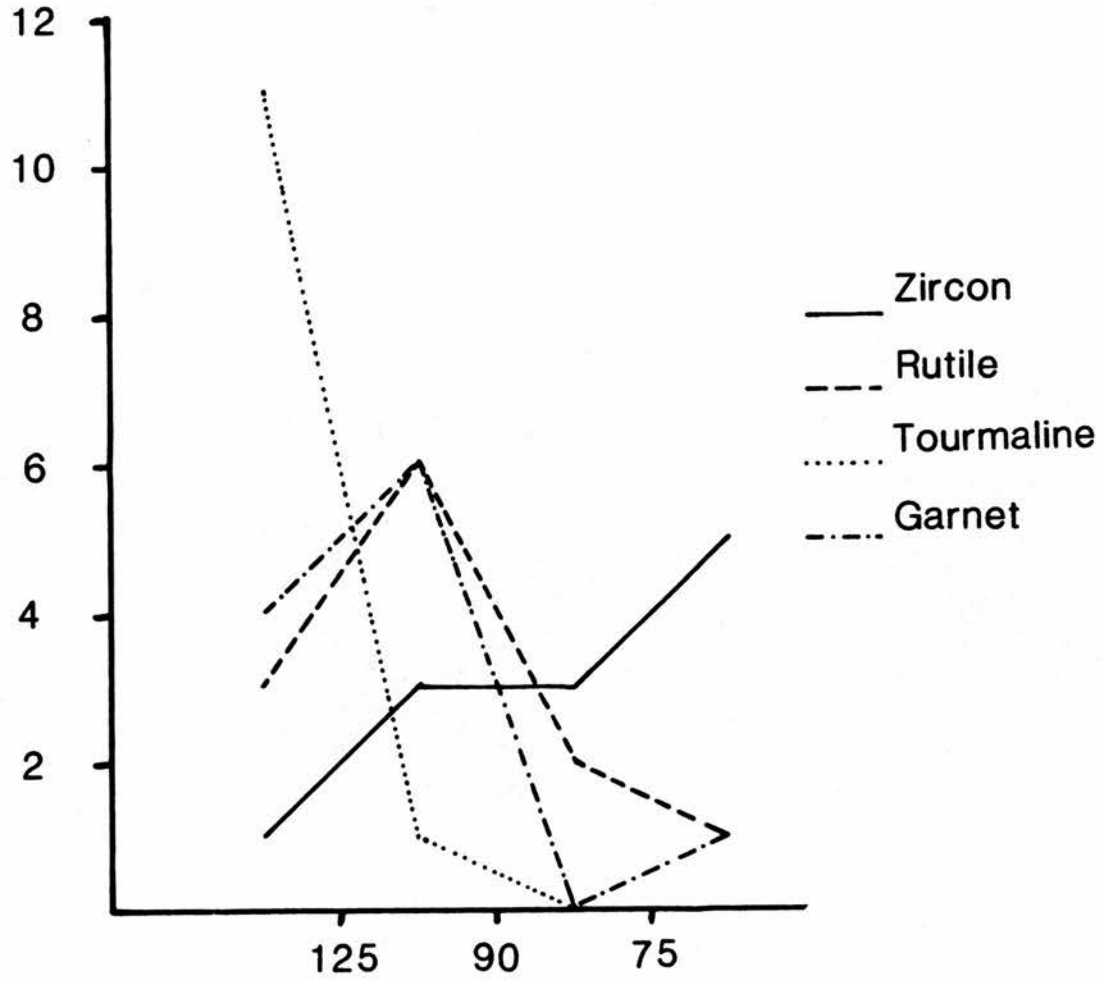


Fig. 17. Plot to show variation in median size for different heavy minerals.

TABLE 3.

DISTRIBUTION OF THE MEDIAN SIZE OF THE THE WEIGHT PERCENTAGES FOR SOME HEAVY MINERALS.

	SIZE (in microns)			
MINERAL	> 125	125-90	90-75	< 75
ZIRCON	1	3	3	5
RUTILE	3	6	2	1
TOURMALINE	11	1	0	0
GARNET	4	6	0	1

platy grains as they remain in suspension.

4.2.4 Diagenetic Effects and Intrastratal Solution.

Diagenetic effects related to the disappearance of the less stable minerals is impossible to estimate, although this process has undoubtedly occurred with the loss of the less stable minerals. Constructive effects are visible in the form of overgrowths on the garnets increasing grain size, (overgrowths - Simpson, 1976, imbricate wedge marks - Rahmani, 1973) formed from solution, and destructive pits present on some grains formed by dissolution (Simpson, 1976).

Rutile is a secondary decomposition product (Brammall and Harwood, 1923), which can be rejuvenated by the accretion of titanium dioxide from breakdown of ilmenite forming euhedral crystals, alternatively authigenic euhedral anatase present in the succession may be formed.

4.2.5 Heavy Mineral Composition of Samples.

The mineralogical composition by number of different size grades for three samples (Bed 123), is represented in Fig. 18.1. In this diagram, the mineral assemblages of all size grades have an equal value (100 %). The curves obtained represent mineralogical variation with size within a sample with the size frequency distributions of the

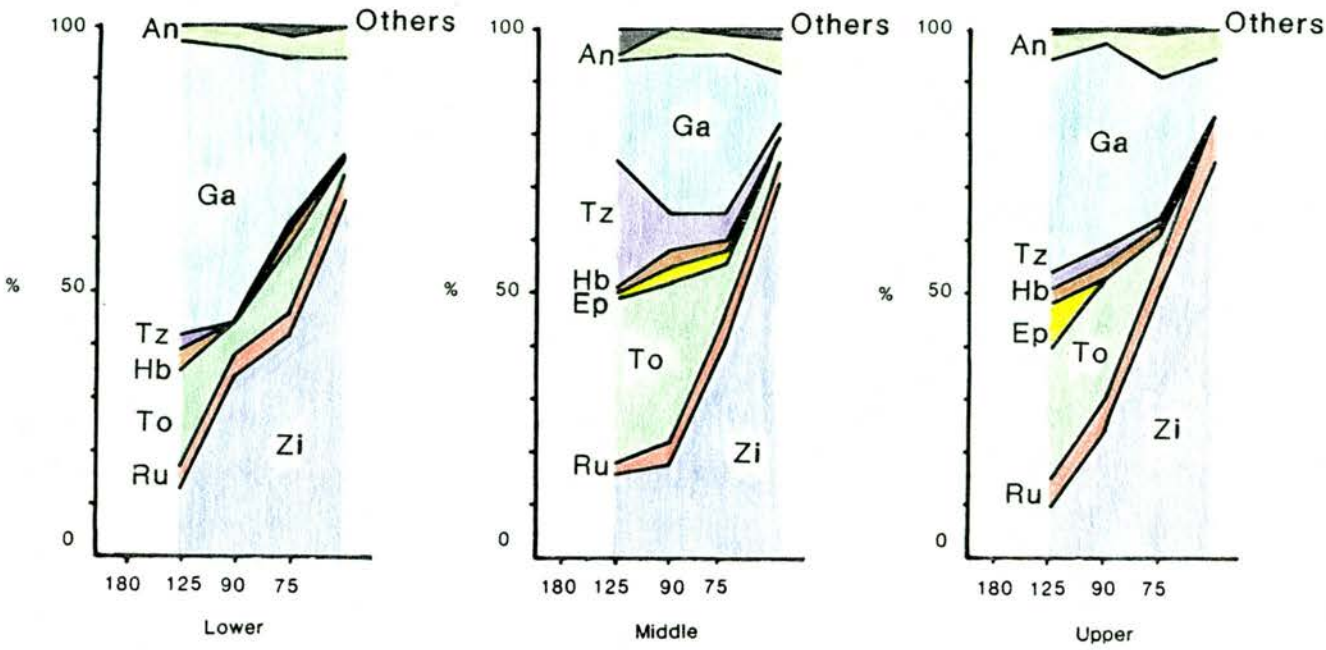


Fig. 18.1 Mineralogical composition of sample B 123 across the unit.

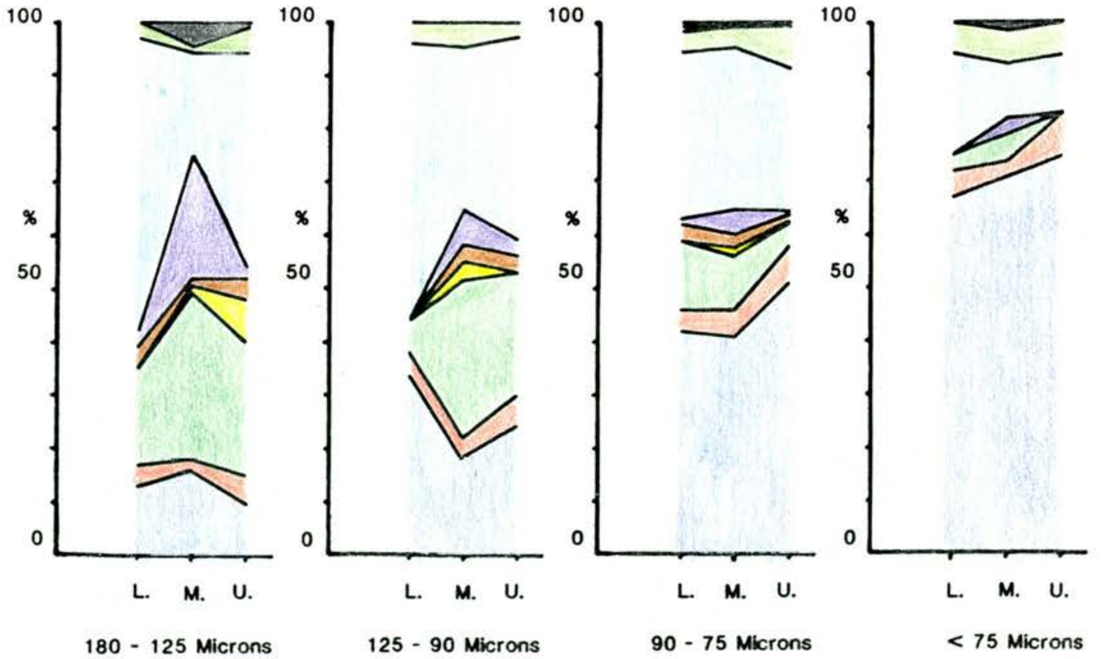


Fig. 18.2 Mineralogical composition of sample B 123 by size (colour coded as in 18.1).

whole samples ignored. The finest grades are largely characterized by a zircon and garnet assemblage, while the coarser grades are characterized by a garnet and tourmaline assemblage with a secondary characteristic of topaz and zircon components (Fig. 18.2). The garnet is concentrated in the stratigraphically lower and upper sample (Fig. 18.1) with the middle sample containing most tourmaline. The upper sample at all size grades contains less garnet by number than the lower sample possibly indicative of a change in the size distribution of the supplied garnet.

From these graphs (Fig. 18.2), it is clear that coarse sands will contain more garnet than finer sediments. An increase in the percentage of 90 - 75 micron grade sediment would shift the relative ratio of garnet : zircon towards zircon. This holds true only if the heavy mineral content of the size grades is actually related to the size frequency distribution of the sediment.

Figure 19 shows the distribution by weight and size of the light (Appendix 7), and heavy minerals (expressed as a percentage of the total heavy minerals present - Appendix 8.2). This graph shows a similar distribution for the bulk of the sample light minerals, to that of the heavy minerals although the mode for the heavy minerals is shifted (90 - 75 microns as opposed to 180 - 125 microns). This distribution and the concentration of heavy minerals within the finer grain sizes again suggests density sorting.

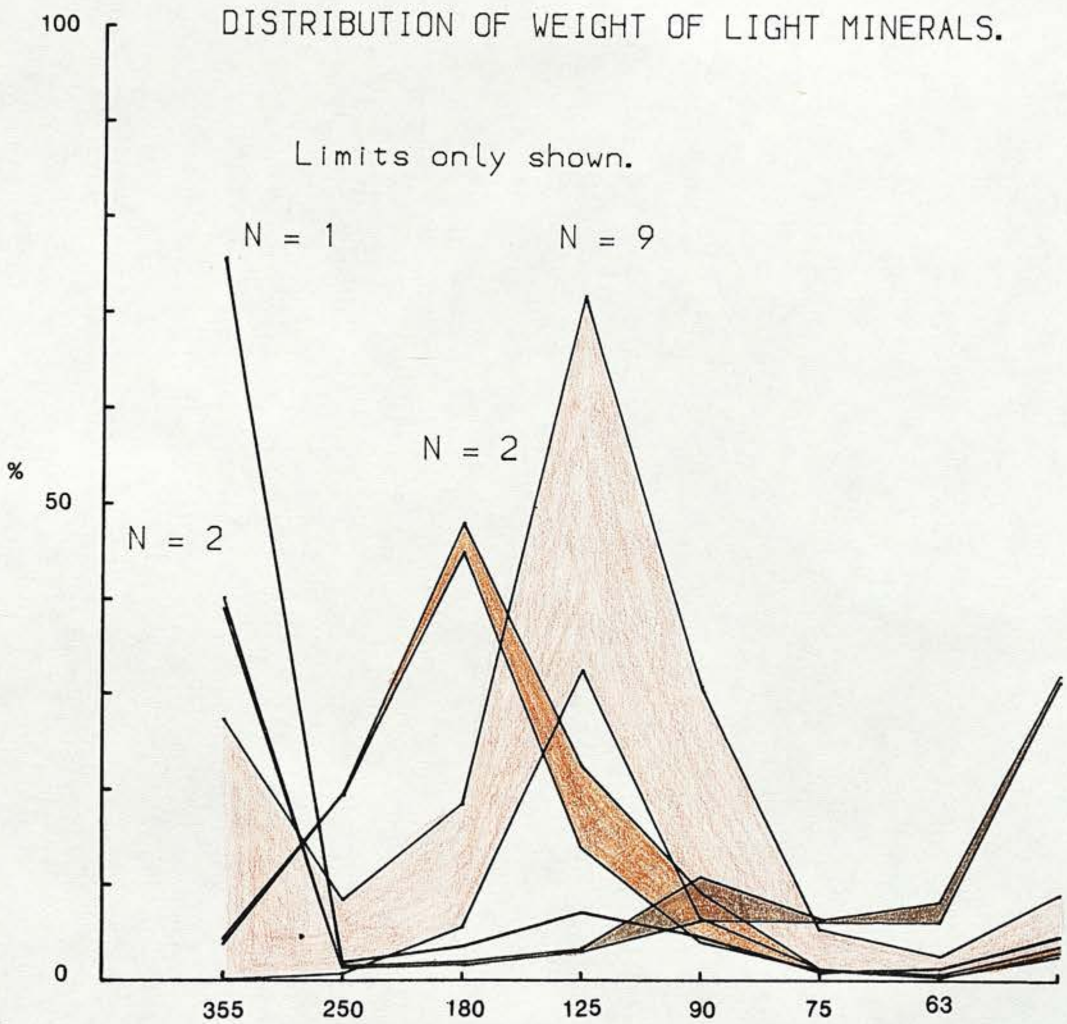


Fig. 19 **Distribution by size of weight of heavy and light minerals.**

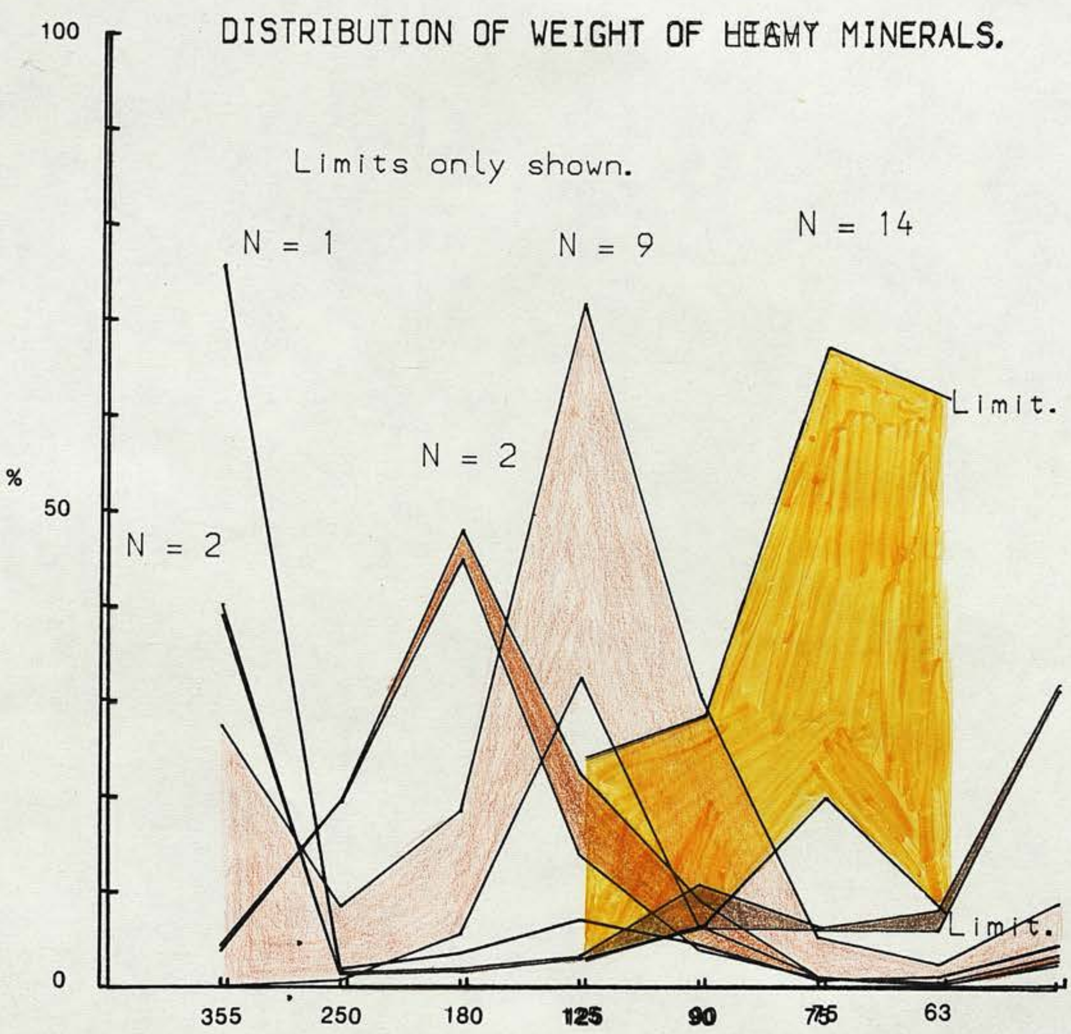


Fig. 19 **Distribution by size of weight of heavy and light minerals.**

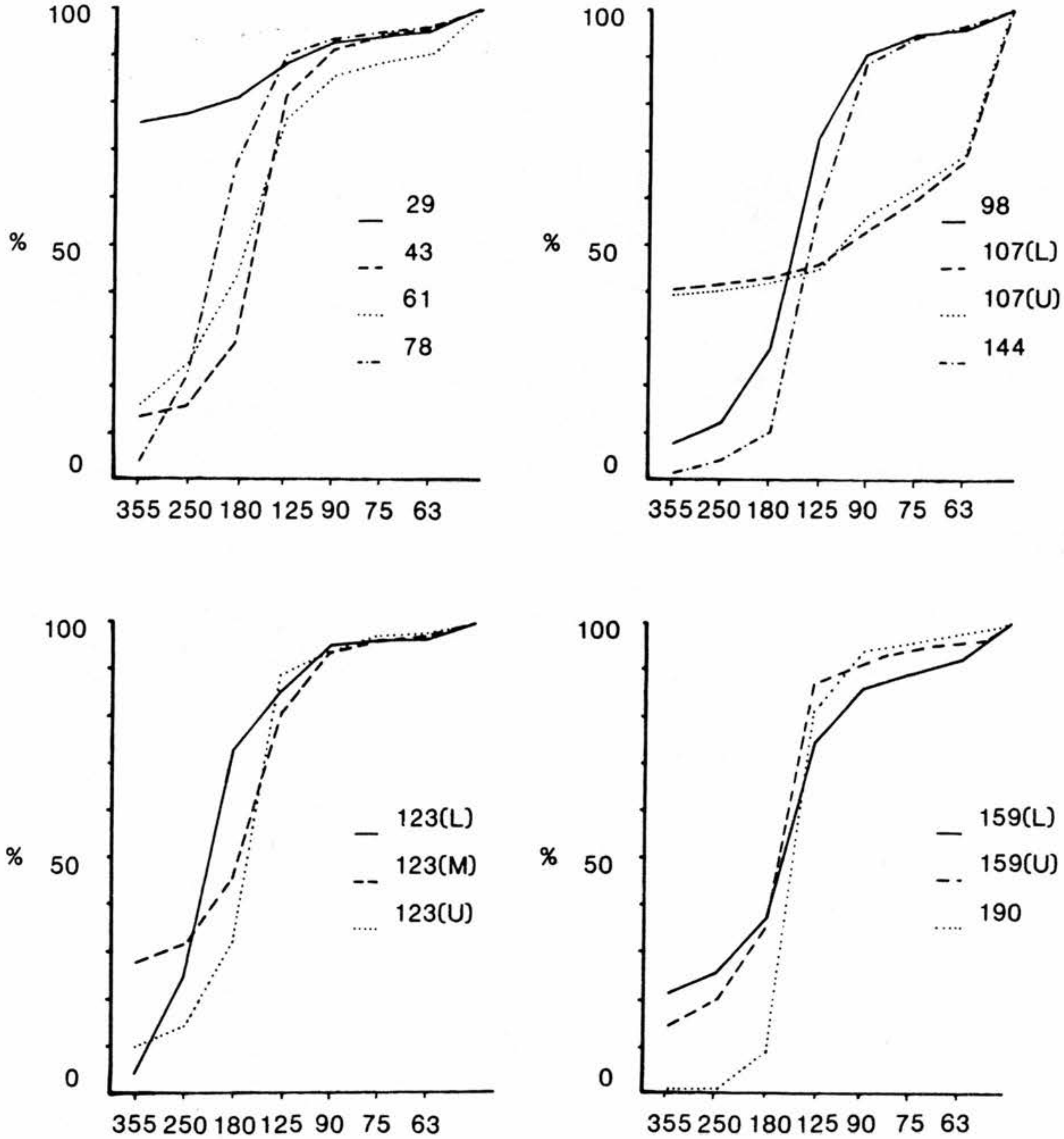


Fig. 20 Cumulative frequency distribution of weight of light minerals.

The size frequency distributions for the light minerals of the samples are approximately similar in form with the exception of samples Bed 29 and Bed 107 (Fig. 20). For the bulk of the samples with standard 'S' shape curves they appear to be channel sands of low energy with a traction load down to 180 microns (20 - 30 %), a saltation load down to 90 microns (60 - 70 %), and a fine suspension load (c. 10 %), if Vishers' (1969) interpretation is followed. Bed 29 appears to be a high - current channel, while Bed 107 appears to be a tidal inlet on a delta front (Visher, 1969). However, no accurate postulations on the type of the deposit can be made from the heavy mineral size frequency distribution, also different heavy minerals show different distribution curves (Fig. 15 and 16).

4.3 MINERALOGY.

The following section is intended as a list of the observed minerals with possible source rocks, and also any particular petrographic features or variability in occurrence which can be used in provenance determinations. Mineral occurrence and abundance is shown in Table 4, (p. 101).

Zircon.

This is by far the most abundant of the heavy minerals with normally two types present, those showing good crystal form with pyramidal terminations, and those which are well rounded. A variety of colours are observed, colourless, yellow and mauve, in which the mauve varieties are well rounded, although colourless varieties are dominant. The mineral shows high relief with high polarisation colours. Inclusions are mainly gas filled but some also contain specks of dust as well as minute zircons indicating second generation forms, these inclusions are irregularly situated throughout grains. Within some of the grains are darker cores suggesting second generation forms. The dark mauve coloured well abraded forms are thought to be of Lewisian origin (Mackie, 1921).

Mackie (1932), suggested that a broad distinction may be made between very acid and less acid granites on the basis of zoning and the character of the zircon. Within the succession limpid unzoned forms predominate suggestive of acid granites and the zoned variety (with dark cores) normally forms < 5 % of the sample and is suggestive of very acid hosts. The well formed varieties are suggestive of basic hosts. Throughout the succession there is only a little variability in the amounts of the various forms present, although the purple varieties are restricted to the base of the succession. The occurrence of inclusions within some grains suggests a magmatic provenance.

Rutile.

Whilst the origin of rutile can possibly be placed it is difficult to account for its high amount. It is a persistent mineral and may have passed through more than one cycle of deposition or may in fact be authigenic if well formed grains. Rutile is virtually absent from all Highland Granites although the brown variety is probably derived from Older Granites, in which it may abound (Mackie, 1932). The yellow and red varieties are common accesssories of the granulites, quartzites, gneisses and phyllites. The abundance of yellow and red rutile indicates a mainly metamorphic source. Throughout the succession there is a small percentage of authigenic rutile present in most samples usually confined to the smaller grain sizes. Throughout the succession there is some change in these forms, Bed 43 contains no brown forms, Beds 61, 78 and 107 contain brown and red forms, Beds 144 and 159 contain red and yellow types, Beds 123 and 190 are mainly red whilst Bed 98 is mainly brown suggesting an older source.

Tourmaline.

Tourmaline usually occurs as prismatic basal or irregular conchoidally fractured grains. In colour, the grains vary from green (schorl) to brown (dravite), with occasional rare blue grains.

Tourmaline has a variable provenance from any pneumatolytic rocks, acid igneous rocks, pegmatites, schists, gneisses or phyllites. Krynine (1946), suggests different provenance for different colours of tourmaline grains. Brown tourmaline (dravite) is associated with metasomatic rocks, while green tourmaline (schorl) is more often associated with granitic rocks. Mackie (1932), found tourmaline in only 6 % of the Newer granites but in 40 % of the Older granites where it occurred as brown and green prisms. Green and brown varieties are rarely listed as accessory minerals for the Dalradian and Moine Series, they seem to occur mostly in quartzites. The olive green variety was present in the garnet schists of the Dalradian. Muir (1963), assigns blue tourmalines to a pegmatitic origin.

Throughout the succession green varieties predominate in Beds 29, 78, 98, 123, 144 and 190, suggesting a granitic or pegmatitic origin. Beds 43, 61 and 159 suggest a metasomatic host while Bed 107 with its blue grains is possibly pegmatitic.

Epidote.

Commonly found in crystalline metamorphic rocks especially impure limestones, it is also found in highly altered igneous rocks. Throughout the succession epidote is not particularly abundant, and with its usual pale colour and rounded shape its occurrence appears to be linked to similar sources.

Hornblende.

An igneous or metamorphic provenance is proposed comprising diorites and or hornblende schists. The lighter varieties (Bed 107), are interpreted as coming from dioritic rocks while the darker varieties are postulated as being derived from plutonic bodies.

Augite.

An intermediate to basic igneous provenance is proposed, in which most grains are inferred as being derived from gabbros and diorites. The limited occurrence within beds 29 and 43 suggests a different source (basic) to the remainder of the succession.

Topaz.

Occurs as dingy plates within the succession, although its variable amount is likely due to its platy habit and stability. It is possibly derived from granite, greissen or other contact metamorphic rocks, although with its widespread occurrence it is considered to have been derived from any of the acid igneous rocks in the Highlands.

The high amount present within Bed 78 and particularly within the finer grain sizes is thought to be indicative of a pegmatitic source, as is the coarse topaz within Bed 123.

Garnet.

Garnet occurs as angular cubic grains, with variable colour from colourless to pale shades of pink. It shows high relief but is optically isotropic. On close examination the faces of the grains exhibit 'step' like features or facets (Simpson, 1976), with few pits visible.

Possible sources are igneous and metamorphic rocks in particular gneisses and schists dependent on composition, although garnets have also been interpreted as being derived from pelites adjacent to the Highland Boundary Fault (Chinner, 1966, Atherton, 1968). Garnet analysis has been used to aid in tracing provenance (Chapter 4.4).

Anatase.

Anatase occurs in the succession as brown to yellow euhedral grains, and less commonly as irregularly fractured grains.

Anatase can be derived from basic crystalline igneous or high grade metamorphic rocks where it is likely abraded, but it can also be derived authigenically from decomposition of ilmenite whereupon the grains are euhedral. Pegmatites are relatively richer in anatase, and in foliated granites it appears to be of more frequent occurrence than in unfoliated types.

Within the succession the occurrence of anatase is limited to the coarse grades of Bed 29 and the finer grades of Bed 43, and is suggested as being linked with the presence of augite and a basic source.

Enstatite.

This mineral is commonly found in basic and ultrabasic igneous rocks; but also less commonly in medium grade metamorphic rocks. It can also be indicative of higher metamorphic grades from the breakdown of biotite.

Its occurrence is limited to Beds 29, 43 and 98 likely suggesting a basic source for Beds 29 and 43. No unique source interpretation can be made for Bed 98 although it could be from rocks associated with basic igneous bodies eg. pegmatites rising through diorites and norites of Aberdeenshire (Mackie, 1932).

Monazite.

Monazite occurs only in the more acid granites or in pegmatites, its variability within the succession is possibly related to chance effects, and as such no definite source interpretations are possible. The grey granites of Banffshire and Aberdeenshire apparently derived from the same magma contain monazite in fair abundance, but it has not been found in the red granite of Peterhead.

Andalusite, Kyanite and Sillimanite.

Within the succession the limited presence of these minerals is likely due to chance effects, and not solely source effects. These minerals are possibly derived from metamorphic zones within the Highlands although they could also be derived from igneous bodies (Mackie, 1932).

However, kyanite is restricted to the base of the succession (below Bed 98), and andalusite is restricted to beds below Bed 107. Within this the 15 % of andalusite in coarse grades of Bed 43 is probably pegmatitic in origin. Sillimanite is present throughout the succession although in variable amounts, suggesting chance variations.

TABLE 4.

OCCURRENCE AND AMOUNT OF MINERALS BY SIZE.

	SIZE (in microns)			
MINERAL	180-125	125-90	90-75	<75
ZIRCON	100.00 45 - 1	100.00 63 - 6	100.00 81 - 34	100.00 86 - 51
RUTILE	95.60 25 - 0	100.00 17 - 3	100.00 17 - 3	100.00 16 - 1
TOURMALINE	100.00 50 - 2	100.00 35 - 3	95.60 22 - 0	82.60 16 - 0
EPIDOTE	61.00 8 - 0	43.47 4 - 0	30.43 2 - 0	4.34 2 - 0
HORNBLENDE	95.65 12 - 0	91.34 5 - 0	69.56 5 - 0	21.73 3 - 0
AUGITE	4.34 4 - 0	8.69 2 - 0	0.00 0	0.00 0
TOPAZ	100.00 24 - 2	82.60 12 - 0	87.00 25 - 0	52.17 16 - 0
GARNET	82.60 55 - 0	91.30 55 - 0	86.90 33 - 0	91.30 36 - 0
ANATASE	87.00 12 - 0	95.60 8 - 0	95.60 10 - 0	95.60 14 - 0
ANDALUSITE	21.70 15 - 0	17.39 3 - 0	4.34 2 - 0	0.00 0
KYANITE	17.40 4 - 0	8.69 2 - 0	4.34 1 - 0	0.00 0
ENSTATITE	0.00 0	4.34 1 - 0	8.69 1 - 0	0.00 0
SILLIMANITE	30.43 5 - 0	4.34 2 - 0	47.82 6 - 0	34.78 3 - 0
MONAZITE	21.74 2 - 0	8.69 2 - 0	17.39 2 - 0	13.04 2 - 0

The upper figures in the table are the minerals occurrence by number of samples, while the lower figures are the limits to its presence within these samples (%).

4.4 GARNET VARIETAL STUDIES.

To minimise the effects of granular variation and intrastratal solution effects as only grains of a certain density and stability are used, varietal studies were carried out on the garnets, as the garnet zone within the Highlands (Chapter 5.1, Fig. 24, p. 114) is the easiest to map and has been delineated for long distances.

To aid in the tracing of the possible host rocks, garnets were microprobed to determine their precise compositions. In this study garnets between 63 and 125 microns were mounted and analysed (Appendix 9) as part of the heavy fraction to avoid density or size errors (Morton, 1985b). The results were then recalculated using 24 oxygens and plotted as triangular plots using Grossular, Pyrope, Almandine and Spessartine, as the end members.

Three groups can be identified (Fig. 21), the first comprises samples 1 to 7, the second is composed of sample 9 and the third is composed of sample 8.

Group 1	Alm. and Spess. 60-90%	(Spess.<35%)	Py. 10-40%	Gross. 5-20%
Group 2	Alm. and Spess. 45-50%	(Spess.< 5%)	Py. 30-40%	Gross. 15-20%
Group 3	Alm. and Spess. 35-40%	(Spess.< 5%)	Py. 55%	Gross. 5-10%

These three groups must be provenance related as few post depositional effects are known to alter garnet compositions. From this three possible situations arise :-

1. each group represents input from a distinct source area,
2. all the groups were derived from the same source area with progressive unroofing of different rock types,

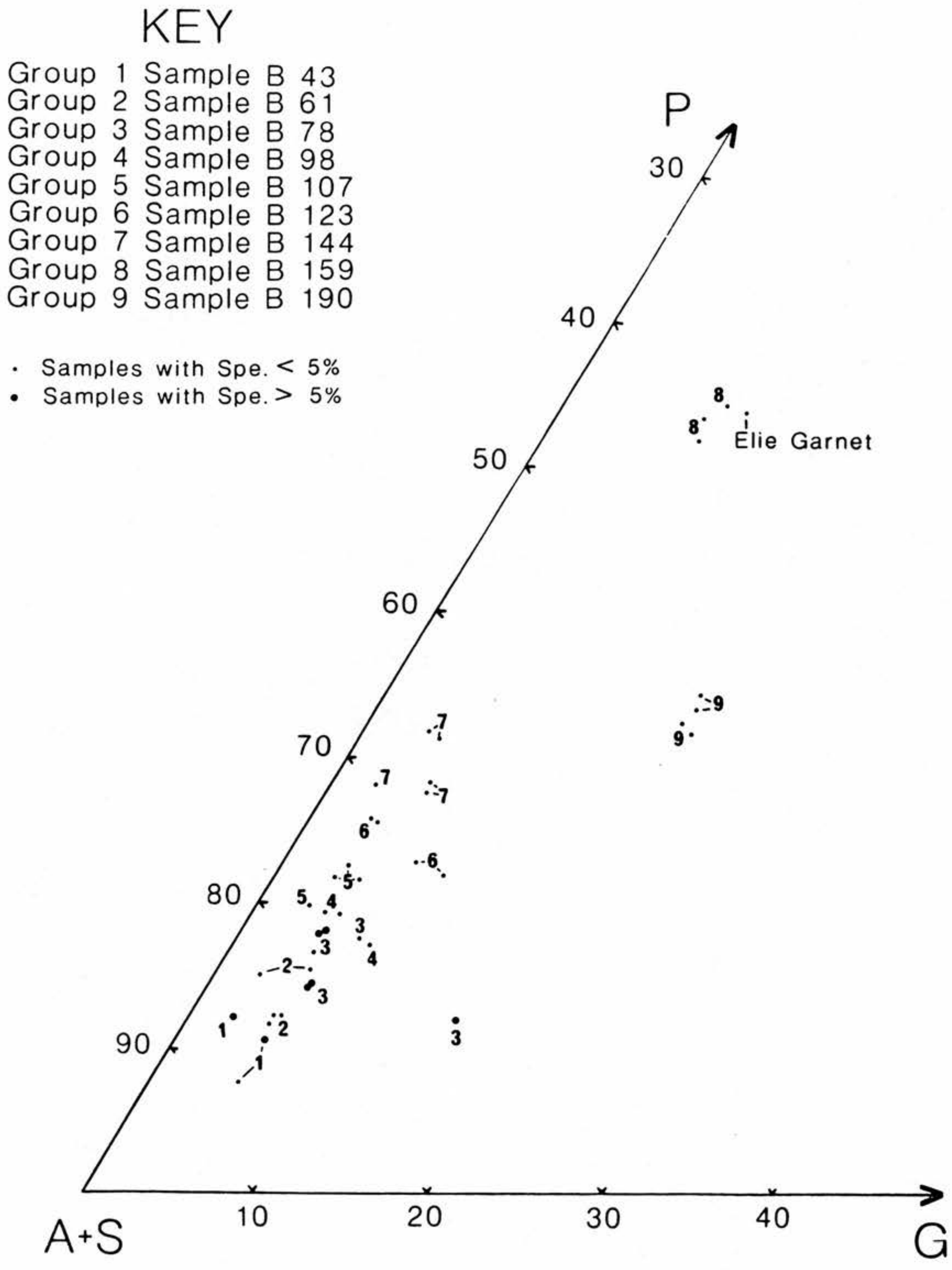


Fig. 21. Triangular plot derived from garnet probe analyses.

3. a combination of 1 and 2 above.

for which in this case 1 is considered to be most likely.

These groups thus imply different sources. Group 1 (samples 1 - 7), with a variable spessartine content is possibly derived from the metamorphic zone adjacent to the Highland Boundary Fault (Atherton, 1968), in which an increase in FeO and MgO : CaO and MnO is indicative of increasing metamorphic grade (Miyashiro, 1943, Sturt, 1962). The very high anomalous values of spessartine are likely related to the initial composition of the host rock.

For group 2 (sample 9, Bed 190), with high grossular values is either derived from a high grade provenance, metamorphism of impure calcareous limestones or from calcium metasomatism. A likely source in this case are the Dalradian Limestones.

Group 3 (sample 8, Bed 159), composed of high pyrope content garnet is possibly derived from a contemporaneous Elie Ness type volcanic vent (Donaldson, 1984); however, distance of transport and / or conditions of deposition have been sufficient to remove the more unstable minerals from such an assemblage. This vent is supported by the occurrence of hornblende in both samples from this unit.

4.5 HEAVY MINERAL ASSEMBLAGES.

Analysis of the mineral assemblages (Fig. 22, continuous percentage plots), shows a variety of heavy mineral associations derived from a variety of sources. Within which the major assemblage is of the zircon, rutile and tourmaline type with components of other minerals reflecting contributions from different sources. The variability of these minerals is important as source indicators, as if they are present in the derived material they must occur in the source. The full provenance implications are discussed in Chapter 5.2. Detailed bed by bed descriptions of the heavy mineral assemblages for the studied samples can be found in Appendix 10.

Throughout the measured succession the association of zircon, rutile and tourmaline (igneous), is ever present, although minor minerals affect it, and must be source related. As expected the disappearance of the less stable minerals leaves a zircon, rutile and tourmaline suite with a decrease of grain size.

Throughout the succession variations in presence / absence or abundance of minerals could be source related, however, minor changes in the occurrence of accessory minerals, monazite or sillimanite could be due to chance variation.

Once this main igneous provenance has been decided, with modifications from other sources, the associations were subjected to X-Ray diffraction analysis (Pryor and Hestor, 1969). This technique being quick and easy allows a fingerprint of the association to be made with respect to the mineral association facilitating comparison

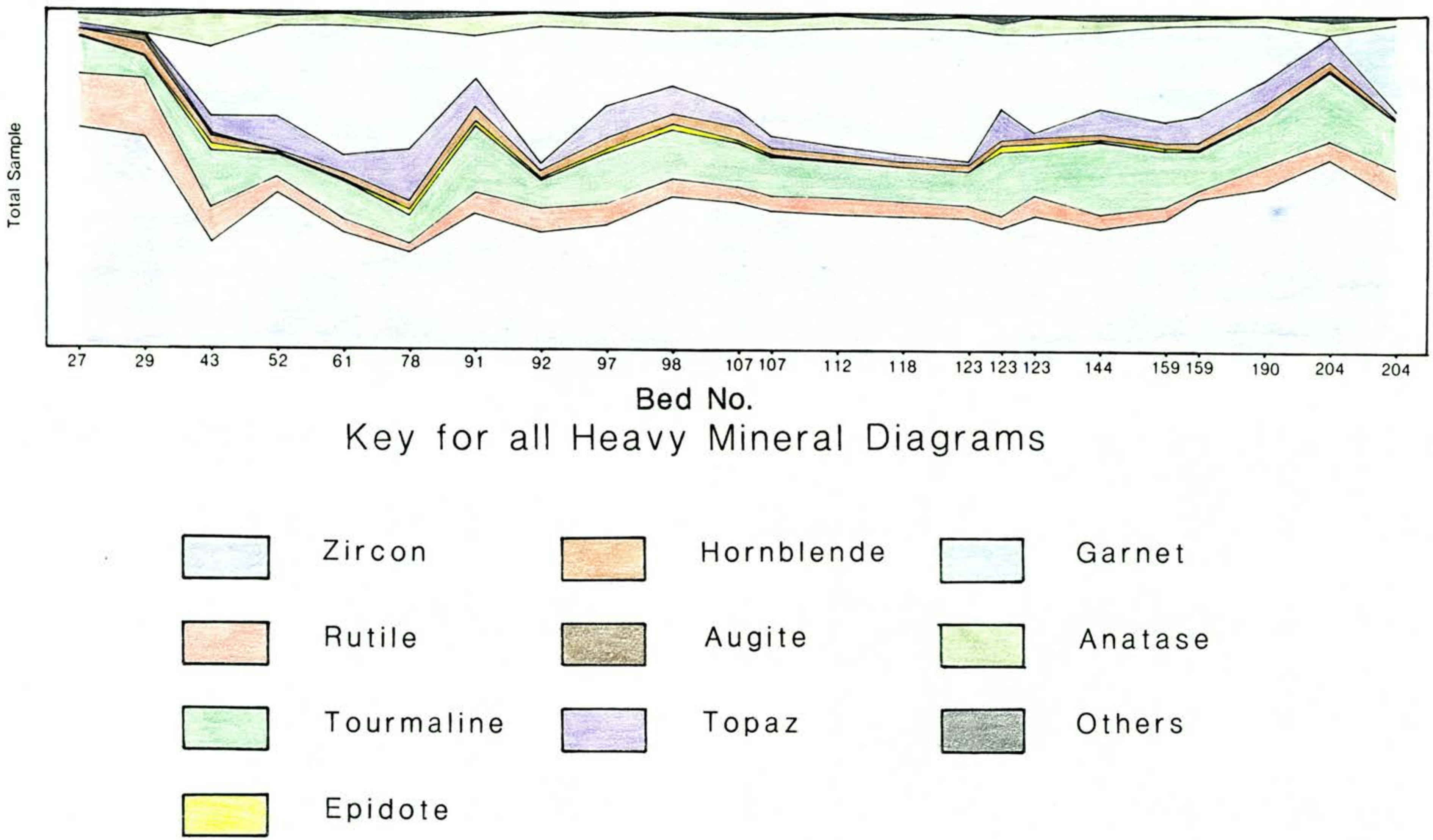


Fig. 22.1 Continuous percentage plots for studied section (Y axis = 100 %).

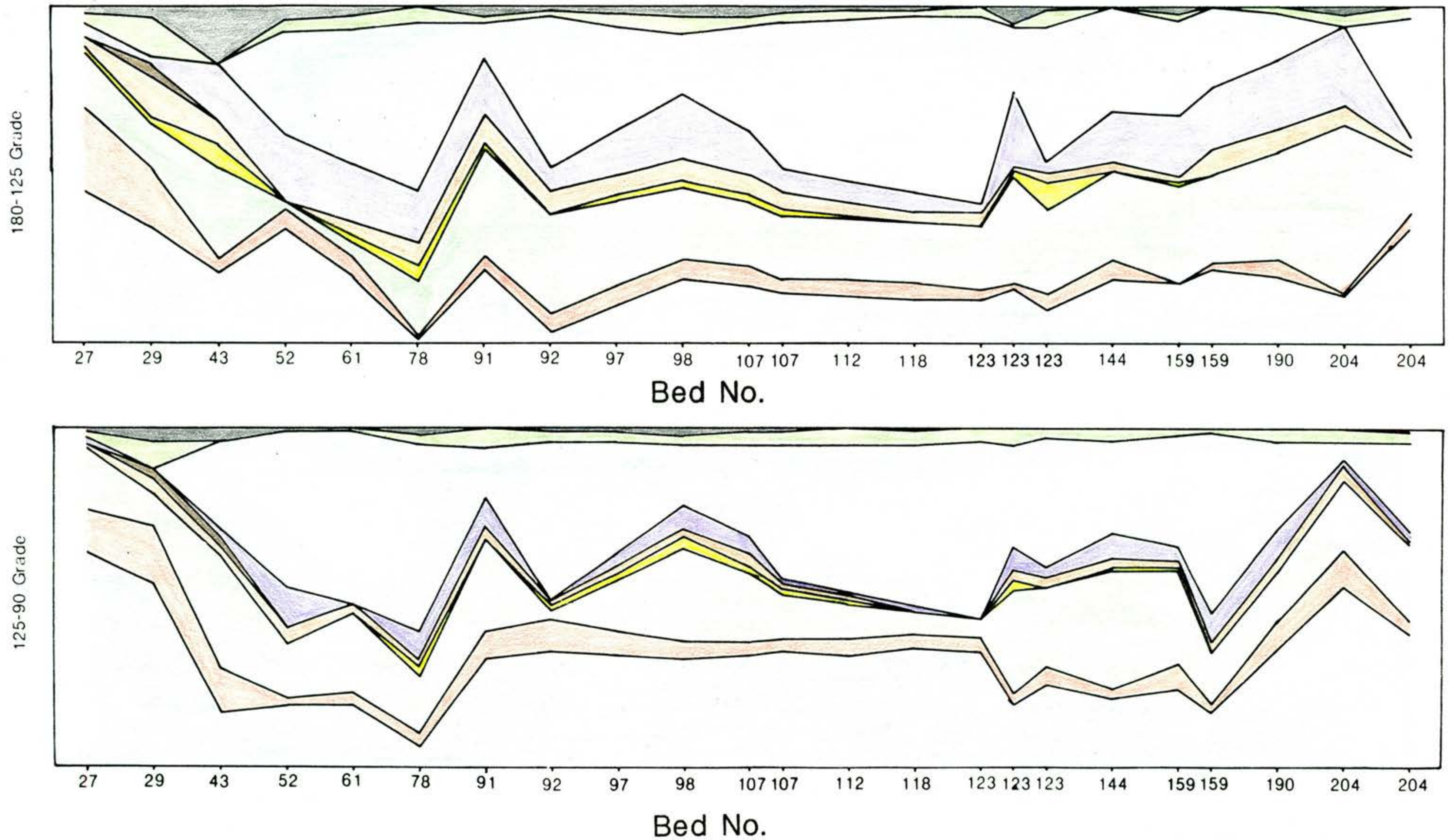


Fig. 22.2 Continuous percentage plots for studied section
(Y axis = 100 %).

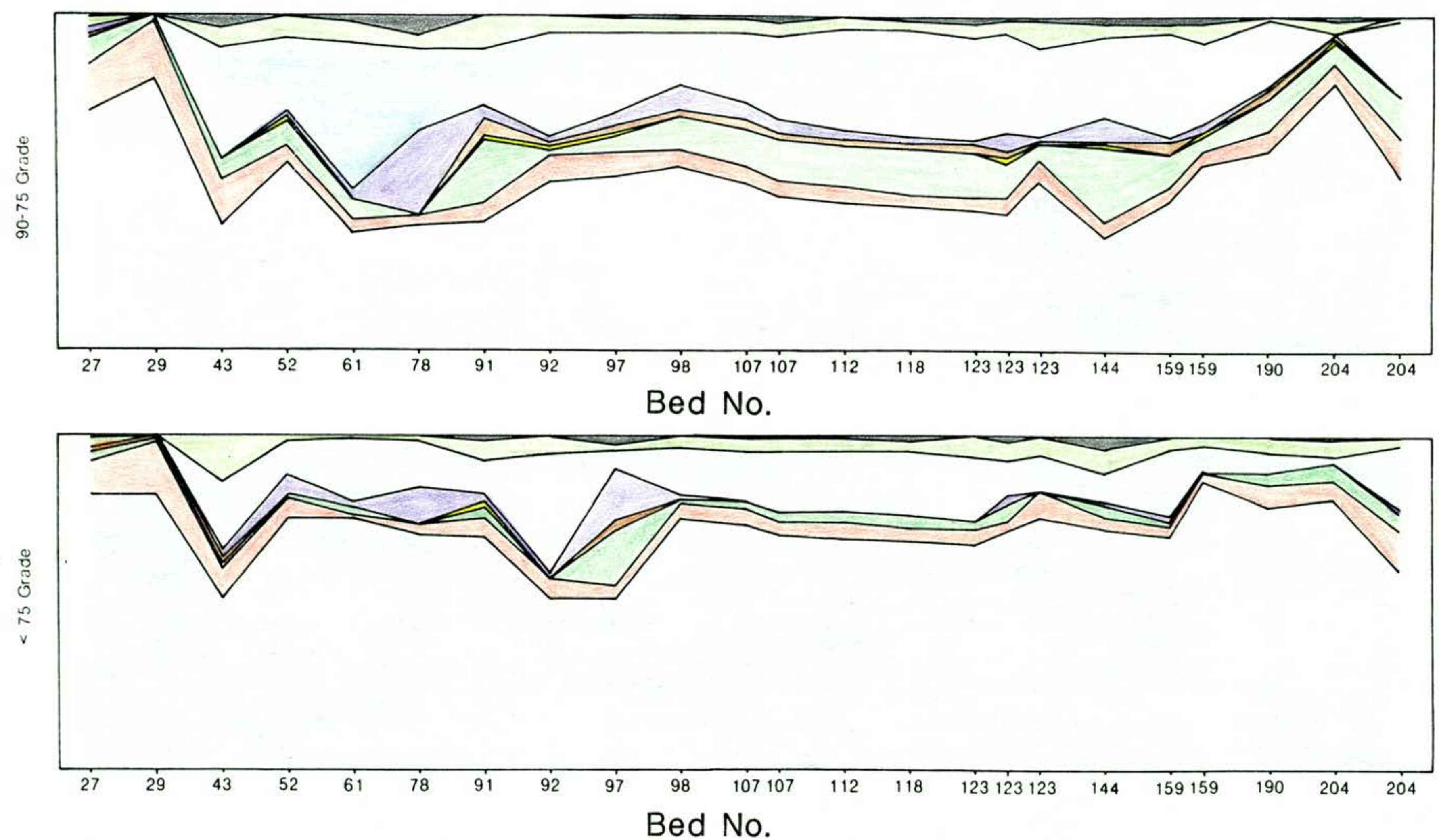


Fig. 22.3 Continuous percentage plots for studied section (Y axis = 100 %).

across samples, to aid in source determinations and for more detailed petrographic studies. For the repeated analyses samples were taken from the base and top of the units, while for the single analyses, samples were taken from the centre of the unit.

This analysis forms seven groups (Fig. 23) composed of the mainly igneous suite with contributions from metamorphic and other sources.

CLASS	ASSOCIATION	BED NO.
Class A	Zi. Ru. To. (Ep. Hb. Tz.)	29
Class B	Zi. Tz. Ga. Ky.	61
Class C1	Zi. Ru. To. Tz. Ga. (Hb. Si.)	107
Class C2	Zi. Ru. To. Tz. Ga. (Ep. Si.)	123 144
Class D	Zi. Ru. To. (Ad. Ep. Hb.)	190
Class E	Zi. Ru. To. Tz. Ga. (Ad. Ky.)	43
Class F	Zi. Ru. To. Tz. Ga. (Ad. Ep. Hb. Si.)	98
Class G	Zi. Ru. To. Tz. Ga. (Ep. Hb. Si.)	159 78

KEY FOR ASSOCIATIONS.

Zi. Zircon Ru. Rutile To. Tourmaline Ep. Epidote Hb. Hornblende
Tz. Topaz Ga. Garnet Ad. Andalusite Ky. Kyanite Si. Sillimanite

Minor variations in the X - ray traces (in the C classes around 30 - 40 degrees), probably result from an influence and variability of the minor or unstable accessory heavy minerals.

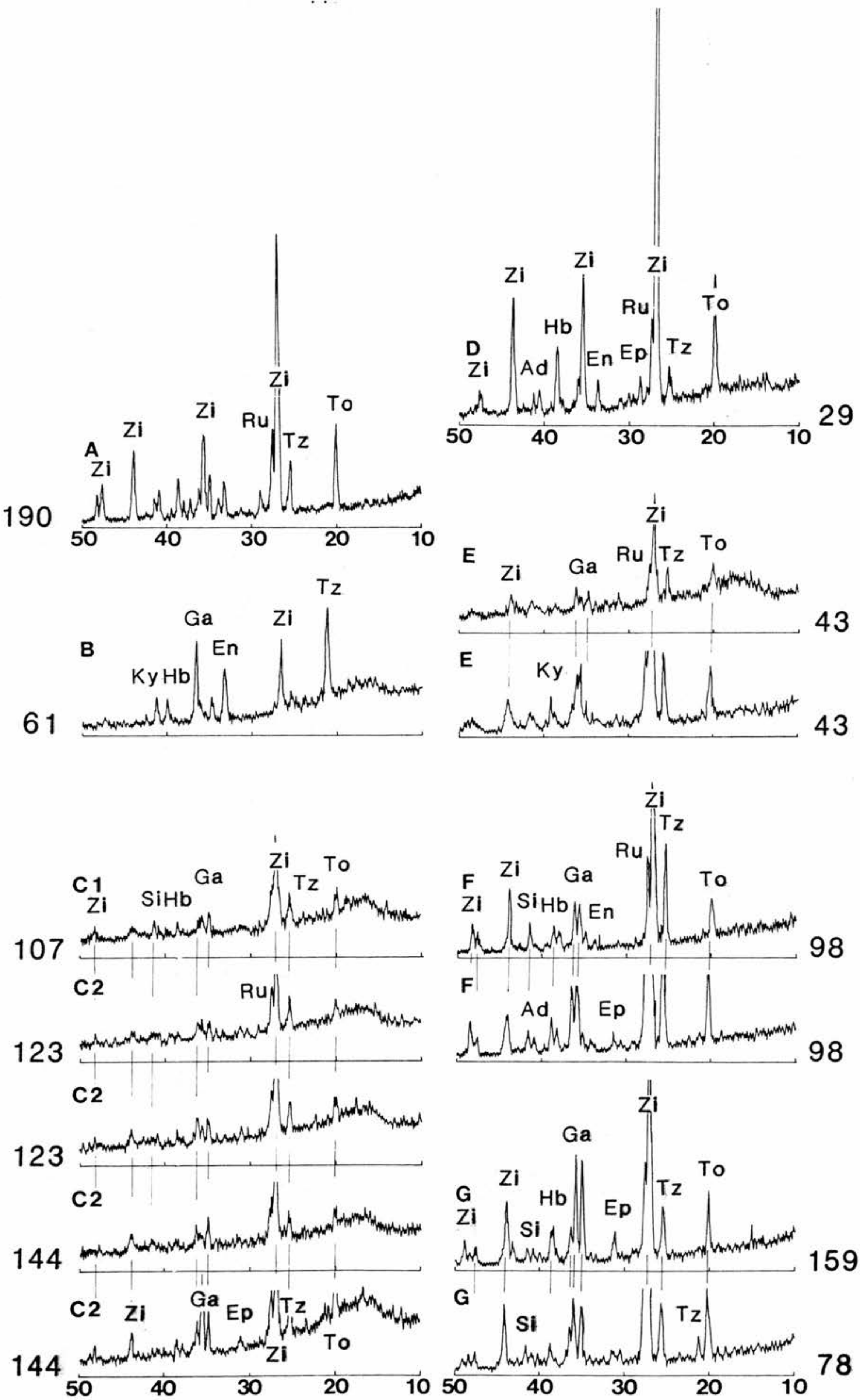


Fig. 23. X - Ray diffraction traces for samples showing grouping into associations. Major peaks identified with relation to indicator minerals (peak heights are not indicative of abundance).

4.6 CONCLUSIONS.

Heavy minerals are extremely sensitive indicators of source area and will remain of paramount importance in studies of sediment provenance and dispersal. However, heavy mineral assemblages are not controlled only by provenance, but may also be affected by source area weathering, processes of transportation and deposition and post - depositional alteration. Polycyclicity of sediments is difficult to prove or assess although it has undoubtedly occurred, the assemblages studied are therefore inferred as taken directly from source to deposit. Any effect of polycyclicity could cause relative enrichment of one mineral species due to cumulative effects of dissolution or weathering in situ, or diagenetic breakdown.

Source area weathering and transportation cause elimination of a species from a detrital heavy mineral suite, but hydraulic conditions during deposition and subsequent diagenesis cause major modifications which must be assessed and compensated for before reconstructing provenance and dispersal patterns. Problems of hydraulic differentiation can be overcome by the use of hydraulic ratios, by mapping only those minerals showing regional presence / absence patterns or by using scatter plots to judge the degree of grain size control. Under such constraints provenance studies are probably best achieved by varietal techniques of optical differentiation, cathodoluminescence, radiometric methods or electron microprobe analysis on a single mineral species from the residue. This eliminates the effects both of density variations, thereby minimising the hydraulic control, and of stability variations, thereby removing the diagenetic control.

Considering all of the samples there is a shift from a high zircon (rutile and tourmaline) largely igneous state, to a transitional state, where both igneous and metamorphic components are present, albeit in varying proportions.

The mineral association appears to be largely igneous (acid and basic), with associated metasediments. The quartz indicators in Chapter 3 suggest a metamorphic source with some acid plutonics. This would suggest a source within the Highlands in which the heavy minerals associated with the metamorphic area have been removed during transport or burial. Alternatively, quartz sources could be in Dalradian or O.R.S., with only low grade metamorphism c. garnet grade forming the metamorphic heavy minerals.

For garnet, the sources for the lower part of the succession appear to be related to migration across the garnet grade rocks adjacent to the Highland Boundary Fault (Chinner, 1966, Atherton, 1968). For the samples at the top of the section (where garnet appears to disappear), headwater erosion may have passed through the garnet zone. However, at this stage a new source of garnets from respectively a proximal volcanic neck and metamorphosed Dalradian limestones are exposed.

It is not considered wise at this stage to attempt to link observed heavy mineral assemblages to their environments of deposition or the original lithology from which they are extracted due to the complex processes inherent in deposition and lithification of sediments (Chapter 3.3).

5 PROVENANCE AND PALAEOGEOGRAPHY.

5.1 INTRODUCTION.

The heavy mineral association described in Chapter 4 suggests an igneous and medium grade metamorphic source. The light minerals suggest a source area of medium to high grade metamorphic rocks with contributions from acid plutonics. The presence of metamorphic quartz and the absence of metamorphic heavy minerals would be expected as these semi-stable heavy minerals would disappear during transport. Within this, transport paths cannot be recognised specifically, although a possible source would be the Highlands of Scotland (Fig. 24).

The palaeogeographic reconstruction shown in Dinantian times (Fig. 25), is one in which movement along the Highland Boundary Fault had ceased (Bluck, 1984). The main geographic features during Dinantian times were the Caledonian Massif, the Southern Uplands Massif and the Midland Valley graben. The former is composed of igneous rocks and Highland metamorphics to the north and east, and further north Lewisian, Torridonian and Moinian rocks. The Southern Uplands Massif to the south is largely of Ordovician, Silurian and Devonian age, whilst the Midland Valley graben contains Devonian as well as a thick Carboniferous fluvio-deltaic sequence. Deposition in the Midland Valley was limited by highlands of Old Red Sandstone age which had not been completely peneplaned by erosion.

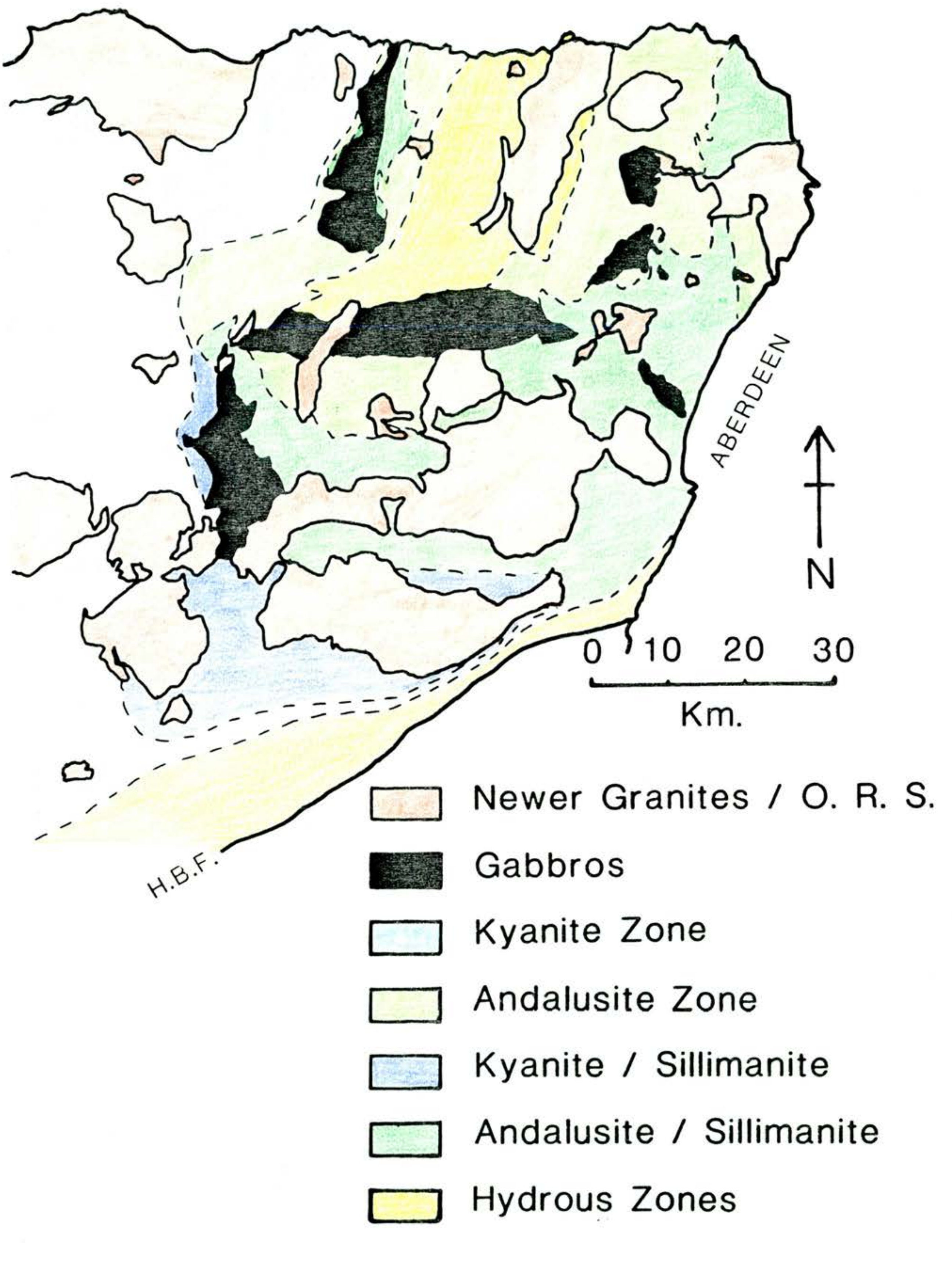


Fig. 24. Generalised geologic map of E. Scotland showing possible source areas of heavy minerals.

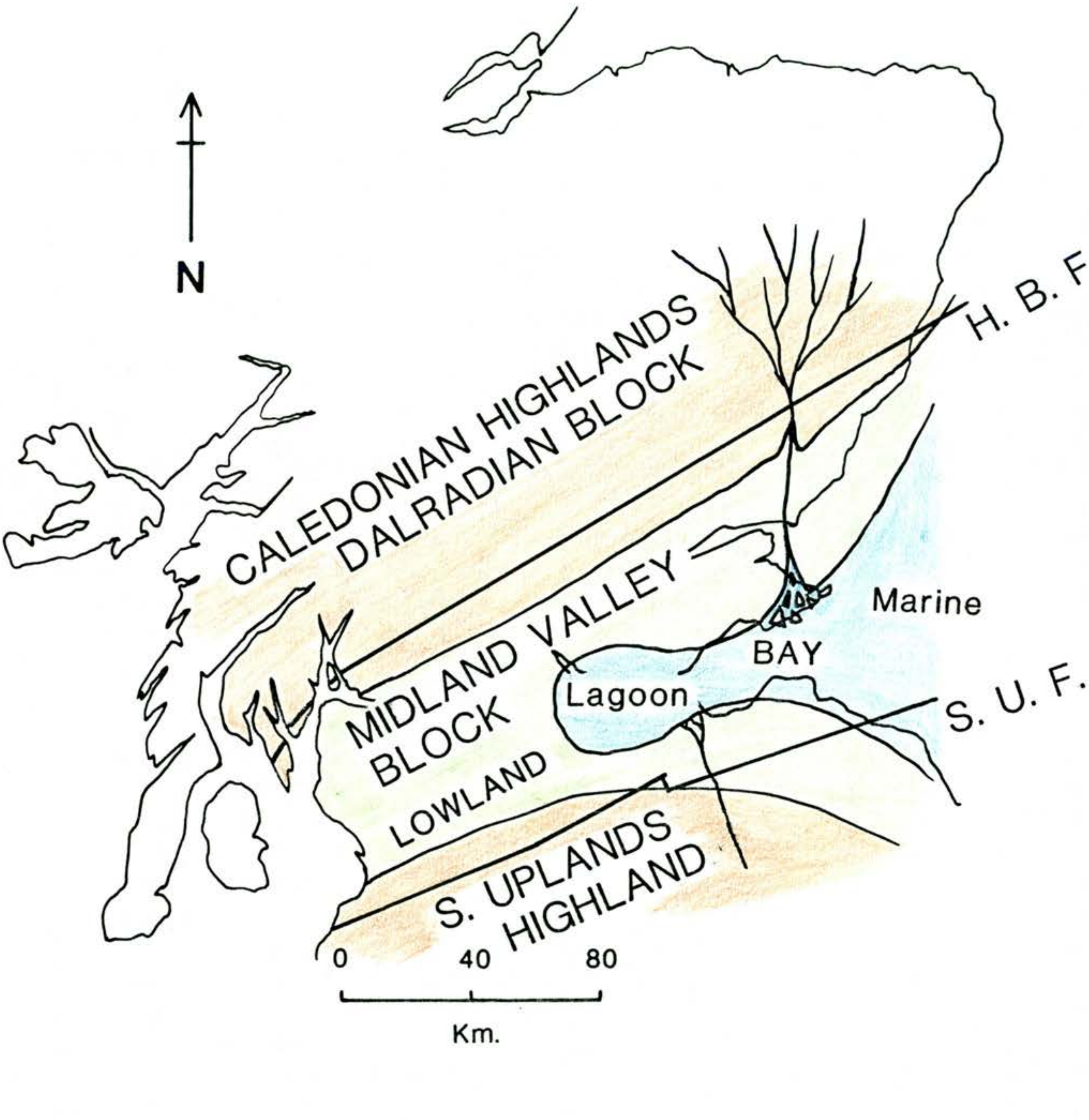


Fig. 25. Possible palaeogeogaphic reconstruction of the NE. Highlands during Dinantian times.

5.2 PROVENANCE STUDIES.

The igneous rocks in the Caledonian Massif cover a great group of intrusions, ranging from ultrabasic to acid in composition, from which two distinct groups may be separated :-

1. Granites of Central Highlands - 'Newer Granites'
2. Gabbros of N. E. Scotland

The 'Newer granites' c. 400 M.A. are predominantly biotite granites with little or no microcline or muscovite although in some 'granites' these minerals become important, particularly when associated with pegmatites. Associated with these large granitic masses are small earlier bodies of more basic character consisting of hornblende - granites, tonalites and diorites. These granites and associated rocks liberate a suite of minerals as shown in Table 5. The basic masses of Insch and Huntly consist of peridotite, olivine - norite, olivine - gabbro, troctolite, granite and syenite and provide a distinctive suite of minerals (Table 5).

The metamophosed rocks in the Southern Highlands (mainly quartz - mica - schists) contain a Barrovian sequence mineralogically (Chinner, 1966). The presence of the metamorphic indicator minerals andalusite, kyanite and sillimanite within the assemblages could be used to infer possible provenance from the east or west of the Caledonian Massif surrounding granitic plutons, if they are not chance variations. The major metamorphic zones (Fig. 24) also include garnets which are generally of almanditic composition. As can be seen in Table 5, (based on Mackie, 1932 and Heddle, 1923) the minerals observed in the succession have a variety of possible sources and are frequently of

Table 5 Minerals with Possible Source Rocks

	ZIRCON	RUTILE	TOURMALINE	EPIDOTE	HORNBLENDE	AUGITE	TOPAZ	GARNET
ACID ROCKS	Very acid grains have dark cores	Brown - older granites	Present - Brown and green	Highly altered	Present		Present in granite and greissen	Gneisses
BASIC ROCKS	Transparent less fissuring	Present	Present	Metamorphosed basic bodies	Present light - dioritic	Intermediate gabbros and diorites		
SCHISTS	Crystalline schists	Yellow and red in granulites	Olive green in garnet schists	Crystalline schists and impure lmst.			Contact metamorphism	Present
PEGMATITES		Present	Present as blue grains	Colourless varieties			Present	Present

	ANATASE	ANDALUSITE	SILLIMANITE	KYANITE	ENSTATITE	MONAZITE
ACID ROCKS	Foliated granites	Present limited occurence	Present in Rubislaw Granite	Present at Hunt Hill	Rubislaw granite	Present in grey granites from same magma
BASIC ROCKS	Present				Basic and ultra-basic	Present
SCHISTS		Metamorphic pelites	Metamorphic pelites	Mica schists and gneisses	Medium grade metamorphics	Moine Schists recrystallised
PEGMATITES	Richer than in most granites				In norites and diorites	Present

mixed source.

An indication of provenance can be inferred from the form of the quartz grains, particularly if the grains are mono - or poly - crystalline, and undulatory or non - undulatory. The predominance of monocrystalline non - undulatory quartz would tend to imply a plutonic - igneous or extrusive igneous host whilst the predominance of polycrystalline undulatory quartz would imply a metamorphic host (3.2.1, (Basu et. al., 1975)).

The form of the bulk of the quartz (Chapter 3), suggests Beds 29, 78 and 19 to be largely high grade metamorphic, with Bed 29 possibly plutonic while the rest of the samples suggest that medium to high grade sources predominated.

The main heavy mineral assemblage (Chapter 4), present is of the zircon, rutile and tourmaline type with other accesssories (which is mainly igneous), although changes in the presence / absence or relative amounts of these accessories from sample to sample could suggest a change in source. This effect is noted in the limiting of augite and enstatite to the base of the succession, and the restriction of andalusite and kyanite to the lower half of the succession.

Conclusions on heavy mineral assemblages.

The bulk of the heavy minerals within the Pathhead Beds are derived from a suite of rocks in the Highlands with both acid and basic igneous bodies, as well as a variety of grades of metasediments, although some recycling and contamination from Dalradian and O.R.S. rocks would explain the absence of high grade metamorphic heavy minerals, but the presence of high grade metamorphic quartz.

Thus, we have a suite of minerals for which only the garnets can at this moment be provenance related with any certainty.

The source of this material did not necessarily change so radically as suggested by the assemblages rather the contributions to the drainage pattern from various areas fluctuated, this could explain the chance variations for the accessory minerals.

5.3 PALAEOGEOGRAPHIC RECONSTRUCTION.

The palaeogeographic reconstruction of the Midland Valley (Fig. 25), assumes movement along the Highland Boundary fault to have ceased (Chapter 5.1). The submergent Carboniferous area during Dinantian times controlled by the Highland Boundary and Southern Uplands Faults (effectively an inherited Devonian landscape retouched by minor movement and erosion in Tournaisian times), was a site of sedimentation. However sedimentation was interrupted by outpourings of lava, which built up to form islands persistent above sea level, these large scale basaltic flows caused lateral variation in sediment thickness and after the eruption of the Clyde Plateau Lavas a barrier was established between the east and west basins. Spasmodic local intra-basinal vulcanicity enhanced the sedimentary barriers to marine influxes in the west (George, 1960, Greensmith, 1968).

The relations within the Calciferous Sandstone Series (George, 1960), suggest that the Southern Uplands Fault, though perhaps the most important, was only one of a number of dislocations that controlled sedimentation, both by delimiting an early initial Carboniferous frame and by active movement in Carboniferous times. The predominant structure at the eastern end was a narrow N.E. - S.W. subsidising zone controlled by pre-existing Caledonian structures.

The early Visean Calciferous Sandstone Measures in the Midland Valley comprise thick sequences deposited by S. and S.W. flowing distributaries of rivers flowing from Caledonian Highlands. These rivers flowed southwards into a shallow fluvio-deltaic / marine environment at the Eastern end of the Midland Valley.

The local inferred palaeogeography and tectonism for the eastern end of the Midland Valley and its immediate surrounds appear to have had the controlling influence upon the sedimentation pattern producing cyclical units. Generally deposition and subsidence kept in step even in more rapidly subsiding zones. Due to possible changes in sediment supply with respect to subsidence, extensive bodies of water would be created effectively pushing back the shoreline (Cycle 16, thick shale accumulation).

It appears that during Calciferous Sandstone times the input of clastic material at the eastern end of the Midland Valley was dominantly from the north and north east (Caledonian Highlands of granitic stocks, associated metamorphics and O.R.S. sediments). The delta evolved by mainly autocyclic means related to delta lobe switching (Goodlet, 1959), although two cycles 14 and 16, contain allocyclic events. The possible causes of allocyclicity are :-

a) tectonism in the Midland Valley graben, causing changes in subsidence rate or sediment supply,

b) eustatic sea level changes,

In this case tectonic factors (2.6.2) with changes in subsidence rate, are considered more likely. If eustatic changes had occurred the effects would be traceable over a wider area.

The analogy has been drawn with the Guadalupe Delta of Texas due to similar size, form and pattern of sedimentation, however the presence of carbonate bands necessitates comparison with the Burdekin Delta of Australia where muddy intertidal areas containing freshwater pools are exposed at low tide producing carbonates.

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INDEX TO APPENDICES.

APPENDIX 1.

TABLE OF THICKNESSES FOR PHASES OF CYCLES (MAIN PART, SWAMP).

DECOMPACTED THICKNESS m.

CYCLE	MAIN PART	SWAMP
1	24.80	13.50
2	40.40	10.00
3	16.87	4.50
4	22.24	15.00
5	40.82	13.00
6	18.65	10.70
7	32.88	6.00
8	40.32	21.70
9	11.15	6.70
10	7.17	12.00
11	11.28	7.00
12	34.14	2.20
13	13.02	6.00
14	33.37	70.90
15	8.24	11.44
16	93.01	5.86
	Mean	Mean
	S.D.	S.D.

APPENDIX 2.

THIN SECTION ANALYSIS.

Bed 29. Channel Sandstone.

This unit is composed almost entirely of quartz with both large (1.0 - 3.0 cm), and small (0.1 - 0.2 cm.) angular, ill sorted grains. In shape the grains are mostly sub-rounded to angular although well rounded grains are present. From 100 contacts (measured along 5 transects) 80 % were grain / grain contacts which are predominantly tangential and 90 % of these are quartz / quartz, with 61 % original : original contacts. However, occasional long contacts are indicative of overgrowths, within these contacts c. 2 % are of pressure solution type. The presence of these smaller grains has reduced the porosity to about 15 % which is predominantly intergranular although intragranular porosity is present due to alteration of the feldspars.

The quartz is generally sub-rounded to angular with few overgrowths (15 %) present. There are both monocrystalline (80 %) and polycrystalline (20 %) forms present, with the monocrystalline forms exhibiting little strain extinction (10 %). The presence in some of the larger grains of 'acicular' and 'irregular' inclusions of rutile and apatite tends to imply that the grains are of igneous origin. Under the S.E.M. 'V' shaped impact marks are visible indicative of a high energy history to the grains (Krinsley and Trusty, 1975, Krinsley and Doornkamp, 1973).

The amount of feldspar is low (< 1 %), and in most cases has been badly altered showing enlarged cleavages. Mica is present although this is also altered to illite and shows lowered polarisation colours and is deformed around the grains in some of the voids.

The cement is predominantly quartz as overgrowths especially on the smaller grains, with kaolinite present partially filling some of the pores as matrix. Intrastratal solution effects can be seen in dissolution features on feldspars (destructive), and the formation of replacive quartz and kaolinite (constructive), in which the kaolinite formation is linked to the feldspar dissolution (Chapter 3.3).

Bed 43.

A fine grained predominantly quartz sample (c. 0.1 cm.) with occasional mica flakes present up to 0.8 cm. in length. Generally a well sorted sample with sub-angular to angular clasts. The predominantly tangential contacts (grain / grain 70 %, quartz / quartz 85 %), with occasional long contacts is largely due to overgrowths (30 %). Intergranular porosity of 15 - 20 % is visible with rare intragranular porosity in the altered feldspars.

The principal component is quartz of sub-angular to angular form often euhedral due to overgrowths. Both mono - and polycrystalline forms are present with a predominance towards the monocrystalline forms (60 % - 40 %). Both undulatory and non - undulatory varieties (30 % - 70 %), are present, with the polycrystalline forms predominantly non - undulatory. The presence of both forms of quartz implies a mixed provenance of igneous and metamorphic form with few visible inclusions.

The feldspar present is microcline with a slight secondary porosity developed along the cleavage (Plate 10). There is a white mica present showing reduced polarisation colours and it is deformed around the clasts. Also present between some of the clasts are small flakes of biotite (from E.D.S). The occurrence of kaolinite varies although it generally forms as discrete masses (Plate 16). Small cubes of pyrite (Plate 12) are visible mantling the clasts; they also occur as discrete patches in voids.

The cement is predominantly silica as overgrowths, with kaolinite present as matrix in the voids, both as a lining and also completely filling them.

Bed 61.

This muddy looking sample contains both non - undulatory (88 %) and undulatory (12 %) forms, and both polycrystalline (15 %) and monocrystalline forms (85 %), with non - undulatory monocrystalline forms predominating. Few irregular, regular and acicular inclusions are visible within the quartz grains suggestive of both igneous and metamorphic host rocks. The sample is moderately well sorted with grain size variable from 0.1cm. - 0.2cm., although 25 % have overgrowths. There are a few triple junctions present along some grain boundaries with 63 % of the contacts grain / grain, with 78 % of these quartz / quartz. The primary porosity has been reduced by the infilling of the matrix to leave c. 5 % relict porosity. Polycrystalline grains containing many sub - grains with sutured internal contacts are present, likely indicative of a highly strained host - metamorphic.

Little feldspar is visible within this sample. Small lithic clasts with a fine grain size (volcanic ?), are visible. Under the S.E.M. small hemispherical masses are visible, these are composed of blades of hematite (Plate 11). Kaolinite occurs as plates and also as more rounded forms. The muddy matrix, largely kaolinite is hematite stained, and discrete patches of hematite are visible.

Bed 78.

This sample is characterized at first glance by its orange colour which is indicative of a significant percentage of iron oxide. A variable grain size is seen from 0.1cm - 0.2cm and the rock is relatively well sorted. Most of the quartz clasts are sub - angular to rounded in form. There is a moderate porosity of c. 10 % although the voids are partly filled by quartz overgrowths. Of the 83 % of contacts which are grain / grain, 73 % are quartz / quartz and mainly tangential (although only 45 % of these are original grain contacts), with sutured contacts also present.

The quartz generally appears to be homogenous (90 %), and non - undulatory (86 %), with thin overgrowths (25 %). However, there are some grains which exhibit severe strain effects and many sub - grains with sutured internal contacts. Acicular inclusions of apatite and rutile are visible as are rows of globules, where the rows of globules are deformed the grains are possibly of metamorphic origin. Predominantly the fabric is grain supported with the iron compound (hematite) forming pore filling cement as well as discrete grains.

Feldspar occurs as microcline which is altered with increased porosity along cleavage. The mica type is white with reduced polarisation colours, and is deformed around grains. Kaolinite is present possibly from the alteration of the feldspars. This kaolinite can be seen as stacks within pits on the quartz overgrowths (Plate 13), these stacks may postdate the overgrowths, alternatively they may be primary and inhibiting overgrowth formation.

The cement to the rock is largely quartz forming overgrowths, while the matrix appears to be a mixture of kaolinite (from decaying feldspar), and a small amount of hematite. Thin rims of 'dust' are visible on the original grains.

Bed 98.

Grain size of this sample varies from 0.1cm - 0.25cm and is not particularly well sorted. The shape of the grains is sub-angular to rounded. Overgrowths (mainly on non - undulatory grains), on 20 % of the quartz grains has reduced the porosity to only 5 % from about 10 %, evidenced by the growth of secondary quartz into voids. Packing of the sediment has led to a grain / grain : grain / matrix contact ratio of 5:2, with 70 % of the grain contacts quartz / quartz, and 40 % of the total contacts original grain / original grain contacts.

For the quartz most of the grains are non - undulatory (82 %), but some show sutured contacts and there are some polycrystalline grains (15 %). Inclusions of the irregular and regular form are present (5 - 10 %). The quartz surfaces show evidence of abrasion and dissolution (steps and pits). Some of these quartz faces show crystallites forming as the first stage of overgrowths (Plate 17), although their apices have been dissolved away.

Feldspar as microcline is very rare in occurrence, some of which has been altered to illite. Small masses of iron minerals are present as mainly limonite and hematite. Mica is present, deformed around the quartz grains, and showing reduced polarisation colours. The kaolinite is limited to filling voids around quartz clasts.

The matrix to the rock is mainly iron compounds mixed with authigenic clays, the cement to the rock is interlocking quartz overgrowing into voids.

Bed 107.

This fine grained well sorted sample with a grain size of c. 0.1cm., shows both undulatory (28 %) and non - undulatory (72 %), mainly monocrystalline forms (83 %). Both regular and irregular inclusions are present within the quartz although their distribution is not uniform throughout the quartz population. The grains appear angular with few overgrowths (15 %), mainly on the non - undulatory grains growing into voids reducing the porosity to c. 5 %. The majority of the grain contacts are grain / grain (70 %), with 80 % quartz / quartz, and 85 % of these original grain contacts. The matrix is a mixture of kaolinite and hematite, although quartz overgrowths act as a bonding agent.

Bed 123.

A fine grained (0.1cm - 0.2cm) well sorted rock with sub-angular to rounded grains present although there are occasional angular grains present. Grain / grain contacts comprise 70 % of all contacts, while of these 85 % are quartz / quartz, and 85 % of these are original grain contacts. The abundance of fine matrix material possibly implies an initial grain support fabric (porosity c. 40 % under high deposition rates), which has been reduced to 10 % intergranularly.

The quartz in the sample is generally monocrystalline (80 %) containing few acicular inclusions, among the monocrystalline grains a non - undulatory habit predominates (65 %). Sutured grain contacts are visible between some of the components within the polycrystalline grains. Few overgrowths (15 %), are visible on the grains and there is only a small percentage of void filling authigenic quartz.

This sample does not show any feldspar and only a limited amount of kaolinite. White hydromica is present showing low polarisation colours and a deformed habit. Of particular interest (S.E.M.), are pyrite cubes which although they reduce intergranular porosity, by their habit leave intragranular porosity (Plate 12).

These cubes act as a coherent cement to the rock, along with a matrix of kaolinite and illite. There is a thin mantling of hematite present around some of the grains.

Bed 144.

A fine grained (0.1cm - 0.25cm) poorly sorted rock with the clasts appearing as angular to sub-angular with some euhedral. However, the long contacts present on the euhedral grains infer overgrowths; these have altered the initial shape of the clasts and sub-rounded cores are visible. The occurrence of grain / grain contacts is 66 % of all contacts, with 70 % quartz / quartz, and 70 % of these original grain contacts. The 5 % porosity is intergranular and has been reduced by authigenic quartz and the formation of discrete masses of hematite.

The quartz is predominantly monocrystalline (75 %), with 30 % undulatory. Pressure solution contacts are visible internally in the few polycrystalline grains. Visible on the initial rounded monocrystalline grains are overgrowths (30 %), forming triple junctions, and euhedral grains.

This sample also shows a minimum of feldspar (that which is present is badly altered). Kaolinite forming from feldspar occurs as books and also mantling the quartz grains. The mica is deformed around the grains and appears to have been sheared into thin laths.

The cement is mainly authigenic quartz, although hematite and kaolinite also occur together in some voids and around some grains. Hematite also forms as masses which appear to have a linear arrangement through the rock.

Bed 159.

This poorly sorted sandstone with angular quartz clasts (0.1cm - 0.3cm) shows few overgrowths (10 %). The grain / grain : grain / matrix contact ratio is 76 : 24, while the quartz / quartz contacts comprise 78 % of these. The limited overgrowth formation leaves 53 % of contacts original grain : original grain.

The quartz is mainly monocrystalline (65 %) with a large percentage of it undulatory (30 %), the few polycrystalline clasts largely contain optically undulatory sub grains. Abundant regular inclusions are visible implying a metamorphic derivation. Straight contacts imply overgrowths, also indicated by faint dust lines on the clasts. These overgrowths show up under the S.E.M. as planar faces (Plates 7 and 8). However, some of the grains appear badly pitted, possibly as a result of transport.

Few feldspars are present and those which are are invariably altered along cleavage to form an intragranular porosity. The occurrence of mica is limited to forming as rafts parallel to bedding, these rafts are deformed adjacent to the quartz clasts. Small stacks of kaolinite are present between the quartz grains. Also present are some lithic clasts of some fine grained volcanic rock.

The cement is predominantly quartz while the matrix is mainly kaolinite with some iron.

Bed 190.

This muddy fine grained well sorted sample with a grain size of c. 0.1cm. appears with a large proportion of the grains non - undulatory (80 %) and monocrystalline (90 %). The few irregular inclusions and lack of straining in the mainly monocrystalline quartz grains implies an igneous source. The grains are generally well rounded with few visible overgrowths. The grain / grain count (predominantly quartz / quartz (85 %), is high in this sample (72 %) possibly indicative of low rates of accumulation of its sorted components. The few overgrowths leave 55 % of all contacts original grain : original grain. There is an orange hematite stained matrix to the sample with a largely grain support fabric.

Present in the sample are carbonaceous laminae possibly rootlets. Only a few badly altered feldspars are present, with a low percentage of kaolinite.

The initial porosity of 10 % has been reduced by the presence of the hematite stained matrix.

APPENDIX 3.

HEAVY MINERAL ANALYSIS PROCEDURE.

The samples were disaggregated in the laboratory with the gentle use of a mortar and pestle to avoid destroying any of the grains. Once reduced to individual grains or small masses the samples were treated with HCl and HNO_3. This was carried out to remove any surface tainting or cementing of the grains with sulphides or carbonates. These clean sands were then sieved on a range of sieves from > 355 microns to < 63 microns and weighed for grain size analysis. The two finest sizes and the next three were then used for heavy mineral separation, the two finest grades being separated together.

In heavy mineral separations it is necessary to choose a sample size such that the effects of 'rafting' of the heavy minerals in the light minerals is kept to a minimum. A sample size of 4 gms. was chosen with the sample being stirred frequently. The bulk of the heavy residue and at least 400 grains were mounted in Canada Balsam and used in microscopic determination.

In the determination of the slides 100 grains were identified with no distinction being made between the various opaque minerals which were grouped together. The percentage of opaque minerals was noted and counting of non-opaque grains continues till that total reaches 200. By this method mutual percentages for the non-opaques were obtained whilst the opaque minerals were expressed as a percentage of the whole heavy fraction.

APPENDIX 4.

ACCURACY OF THE ANALYSING TECHNIQUE.

The accuracy of a technique may be prescribed by the use to which the analysis will be put. It is not necessary to determine proportions in 0.1 percent if conclusions are to be based on differences in composition in the area of 3-5 percent. Moreover the natural statistical variation in a series of samples will normally exceed that small amount. Increasing the accuracy makes the analysis more time consuming, (Dryden and Dryden, 1946, Muller, 1943). The sizes for analysis Table 1, contain the bulk of the heavy minerals while the coarser fractions are usually devoid of heavy minerals. The number of grains chosen was 200 ensuring accuracy and reproducibility yet also allowing fast confident analysis.

The minerals were observed on a mechanical stage and parallel traverses were made across the slide and each grain touching the centre of the cross-hairs was identified. This method of line counting is preferred over field counting for the following reasons :-

1. the grain to be identified is always in the centre of the field so identification is made easier,

2. each grain touching the centre of the cross-hairs must be identified,

3. the influence of an irregular distribution can be lessened by counting along regularly spaced lines.

To ensure no grain was counted twice the traverses were spaced further apart than the largest expected dimension of grains on a slide.

APPENDIX 5.

SIZE FREQUENCY DISTRIBUTIONS OF SOME HEAVY MINERALS (CUMULATIVE WEIGHT PERCENT).

Sample	Size u	Zircon	Rutile	Tourmaline	Garnet
B 29.	180-125	24.44	41.86	65.41	0.00
	125-90	48.70	66.57	93.71	0.00
	90-75	70.53	81.40	97.48	0.00
	< 75	100.00	100.00	100.00	0.00
B 43.	180-125	45.45	33.10	61.53	0.00
	125-90	61.43	72.84	97.57	71.45
	90-75	71.70	84.72	99.39	96.64
	< 75	100.00	100.00	100.00	100.00
B 61.	180-125	32.43	77.25	62.50	63.39
	125-90	51.89	94.42	96.73	90.33
	90-75	59.46	97.85	98.51	94.98
	< 75	100.00	100.00	100.00	100.00
B 78.	180-125	3.41	26.58	72.13	60.89
	125-90	10.84	65.25	100.00	85.25
	90-75	56.66	85.50	100.00	96.32
	<75	100.00	100.00	100.00	100.00

APPENDIX 5. cont'd.

SIZE FREQUENCY DISTRIBUTIONS OF SOME HEAVY MINERALS
(CUMULATIVE WEIGHT PERCENT).

Sample	Size u	Zircon	Rutile	Tourmaline	Garnet
B 98.	180-125	14.75	40.25	57.68	39.83
	125-90	25.62	54.93	90.13	71.07
	90-75	36.30	63.31	96.99	82.06
	< 75	100.00	100.00	100.00	100.00
B 107.	180-125	2.78	12.00	31.15	16.76
	125-90	8.18	20.00	63.93	31.89
	90-75	16.36	30.00	81.96	43.24
	< 75	100.00	100.00	100.00	100.00
B 123.	180-125	17.86	41.67	74.53	53.35
	125-90	45.88	66.67	89.44	83.61
	90-75	63.19	79.17	97.51	92.63
	<75	100.00	100.00	100.00	100.00
B 123.	180-125	11.12	16.84	46.97	26.12
	125-90	20.50	42.10	81.06	57.05
	90-75	38.31	68.42	90.53	82.82
	<75	100.00	100.00	100.00	100.00

APPENDIX 5. cont'd.

SIZE FREQUENCY DISTRIBUTIONS OF SOME HEAVY MINERALS (CUMULATIVE WEIGHT PERCENT).

Sample	Size μ	Zircon	Rutile	Tourmaline	Garnet
B 123.	180-125	6.87	22.22	54.50	41.48
	125-90	20.27	43.89	95.24	73.50
	90-75	35.60	55.56	100.00	85.75
	<75	100.00	100.00	100.00	100.00
B 144.	180-125	33.54	59.41	40.80	53.10
	125-90	60.90	82.43	83.37	88.95
	90-75	71.40	91.09	89.41	96.14
	<75	100.00	100.00	100.00	100.00
B 159.	180-125	15.58	0.00	58.23	35.63
	125-90	29.02	27.10	94.83	63.98
	90-75	34.86	65.04	97.84	69.90
	< 75	100.00	100.00	100.00	100.00
B 190.	180-125	23.79	39.38	78.13	46.13
	125-90	40.09	64.04	92.46	79.65
	90-75	50.96	71.23	96.15	89.68
	< 75	100.00	100.00	100.00	100.00

APPENDIX 6.1.

MODAL ANALYSIS OF SAMPLES WITH RESPECT TO HEAVY MINERALS.

TOTAL SAMPLE.

Sample	Zi.	Ru.	To.	Ep.	Hb.	Au.	Tz.	Ga.	An.	Ad.	Ky.	En.	Si.	Mo.
B27	261	62	45	2	6	0	8	0	11	0	0	0	4	1
B29	251	68	25	2	18	7	2	0	20	5	1	1	0	0
B43	125	41	66	7	11	3	21	81	20	19	3	1	2	0
B52	183	19	26	1	5	0	40	108	14	0	4	0	0	0
B61	138	15	45	2	7	0	22	154	12	0	3	0	0	2
B78	114	11	33	7	9	0	60	144	14	0	0	0	6	2
B91	161	24	79	5	18	0	31	53	24	0	0	0	5	0
B92	138	28	34	2	9	0	10	161	16	0	2	0	0	0
B97	147	24	61	5	13	0	37	93	13	1	0	0	6	0
B98	181	21	59	6	11	0	34	66	16	3	0	1	2	0
B107	173	20	52	4	13	0	22	95	15	2	0	0	3	1
B107	165	17	47	3	8	0	13	126	15	3	0	0	3	0
B112	160	20	43	2	7	0	10	140	16	0	0	0	1	1
B118	159	17	42	0	5	0	9	151	12	0	0	0	2	3
B123	156	17	40	0	7	0	4	157	17	0	0	0	1	1
B123	146	14	76	6	6	0	39	89	16	0	0	0	7	1
B123	160	25	53	8	7	0	7	116	22	0	0	0	1	1
B144	145	18	86	2	7	0	30	92	14	0	0	0	4	2
B159	156	15	67	2	7	0	25	114	10	0	0	0	2	2
B159	180	12	45	1	10	0	31	109	10	0	0	0	2	0
B190	194	26	60	0	13	0	29	66	12	0	0	0	0	0
B204	228	24	81	1	12	0	29	3	18	0	0	0	2	2
B204	185	33	58	0	3	0	7	104	9	0	0	0	0	1

Key for tables :-

Zi.	Zircon	Ru.	Rutile	To.	Tourmaline
Ep.	Epidote	Hb.	Hornblende	Au.	Augite
Tz.	Topaz	Ga.	Garnet	An.	Anatase
Ad.	Andalusite	Ky.	Kyanite	En.	Enstatite
Si.	Sillimanite	Mo.	Monazite		

APPENDIX 6.2.

180 - 125 MICRON GRADE.

Sample	Zi.	Ru.	To.	Ep.	Hb.	Au.	Tz.	Ga.	An.	Ad.	Ky.	En.	Si.	Mo.
B27	45	25	16	2	3	0	4	0	3	0	0	0	2	0
B29	34	18	13	2	2	4	2	0	12	2	1	0	0	0
B43	21	5	26	7	7	0	17	0	0	15	0	0	2	0
B52	34	6	2	0	0	0	20	30	4	0	4	0	0	0
B61	10	6	14	2	4	0	17	40	4	0	3	0	0	0
B78	1	1	16	5	7	0	15	50	5	0	0	0	0	0
B91	22	4	31	2	8	0	17	11	2	0	0	0	3	0
B92	3	6	29	0	7	0	7	45	2	0	1	0	0	0
B97	11	6	25	2	6	0	13	31	4	0	0	0	2	0
B98	19	6	21	2	7	0	19	18	5	3	0	0	0	0
B107	17	6	19	2	6	0	13	31	3	2	0	0	1	0
B107	15	4	19	2	5	0	7	43	3	2	0	0	0	0
B112	14	5	18	1	4	0	6	48	3	0	0	0	1	0
B118	13	5	18	0	3	0	6	52	2	0	0	0	1	0
B123	13	4	18	0	4	0	3	55	3	0	0	0	0	0
B123	16	2	31	1	1	0	24	19	1	0	0	0	5	0
B123	10	5	25	8	3	0	3	40	5	0	0	0	1	0
B144	19	6	26	0	3	0	15	31	0	0	0	0	0	0
B159	18	0	29	1	2	0	18	28	2	0	0	0	0	2
B159	22	2	26	0	8	0	18	24	0	0	0	0	0	0
B190	20	5	32	0	7	0	20	14	2	0	0	0	0	0
B204	14	1	50	0	6	0	23	0	4	0	0	0	0	2
B204	34	5	17	0	2	0	3	36	3	0	0	0	0	0

APPENDIX 6.3.

125 - 90 MICRON GRADE.

Sample	Zi.	Ru.	To.	Ep.	Hb.	Au.	Tz.	Ga.	An.	Ad.	Ky.	En.	Si.	Mo.
B27	63	13	18	0	1	0	2	0	2	0	0	0	0	1
B29	54	17	9	0	5	3	0	0	8	3	0	1	0	0
B43	16	13	33	0	3	3	2	26	0	2	2	0	0	0
B52	18	2	16	0	5	0	12	46	1	0	0	0	0	0
B61	18	4	23	0	3	0	0	51	1	0	0	0	0	0
B78	6	4	17	2	2	0	9	55	3	0	0	0	0	2
B91	32	8	26	0	5	0	8	15	6	0	0	0	0	0
B92	34	9	3	1	1	0	0	48	3	0	1	0	0	0
B97	33	7	15	2	2	0	4	33	3	1	0	0	0	0
B98	32	5	27	4	2	0	7	18	3	0	0	0	2	0
B107	33	4	20	2	4	0	4	28	4	0	0	0	0	1
B107	34	4	13	1	1	0	2	40	4	1	0	0	0	0
B112	33	5	10	1	1	0	1	44	5	0	0	0	0	0
B118	35	4	7	0	0	0	1	48	4	0	0	0	0	1
B123	34	4	6	0	0	0	0	52	4	0	0	0	0	0
B123	18	4	30	3	3	0	7	30	5	0	0	0	0	0
B123	24	6	23	0	3	0	3	38	3	0	0	0	0	0
B144	20	3	35	1	3	0	7	27	4	0	0	0	0	0
B159	23	8	27	1	2	0	4	33	2	0	0	0	0	0
B159	16	3	15	0	2	0	10	53	1	0	0	0	0	0
B190	35	8	15	0	4	0	8	26	4	0	0	0	0	0
B204	53	11	20	0	5	0	6	1	4	0	0	0	0	0
B204	39	4	23	0	1	0	2	27	3	0	0	0	0	1

APPENDIX 6.4.

90 - 75 MICRON GRADE.

Sample	Zi.	Ru.	To.	Ep.	Hb.	Au.	Tz.	Ga.	An.	Ad.	Ky.	En.	Si.	Mo.
B27	71	14	8	0	1	0	2	0	3	0	0	0	1	0
B29	81	17	2	0	0	0	0	0	0	0	0	0	0	0
B43	37	14	6	0	0	0	0	33	6	2	1	1	0	0
B52	56	5	7	1	0	0	2	22	7	0	0	0	0	0
B61	35	4	6	0	0	0	3	44	6	0	0	0	0	2
B78	37	4	6	0	0	0	25	25	4	0	0	0	6	0
B91	38	6	19	1	5	0	4	17	10	0	0	0	0	0
B92	50	7	2	1	1	0	2	32	5	0	0	0	0	0
B97	52	7	5	1	2	0	4	24	4	0	0	0	1	0
B98	55	5	10	0	2	0	7	16	4	0	0	1	0	0
B107	50	5	11	0	3	0	5	21	4	0	0	0	1	0
B107	46	5	12	0	2	0	4	25	4	0	0	0	2	0
B112	44	5	12	0	2	0	3	30	4	0	0	0	0	0
B118	43	4	13	0	2	0	2	32	3	0	0	0	1	0
B123	42	4	13	0	3	0	1	31	4	0	0	0	1	1
B123	41	5	10	2	2	0	5	30	4	0	0	0	0	1
B123	51	6	5	0	1	0	1	27	8	0	0	0	0	1
B144	34	5	22	1	1	0	7	24	4	0	0	0	2	0
B159	45	4	10	0	3	0	2	31	3	0	0	0	2	0
B159	56	4	4	1	0	0	3	24	6	0	0	0	2	0
B190	60	6	10	0	2	0	1	20	1	0	0	0	0	0
B204	80	6	6	1	1	0	0	0	5	0	0	0	1	0
B204	52	12	13	0	0	0	1	21	1	0	0	0	0	0

APPENDIX 6.5.

< 75 MICRON GRADE.

Sample	Zi.	Ru.	To.	Ep.	Hb.	Au.	Tz.	Ga.	An.	Ad.	Ky.	En.	Si.	Mo.
B27	82	10	3	0	1	0	0	0	3	0	0	0	1	0
B29	82	16	1	0	1	0	0	0	0	0	0	0	0	0
B43	51	9	1	0	1	0	2	22	14	0	0	0	0	0
B52	75	6	1	0	0	0	6	10	2	0	0	0	0	0
B61	75	1	2	0	0	0	2	19	1	0	0	0	0	0
B78	70	3	0	0	0	0	11	14	2	0	0	0	0	0
B91	69	6	3	2	0	0	2	10	6	0	0	0	2	0
B92	51	6	0	0	0	0	1	36	6	0	0	0	0	0
B97	51	4	16	0	3	0	16	5	2	0	0	0	3	0
B98	75	5	1	0	0	0	1	14	4	0	0	0	0	0
B107	73	5	2	0	0	0	0	15	4	0	0	0	1	0
B107	70	4	3	0	0	0	0	18	4	0	0	0	1	0
B112	69	5	3	0	0	0	0	18	4	0	0	0	0	1
B118	68	4	4	0	0	0	0	19	3	0	0	0	0	2
B123	67	5	3	0	0	0	0	19	6	0	0	0	0	0
B123	71	3	5	0	0	0	3	10	6	0	0	0	2	0
B123	75	8	0	0	0	0	0	11	6	0	0	0	0	0
B144	72	4	3	0	0	0	1	10	6	0	0	0	2	2
B159	70	3	1	0	0	0	1	22	3	0	0	0	0	0
B159	86	3	0	0	0	0	0	8	3	0	0	0	0	0
B190	79	7	3	0	0	0	0	6	5	0	0	0	0	0
B204	81	6	5	0	0	0	0	2	5	0	0	0	1	0
B204	60	12	5	0	0	0	1	20	2	0	0	0	0	0

APPENDIX 7.

SIZE FREQUENCY TABLE FOR SIEVED SAMPLES.

Sample.	Size u	Weight gms.	%	Cumulative %
B 29	> 355	188.16	75.76	75.76
	355 - 250	4.68	1.88	77.64
	250 - 180	9.09	3.66	81.30
	180 - 125	17.79	7.16	88.46
	125 - 90	11.43	4.60	93.06
	90 - 75	2.14	.86	93.92
	75 - 63	3.26	1.31	95.23
	< 63	11.80	4.75	99.98
B 43	> 355	21.00	13.56	13.56
	355 - 250	4.57	2.95	16.51
	250 - 180	20.55	13.27	29.78
	180 - 125	78.85	50.93	80.71
	125 - 90	18.45	11.92	92.63
	90 - 75	3.10	2.00	94.63
	75 - 63	1.23	.79	95.42
	< 63	7.07	4.57	99.99
B 61	> 355	29.89	15.97	15.97
	355 - 250	15.85	8.47	24.44
	250 - 180	34.74	18.56	43.00
	180 - 125	60.93	32.56	75.56
	125 - 90	20.65	11.03	86.59
	90 - 75	4.14	2.22	88.81
	75 - 63	4.00	2.14	90.95
	< 63	16.90	9.03	99.98
B 78	> 355	3.81	3.83	3.83
	355 - 250	19.04	19.15	22.98
	250 - 180	44.83	45.09	68.07
	180 - 125	22.42	22.55	90.62
	125 - 90	4.00	4.02	94.64
	90 - 75	1.00	1.00	95.64
	75 - 63	.63	.63	96.27
	< 63	3.69	3.71	99.98

APPENDIX 7. cont'd.

SIZE FREQUENCY TABLE FOR SIEVED SAMPLES.

Sample.	Size u	Weight gms.	%	Cumulative %
B 91	> 355	8.47	8.25	8.25
	355 - 250	5.07	4.32	12.57
	250 - 180	25.68	15.68	28.25
	180 - 125	75.78	44.73	72.98
	125 - 90	72.00	17.12	90.10
	90 - 75	18.92	5.36	95.46
	75 - 63	9.52	1.89	97.35
	< 63	19.16	2.65	100.00
B 107 (L)	> 355	61.32	40.25	40.25
	355 - 250	2.37	1.55	41.80
	250 - 180	3.00	1.97	43.77
	180 - 125	4.51	2.96	46.73
	125 - 90	9.67	6.35	53.08
	90 - 75	9.87	6.47	59.55
	75 - 63	12.63	8.29	67.84
	< 63	48.97	32.14	99.98
B 107 (U)	> 355	78.58	39.11	39.11
	355 - 250	2.72	1.35	40.46
	250 - 180	3.26	1.62	42.08
	180 - 125	6.66	3.31	45.39
	125 - 90	21.82	10.86	56.25
	90 - 75	12.46	6.20	62.45
	75 - 63	12.30	6.12	68.57
	< 63	63.12	31.41	99.98
B 123 (L)	> 355	6.33	4.36	4.36
	355 - 250	28.39	19.56	23.92
	250 - 180	69.86	48.14	72.06
	180 - 125	20.19	13.91	85.97
	125 - 90	13.44	9.26	95.23
	90 - 75	1.82	1.25	96.48
	75 - 63	.62	.42	96.90
	< 63	4.45	3.07	99.97

APPENDIX 7. cont'd.

SIZE FREQUENCY TABLE FOR SIEVED SAMPLES.

Sample.	Size u	Weight gms.	%	Cumulative %
B 123 (M)	> 355	26.00	27.51	27.51
	355 - 250	3.54	3.75	31.26
	250 - 180	13.15	13.92	45.18
	180 - 125	33.00	34.92	80.10
	125 - 90	13.53	14.32	94.42
	90 - 75	1.42	1.50	95.92
	75 - 63	.95	1.00	96.92
	< 63	2.90	3.07	99.99
B 123 (U)	> 355	13.43	10.05	10.05
	355 - 250	6.23	4.66	14.71
	250 - 180	22.88	17.13	31.84
	180 - 125	65.50	49.04	80.88
	125 - 90	18.00	13.47	94.35
	90 - 75	1.89	1.42	95.77
	75 - 63	1.42	1.06	96.83
	< 63	4.21	3.15	99.98
B 144	> 355	3.06	1.49	1.49
	355 - 250	6.44	3.14	4.63
	250 - 180	11.50	5.61	10.24
	180 - 125	97.01	47.36	57.60
	125 - 90	63.40	30.95	88.55
	90 - 75	9.91	4.84	93.39
	75 - 63	5.09	2.48	95.87
	< 63	8.41	4.10	99.97
B 159 (L)	> 355	46.55	21.50	21.50
	355 - 250	8.78	4.06	25.56
	250 - 180	25.37	11.72	37.28
	180 - 125	80.00	36.96	74.24
	125 - 90	27.00	12.47	86.71
	90 - 75	6.97	3.22	89.93
	75 - 63	5.56	2.57	92.50
	< 63	16.22	7.49	99.99

APPENDIX 7. cont'd.

SIZE FREQUENCY TABLE FOR SIEVED SAMPLES.

Sample.	Size u	Weight gms.	%	Cumulative %
B 159 (U)	> 355	24.10	14.14	14.14
	355 - 250	11.00	6.46	20.60
	250 - 180	24.20	14.20	34.80
	180 - 125	88.71	52.07	86.87
	125 - 90	11.24	6.60	93.47
	90 - 75	3.19	1.87	95.34
	75 - 63	2.05	1.20	96.54
	< 63	5.88	3.45	99.99
B 190	> 355	.13	.05	.05
	355 - 250	1.80	.69	.74
	250 - 180	19.65	7.59	8.33
	180 - 125	186.27	71.96	80.29
	125 - 90	36.20	13.98	94.27
	90 - 75	4.10	1.58	95.85
	75 - 63	3.34	1.29	97.14
	< 63	7.36	2.84	99.98

APPENDIX 8.1.

HEAVY MINERAL CONTENT IN DIFFERENT SIZE GRADES (IN WEIGHT PERCENTAGES OF THE TOTAL SIZE GRADE).

Sample.	180-125	125-90	90-75	<75
B 27.	.49	1.00	.80	.48
B 29.	.44	.43	1.40	.26
B 43.	.49	.97	1.61	1.20
B 52.	.49	.76	.87	.76
B 61.	.49	.48	.48	.23
B 78.	.49	1.00	4.00	.46
B 91.	.23	.50	.95	.97
B 92.	.24	.90	1.78	.46
B 97.	.69	.48	.49	.24
B 98.	.49	.47	1.71	4.33
B 107 (L.).	.22	.10	.10	.09
B 107 (U.).	.15	.22	.24	.49
B 107 (Av.).	.18	.16	.17	.29
B 112.	.25	.48	.24	.37
B 118.	.21	.24	.23	.44
B 123 (L.).	.49	.44	1.64	.78
B 123 (M.).	.24	.44	3.52	2.59
B 123 (U.).	.24	.72	3.70	3.55
B 144.	.50	.48	.70	.66
B 159 (L.).	.50	1.00	.86	1.97
B 159 (U.).	.24	.71	1.88	1.21
B 159 (Av.).	.37	.85	1.37	1.59
B 190.	.24	.49	1.71	2.24
B 204.	.24	2.00	5.79	2.77
B 204.	.24	.24	.21	.76

APPENDIX 8.2.

HEAVY MINERALS AS A PERCENTAGE OF THE TOTAL HEAVY MINERALS PRESENT.

Sample.	180-125	125-90	90-75	<75
B 29.	17.39	16.99	55.34	10.27
B 43.	11.47	22.71	37.70	28.10
B 61.	29.16	28.57	28.57	13.69
B 78.	8.23	16.80	67.20	7.73
B 98.	7.00	6.71	24.42	61.85
B 107.	22.50	20.00	21.25	36.25
B 123 (L.).	14.62	13.13	48.95	23.28
B 123 (M.).	3.53	6.48	51.84	38.14
B 123 (U.).	2.92	8.76	45.07	43.24
B 144.	21.36	20.51	29.91	28.20
B 159 (L.).	11.55	23.09	19.86	45.49
B 159 (U.).	5.94	17.57	46.35	29.95
B 190.	5.13	10.47	36.54	47.86

APPENDIX 9.1.

PROBE DATA FOR GARNETS.

GROUP	SAMPLE	MgO	CaO	FeO	MnO	
1	B43	1.873	1.616	36.302	0.687	
1	"	2.590	1.803	31.873	5.146	*
1	"	3.017	0.954	33.583	4.187	*
2	B61	2.827	1.610	34.859	1.541	
2	"	2.963	1.741	35.672	1.316	
2	"	3.059	1.797	35.521	1.323	
2	"	3.740	0.998	36.524	0.635	
2	"	3.686	1.858	32.324	1.771	
3	B78	1.422	4.178	28.449	8.466	*
3	"	3.542	2.105	32.250	3.750	*
3	"	3.575	2.120	23.038	12.039	*
3	"	4.315	1.779	35.057	0.687	
3	"	4.488	2.529	33.406	0.848	
3	"	4.423	1.588	32.214	2.398	*
3	"	4.630	1.744	32.484	2.789	*
4	B98	4.424	2.640	32.733	1.064	
4	"	4.583	1.740	31.614	0.688	
4	"	4.926	1.554	33.960	0.742	
5	B107	4.780	1.084	31.741	1.674	
5	"	5.358	1.718	31.522	0.840	
5	"	5.377	1.175	31.743	1.282	
5	"	5.762	1.403	32.771	0.742	
6	B123	5.407	3.526	29.507	1.210	
6	"	5.899	2.870	31.115	1.118	
6	"	6.390	1.312	30.830	0.610	
6	"	6.677	1.296	31.607	0.854	
7	B144	6.881	2.020	28.916	0.806	
7	"	7.315	1.047	31.558	0.585	
7	"	7.004	1.941	28.822	0.439	
7	"	7.861	1.369	27.888	0.648	
7	"	8.300	1.168	30.147	0.684	
9	B190	8.118	6.518	22.093	0.864	
9	"	8.303	6.263	21.744	0.771	
9	"	8.330	6.434	20.935	0.735	
9	"	8.530	6.426	20.722	0.765	
8	B159	17.343	4.313	10.838	1.604	
8	"	18.398	4.161	10.601	1.936	
8	"	19.547	4.911	10.770	1.636	
Elie Garnet		18.520	5.230	10.610	0.310	

* Denotes samples with Spess. > 5%.

APPENDIX 9.2

PROBE DATA FOR GARNETS.

GROUP	SAMPLE	PYROPE	GROSS.	ALM.	SPESS.	
1	B43	7.83	4.93	85.60	1.64	
1	"	10.51	5.25	72.54	11.70	*
1	"	12.05	2.71	75.72	9.52	*
2	B61	11.53	4.82	80.03	3.62	
2	"	11.93	4.87	80.17	3.03	
2	"	12.18	5.15	79.76	2.91	
2	"	14.71	2.82	81.03	1.44	
2	"	15.23	5.43	75.13	4.21	
3	B78	11.95	15.55	63.47	9.03	*
3	"	13.91	6.01	71.65	8.43	*
3	"	14.35	5.98	52.14	27.53	*
3	"	16.58	4.95	76.94	1.53	
3	"	17.51	7.07	73.57	1.85	
3	"	17.74	4.61	72.18	5.47	*
3	"	17.94	4.90	71.06	6.10	*
4	B98	17.44	7.52	72.65	2.39	
4	"	19.04	5.11	74.25	1.60	
4	"	19.25	4.25	74.78	1.72	
5	B107	19.76	3.12	73.13	3.99	
5	"	21.61	4.97	71.52	1.90	
5	"	21.74	3.42	71.92	2.91	
5	"	22.43	3.88	72.03	1.66	
6	B123	21.47	9.96	65.80	2.77	
6	"	22.71	7.80	67.12	2.37	
6	"	25.63	3.76	69.21	1.40	
6	"	25.84	3.52	68.79	1.85	
7	B144	27.48	5.80	64.88	1.84	
7	"	27.94	2.84	67.94	1.28	
7	"	28.26	5.55	65.05	1.14	
7	"	31.28	3.19	64.06	1.47	
7	"	31.56	3.81	63.13	1.50	
9	B190	31.60	18.24	48.25	1.90	
9	"	32.63	17.70	47.95	1.71	
9	"	33.15	18.41	46.76	1.66	
9	"	33.83	18.32	46.12	1.71	
8	B159	51.74	9.25	36.29	2.72	
8	"	53.50	8.70	34.60	3.20	
8	"	54.25	9.80	33.50	2.58	
Elie Garnet		53.88	10.94	34.66	0.51	

* Denotes samples with Spess. > 5%.

APPENDIX 10.

BED BY BED HEAVY MINERAL ASSEMBLAGES.

Bed 29.

X.R.D. Class D

This sample from a pebbly massive unit shows a zircon dominated, variable rutile, tourmaline association in the larger grades (180 - 125 microns) which changes to a zircon and rutile association in the finer fractions of the sample. The loss of the less stable minerals ie. hornblende, augite and topaz is most pronounced in this example and physical destruction of the grains is thought to have been the major controlling feature in this high energy environment. However, as stated previously (Chapter 4.2.3) there is also likely to have been a minor dissolution effect on any less stable grains as the deposit was originally quite porous (10 percent) although cementation during diagenesis has left a porosity of c. two percent. This aspect has been discussed in greater detail in Chapter 3.3.

The deposit as a coarse channel bed - load has undergone moderate reworking and it is possible that finer grains with densities less than 4.0 have been withdrawn from a high water velocity environment.

The form of the zircon is largely unzoned indicative of a basic igneous host, although it shows two distinct populations. In the finer grades rounded ovoid grains predominate, whilst in the coarser grades grains with good crystal shape predominate. In certain of the well formed crystals can be found zoned cores (acid host), and also present are well rounded purple varieties. Both types of rutile are present (brown and red / yellow), although these do not show any good crystal form and are likely reworked. The tourmaline is predominantly green indicative of granitic or schistose rocks. The augite is present as rounded grains with no inclusions and dark in colour and is interpreted as being of dioritic or gabbroic source. The provenance is therefore interpreted as being predominantly igneous from an area composed of both acid and basic bodies.

Bed 43.

X.R.D. Class E

The zircon present in this unit is mainly of the well rounded form with few well formed crystals present and few purple grains. The tourmalines are mainly of the rectangular green form although with rounded corners and with some containing inclusions (zircon). As with Bed 29 the percentage of rutile is approximately constant throughout the sample and occurs as irregular flecks, deep red in colour and possibly authigenic.

This flat laminated unit has a high (15) percentage of garnet in the 90 - 75 micron grade but garnet decreases in both coarser and finer fractions. Other less stable minerals eg. kyanite and topaz decrease in the finer grades. On microscopic examination the garnets show 'step' like features along their margins which could be a result of physical disintegration along planes of weakness or overgrowths (Simpson, 1976). (4.4.6).

This sample is also characterised by a large (15) percentage of andalusite, which decreases rapidly in the finer grades, as well as minor kyanite and sillimanite. The rapid disappearance of these minerals (semi - stable) with respect to size is consistent with a significant distance of transport (circa 100 Km. Figs. 22 and 23).

The observed heavy mineral assemblage of zircon, rutile and tourmaline is consistent with an igneous province although the presence of the accessory minerals andalusite, kyanite and sillimanite indicate a variety of grades of metamorphism. This is therefore postulated as being from igneous and metamorphic sources.

Bed 61.

X.R.D. Class B

This channel sand sample with its assemblage containing epidote, topaz, andalusite and kyanite as well as the normal zircon, rutile and tourmaline also contains coarse garnet. The form of the zircon is as fractured irregularly shaped grains with poor crystal terminations, and rounded corroded grains. Towards the finer grades the zircon becomes very well rounded and abraded with dark inclusions (however unzoned). Few elongate well formed purple zircons are present. The few rutile grains present are largely irregular in form although good crystal grains (authigenic) are also present. Tourmaline (largely green), forming rectangular plates with rounded corners, some containing minute zircons appears in a relatively large percentage (23) in the 125 - 90 micron grade possibly derived from metasomatic rocks and associated pegmatites. The small percentage of coarse kyanite is present as thin irregular flakes.

Overall, the provenance is interpreted as being metasediments although a component from granites and pegmatites is present.

Bed 78.

X.R.D. Class G

Sample Bed 78 is from a 2.4m trough cross-bedded unit and is characterised by large percentages of garnet in its assemblage containing epidote and topaz. By grade size, there is a change from a coarse topaz and tourmaline predominancy to a fine zircon and topaz suite. Zircon occurs mainly in the finer grades, and as such as well abraded rounded elongate grains with surface markings and inclusions. Also present is a significant percentage of well rounded purple grains. Rutile occurs as regularly shaped brown and red grains derived from older igneous rocks. Tourmaline present predominantly as the green variety with few inclusions is noted to disappear by the 90-75 grade and from this it is postulated that the source area was supplying coarse tourmaline possibly from pegmatites. Flat plates of topaz are colourless and irregularly shaped. The garnets present show 'step' like features as a result of overgrowths.

The heavy mineral weight in relation to weight of sample, peaks in the 90 - 75 grade and the first significant appearance of zircon occurs in this grade. Thus it would appear that a large amount of fine zircon has been newly supplied to system. This peak also coincides with the occurrence of topaz, and the virtual disappearance of tourmaline.

The inferred provenance for this sample is therefore interpreted as being from pegmatites with associated metasediments. The presence of andalusite and sillimanite suggests derivation from the Central Highland metamorphic zone. The form of the zircons suggests they could have been derived ultimately from older igneous rocks.

Bed 98.

X.R.D. Class F

The plot (Fig. 14) for this horizontally laminated unit shows a sharp increase in heavy mineral content towards the finer grades, however no mineral species can be seen to be responsible for this rise. Initially size wise the association is of zircon, rutile, topaz, tourmaline plus epidote, andalusite and kyanite, but shifts to a zircon dominated suite with very minor rutile, topaz and tourmaline. As a flat horizontally laminated unit it appears to be the product of a low velocity environment; in which the smaller grains have been concentrated (Fig. 18).

The form of the zircon is varied in that both rounded and angular grains with well formed terminations are present. For the rounded type both elongate and spherical types are present indicating a mixed provenance. The ubiquitous rutile appears to be of both older granites and a metamorphic source. The brown rutiles appear generally to be well rounded while the red and yellow types appear more angular. The predominantly green tourmalines are well rounded and abraded with no visible inclusions.

The provenance for this sample would appear to be a granitic host, possibly foliated. The metamorphic minerals and rutile could imply derivation from one of the older masses with associated metasediments.

Bed 107

X.R.D. Class C 1

This unit shows a consistent rise in heavy mineral content although the percentage is low throughout the unit (Fig. 18). The composition of the unit is from a mixed igneous / metamorphic provenance. Both types of zircon are present although the more rounded varieties predominate towards the finer fractions. Both types of rutile are present the brown grains related to older granites and the red varieties related to metamorphic rocks. The tourmaline is predominantly green and well rounded, although a few blue grains are present indicative of a pegmatitic origin.

The hornblende is predominantly of the light form indicating a dioritic source. The presence of andalusite (3 %) and sillimanite (3 %) along with zircon, rutile and tourmaline implies a largely igneous host with contributions from basic bodies with adjacent metamorphics. The andalusite occurs as irregularly shaped grains due to abrasion as does the sillimanite. An interesting feature is the increased importance of garnet towards the top of the unit.

Bed 123.

X.R.D. Class C 2 closely similar to 107.

This massive trough cross-bedded unit shows an increase in total heavy mineral percentage towards the top of the unit and in the finer fractions. The sample shows a relative increase of tourmaline and topaz in the middle of the unit with a proportional drop in the percentage of garnet. Its association is similar to that of Bed 107 with similar coarse sillimanite. Differences in heavy mineral percentage per size grade (Appendix 8), may possibly be due to the differing environments of deposition.

Within this sample all shapes and sizes of zircon are present with no form predominating, with most grains corroded in some way. The presence of blue tourmaline in the upper sample is indicative of a pegmatitic source. The majority of the tourmaline is of the green type, mainly rectangular with rounded corners exhibiting few inclusions. Angular red rutile is present in the coarse and lower samples, although these grains become well abraded both finer and upwards. The presence of anatase in the finer grades and towards the top of the unit is attributed to an igneous source.

The heavy mineral content per size grade increase up to the 90 - 75 micron grade and is related to the increase in zircon occurrence toward the top of the sample. The source for this sample has therefore been postulated as being from an igneous source with proximal metamorphic pelites.

Bed 144.

X.R.D. Class C 2 very similar to 123.

This epsilon cross - bedded unit has a low occurrence of heavy minerals throughout. Zircon, topaz, tourmaline and sillimanite predominate with a relatively high percentage of tourmaline which decreases suddenly at < 75 microns grade.

The zircons present in this unit occur as mainly rounded although some are elongate with pyramidal terminations. The rounded grains contain dark inclusions as well as minute zircons. Towards the finer grain size the zircons are all rounded whether they are elongate or not. Purple reworked forms are present with a well rounded corroded habit. Brown and yellow rutile varieties predominate and generally have rounded terminations. The tourmaline is largely of the green variety in which some grains have smaller zircon inclusions. Topaz is present as irregular dingy plates.

The source for this sample has therefore been postulated as b of igneous form very possibly with proximal pegmatites or c schists, similar to that of Bed 123.

Bed 159.

X.R.D. Class G similar to 78.

Samples were taken at the base and top of a symmetrical sand wave unit and these show distinctive mineralogy with the heavy mineral content, as a percentage of size grade, increasing as grain size decreases. The basal samples show an initial coarse mixed association which alters with reduction in particle size to a heavily zircon dominated minor topaz and tourmaline association. The top of the unit shows a similar association to the base which again shifts dramatically with a reduction of grain size to a zircon predominancy taken up by a decrease in all other minerals.

Zircon predominates in the finer sediments < 90 microns, and is generally well rounded even though pyramidal terminations are present - few show inclusions. Some purple varieties are present well rounded, as are the very fine zircons. Rutile appears as mainly dark red and dull yellow grains, although brown abraded grains are also present. Tourmaline is present in both green and brown form with well rounded grains with few visible inclusions. Fine sillimanite is also present suggesting source was related to metamorphosed pelites, possibly with adjacent pegmatites which supplied coarse tourmaline and a bulk of fine zircon.

Bed 190.

X.R.D. Class A

This sample shows a swing from a coarse zircon, rutile and tourmaline suite, to a heavily zircon dominated assemblage towards the finer fractions containing rutile and topaz. The zircon occurs as both abraded and unabraded types, where the abraded form is generally well pitted. Very few purple reworked grains are present. The occurrence of the rutile is mainly as dark red well rounded grains. The tourmaline grains are generally well rounded and are mainly green with few inclusions. The occurrence of the topaz is restricted to forming irregular dingy plates.

Significantly there is a loss of garnet in the succession, which is replaced by an increase in the abundance of zircon. Within the sample there is a relative enrichment in heavy mineral abundance toward the finer grades (Fig. 18).

This sample is suggested as being derived from a mainly igneous host although contamination with other host rocks will undoubtedly have occurred.