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DEPARTMENT OF MINES
SOUTH AUSTRALIA

GEOLOGICAL SURVEY

PETROLEUM EXPLORATION DIVISION

A SUBDIVISION OF THE OTWAY GROUP BASED ON A SEDIMENTARY STUDY AND ELECTRIC LOG INTERPRETATION

by

K. ROCHOW
ASSISTANT SENIOR GEOLOGIST
PETROLEUM SECTION

S.R. 11/5/123

12th February, 1968.

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SUMMARY

This study was undertaken by the Australian Mineral Development Laboratories on behalf of the South Australian Mines Department and includes petrographic descriptions, heavy mineral and clay mineral analyses, sorting, roundness and sphericity determinations, and trace element analyses. The heavy mineral analyses reveal a distribution which not only distinguishes the Otway Group from the remaining sediments but suggests subdivision of that group into three sequences which can be correlated from well to well. Relative concentrations of the clay minerals, smectite and kaolin, indicate basic differences between the Otway Group, Upper Cretaceous, and Tertiary sediments, but sensitivity to environment of deposition and diagenesis create some inconsistencies.

Spectrographic analyses indicate that the trace elements, especially phosphate and vanadium, are also influenced predominantly by environment of deposition and are not suitable for regional correlation.

Sphericity, roundness, and sorting measurements show no systematic differences that can be related to other properties of the sediments.

The above properties are integrated with other sedimentary parameters, such as electric log character, to assist in correlation of sedimentary sequences from well to well. In this way Otway Group sediments in Kalangadoo No. 1 well are subdivided into four units on the basis of heavy minerals, clay minerals, electric logs, and a dipmeter survey. Using the same parameters, these sequences are correlated with equivalent sequences in all of the deeper oil exploration wells in the Gambier Embayment.

Similar subdivision of the Upper Cretaceous and Tertiary sequences is not possible at this stage due primarily to the few cores available.

SEDIMENTARY STUDY OF CORES FROM WELLS IN THE GAMBIER EMBAYMENT

INTRODUCTION

This detailed study of subsurface samples from the sediments in the Gambier Embayment was in general undertaken to provide additional information on sedimentation in the Gambier Embayment. More specifically, the study was intended to determine whether the lithological differences within the sedimentary sequence could be used to correlate lithological units from well to well.

The detailed studies including petrography, heavy mineral determination, clay mineralogy, trace element analyses, and sorting, sphericity, and roundness determinations, were carried out by D. Smale, E.C. Stock and N.A. Trueman of the Australian Mineral Development Laboratories. A total of 54 core samples from Penola No. 1, Beachport No. 1, Geltwood Beach No. 1, Kalangadoo No. 1, and Mt. Salt No. 1 were studied and analysed (figure 1). The following account represents a summary of the findings and is taken from Amdel Report No. 489 by D. Smale, E.C. Stock, and N.A. Trueman.

B.P.N.L. Geltwood Beach No. 1			A.O.D.A.N.L. Kalangadoo No. 1		
Core 1	from	2000' - 2015'	Core 1	from	1993' - 2008'
Core 3	"	2328' - 2340'	Core 2	"	2503' - 2513'
Core 4	"	2651'	Core 3	"	2930' - 2940'
Core 6	"	3317' - 3332'	Core 4	"	3404' - 3414'
Core 7	"	3632' - 3647'	Core 5	"	3917' - 3927'
Core 8	"	3774'	Core 6	"	4358' - 4363'
Core 9	"	4097' - 4098'	Core 7	"	4771' - 4776'
Core 11	"	4515'	Core 9	"	5288' - 5299'
Core 13	"	5058' - 5059'	Core 10	"	5634' - 5644'
Core 17	"	6524'	Core 11	"	6120' - 6134'
Core 19	"	7546' - 7556'	Core 12	"	6632' - 6642'
Core 21	"	8479'			

B.P.N.L. Geltwood Beach No. 1 (Contd.)

Core 23	from	9367'
Core 27	"	11236'
Core 28	"	11741'

O.D.N.L. Mt. Salt No. 1

Core 1	from	998'
Core 3	"	1601'
Core 5	"	2189'
Core 8	"	2913'
Core 9	"	3145'
Core 11	"	3680'
Core 13	"	4217'
Core 15	"	4790'
Core 17	"	4950'
Core 20	"	5506'
Core 23	"	6402'
Core 25	"	6987'
Core 28	"	7946'
Core 31	"	9424'
Core 34	"	10033'

S.E.O.S. Beachport No. 1

Core 1	from	2097'
Core 2	from	2291'
Core 3	from	2507'
Core 6	"	3030'
Core 9	"	3672'
Core 10	"	3939'

O.D.N.L. Penola No. 1

Core 3	from	1611'
Core 8	"	2587'
Core 11	"	3187'
Core 14	"	3721'
Core 17	"	4087'
Core 20	"	4602'
Core 21	"	4771'

Figure 1. Cores included in The Sedimentary Study.

SUMMARY OF RESULTS FROM INDIVIDUAL WELLS

B.P.N.L. Geltwood Beach No. 1 (Fig. 2)

Nearly all of the specimens are argillaceous and carbonaceous siltstones and sandstones. However, the proportion of clay and carbonaceous material is less in the lower cores.

The specimens from core 7 and below are dominantly argillaceous greywackes, but as quartz is so dominant in the matrix, it is difficult to classify the rocks as lithic or feldspathic greywackes. However, most appear to be feldspathic greywackes.

Igneous fragments are present, especially in Core 9, and fresh plagioclase is abundant in cores 9, 13, 19, 27 and to a lesser extent in cores 11, 23 and 28. Plagioclase is rarely entirely absent and potassic feldspar is common in most specimens. Greenish minerals occur in minor amounts from Core 7 downwards. In cores 8, 9, 11 and 21 these grains resemble glauconite, but in cores 11, 13, 19, 23, 27 and 28 a chloritic mineral appears to be more common. However, the concentration is low and the distinction and identification is doubtful.

A marked change in mineral constituents between cores 7 and 9 suggests a possible subdivision of the sequence. In core 9 and below, the presence of igneous fragments and fresh plagioclase (Plate 1D) is a distinctive feature. Core 8 (Plate 1C) contains similar fragments, but in much smaller concentration, whereas the cores above Core 8 contain few or no igneous fragments. Chlorite or glauconite also disappears up the sequence in this zone, but occurs as high as Core 7 and consequently does not define the break. However, the almost complete absence of the heavy minerals apatite, sphene, garnet, and epidote above Core 9 gives a strong basis for subdividing the sequence between Cores 8 and 9.

Another subdivision of the sequence is suggested on lithological grounds between the cores above and below core 23. Many of the cores above 23 are argillaceous greywackes. Core 23 itself is an argillaceous siltstone and it is difficult to determine whether it has affinities with the cores above or with the lithic feldspathic greywackes below. The heavy minerals do not exhibit any clear break in this interval except for the absence of sphene below core 23.

Most of the tourmaline in the heavy mineral suites is pleochroic from brown to blue, or green to pink, but blue-pink tourmaline is present in cores 1 and 9, and blue-green in cores 3, 6, 8 and 9. The brown colour, together with the presence of gaseous inclusions indicates, as in Mt. Salt No. 1, that most of the tourmaline was originally derived from a plutonic source. Some of the remaining tourmaline may have been derived from a pegmatitic source (Krynine, 1946). The number of different varieties present, however, indicate that they were probably derived from a dominantly sedimentary terrain. Euhedral zircons are present in addition to rounded zircons, indicating that part at least of the source area was igneous. The increase in the proportion of euhedral zircons with depth suggests that as time went on less igneous material was exposed in the source area.

Glauconite-like material occurs in cores 8, 9, 11 and 21; at least that in core 9 is in the form of fossil casts. This mineral is distinct from the clay matrix, but is not present in sufficient quantity to enable it to be identified by x-ray diffraction. Clayey material in core 13 may have formed similarly. Consequently, the environment of deposition may have been slow sedimentation with current agitation at depths between 10 and 400 fathoms. However, as the glauconite-like material forms only a small percentage of the sediment, any of these factors may have varied.

One other basis for subdivision is suggested between cores 3 and 4 by heavy mineral distributions. The heavy minerals in cores 1 and 3 are similar, and are distinct from those in cores 4, 6 and 7, especially in the content of opaques, tourmaline, and rutile. Lithologically, however, there is no distinction.

The clay mineral assemblages also have distinctive groupinge. Cores 23, 27 and 28 form a group with dominant illite and accessory smectite. In cores 7 to 21 smectite is dominant. Another group consisting of cores 4 and 6 has dominant kaolin with accessory random mixed-layer clays and no chlorite. Cores 1 and 3 have no chlorite or random mixed layer clays.

O.D.N.L. Mt. Salt No. 1 (Fig. 3)

All of the specimens studied are sandstones or siltstones. The sands are generally pale brown to buff and the siltstones are dark grey. Quartz is the dominant constituent of the framework in all cores except core 9 where ferruginous oolites are dominant (Plate 1A). All the specimens are poorly cemented and porous although clay is common in the matrix. Carbonate occurs as cement in cores 20 and 31 (Plate 1 B). Carbonaceous material is abundant in most specimens in addition to small quantities of muscovite, biotite, and potassic feldspar. Rare sericitic siltstone fragments are also present in cores 11 and 13, felsitic fragments in core 17 and green clay or chlorite of a distinctive type in cores 28 and 34.

Sedimentary structures such as current bedding (core 15), graded bedding (core 25), and possibly scouring (cores 23 and 34) are not uncommon. Very fine interbeddingof coarse and fine material is present in some of the more carbonaceous specimens (cores 15, 23 and 34).

In cores 25 and 31, most of the quartz grains have been secondarily enlarged or possibly affected by pressure solution. Biotite, where present, is commonly altered to chlorite. In the oolitic specimen from core 9, the peculiarly rounded shape of the biotite flakes suggests that they have been chemically corroded.

Core 9 (Plate 1A) has a highly distinctive lithology, however, the distinction between the lithologies above and below this core is not well defined. Both above and below core 9 the cores are porous, poorly cemented sandstones or siltstones in which quartz is the dominant constituent of the framework. However, rock fragments are more abundant below core 9.

The similarity of all properties in the cores below core 9, especially in heavy minerals, indicates that the area of provenance remained very much the same. However, the rock fragment types vary, suggesting that initially some basic rocks were present in the area of provenance, resulting in a notably chloritic detritus. Acid volcanic fragments are included later in the sequence.

However, the majority of constituents were probably derived from a sedimentary terrain, as quartz and clay are so abundant, and the grains of both light and heavy fractions give indications of reworking. Microcline in cores 13 and 17 probably came from a granitic source. The variety and rounding of the tourmaline also indicates that the sediments have been reworked. Most of the tourmaline is pleichroic from brown or greenish brown, to pale pink or yellow. Some blue-pink grains are present in cores 9, 13, 20 and 28. The brown colour and abundance of gaseous inclusions in most of the grains indicates that they were originally derived from a plutonic source (Krynine 1946).

The presence of both rounded and euhedral zircons supports the suggestion that outcrops of igneous rocks were present in the source area in addition to sedimentary rocks. Euhedral zircons become significant above core 20 so erosion of igneous rocks probably took place during this stage of deposition.

The presence of sparse brookite in core 25 and a trace in core 28 suggests some distinction between these cores and the remaining cores, but this is not supported by the distribution of the other heavy minerals. One negative, though significant aspect of the heavy mineral distribution is the extreme scarcity of apatite, sphene, epidote and garnet throughout the sequence.

Pyrite is distributed irregularly through the specimens and cannot assist subdivision of the sequence. However, the clay minerals have a significant distribution.

Core 11 and those below it, have kaolin as the dominant clay. Greenalite distinguishes core 9 from all the others (Plate 2c) and cores 1, 3, 5 and 8 contain no chlorite or random mixed-layer clays.

A.O.D.A.N.L. Kalangadoo No. 1 (Figure 4)

The cores are mostly lithic greywackes, but there is little difference in many of them from feldspathic greywackes, as feldspar and lithic fragments are present in almost equal quantities. Only in cores 1 and 2 do feldspar grains actually exceed thelithic grains. Cores 3 and 5 are argillaceous siltstones, but do not resemble each other; carbonaceous material is abundant in core 3, whereas core 5 has a greater abundance of clay.

Core 9 is a calcareous protoquartzite, but the detrital fraction is similar to that in other cores. Sideritic material is present in minor quantities in cores 4 and 12, and there is a small amount of secondary carbonate in core 11.

Cores 1, 2 and 3 contain a larger proportion of plagioclase and volcanic fragments in relation to lithic fragments than those lower in the sequence. They also show more pronounced fine bedding and contain more carbonaceous material. This suggests a break coinciding with that indicated between cores 3 and 4 by the heavy mineral suites. In addition, the coefficient of skewness is higher in cores 1 and 2, than in core 4 and below.

Fragments of probable volcanic rock are prominent in most of the cores. Many of the fragments in core 7 are very clearly from a volcanic rock, as are some from cores 2 and 11. Many others in cores 4, 6, 10 and 12 are not readily identifiable as volcanic fragments, probably due to weathering prior to deposition.

Zeolites were detected optically in cores 10, 11 and 12, but not in the shallower cores. The upper limit of zeolite distribution is not definite, however, as there is very little in core 10, and it is doubtful whether it could be detected in core 9 owing to the presence of carbonate which obscures the other matrix. The euhedral shape of the zeolite crystals suggests a diagenetic origin.

The heavy mineral suites in the samples show a clear division between cores 3 and 4 similar to that in Geltwood Beach between cores 8 and 9 (Fig. 2). This heavy mineral break is reflected in the over-all lithology only by the pronounced finer bedding in the shallower cores.

In addition, although cores 3 and 5 are both argillaceous sandstones they do not resemble each other, suggesting a lithological break between the two.

Rock fragments that may have been volcanic are present in cores 4, 6, 10 and 12, providing a correlation with the lower part of Geltwood Beach No. 1, as does the presence of sphene (Fig. 9), in the heavy mineral suites. However, some volcanic fragments are present in core 2.

The presence of zeolite in core 10 and below, suggests that there may be a distinction between these and the shallower cores, but it could be due merely to diagenesis.

Tourmaline is uncommon in the heavy mineral suites in this well, preventing similar deductions to those for Mt. Salt and Geltwood Beach.

The abundance of garnet in cores 9, 10 and 11, is probably due to high grade metamorphic or igneous rocks in the source area. The pink and colourless varieties present, suggest that the garnet came from two different sources, and the brown garnet in core 6 is almost certainly from a different source again.

The colourless sphene in cores 4, 6 and 7 probably comes from the same source material as that in Geltwood Beach.

Pyritic opaques are very abundant in cores 1 and 2, but are not generally present elsewhere. However, these minerals are probably secondary and do not represent a significant break.

The clay minerals in this well also have significant groupings and distributions.

Smectite is dominant in cores 2 to 9 but accessory in cores 10 to 12. Kaolin dominates in core 1 with accessory chlorite and a random mixed layer clay.

S.E.O.S. Beachport No. 1 (Figure 5).

All of the specimens are fairly similar and most are lithic greywackes. Although quartz is the dominant material in the framework in most specimens, rock fragments are particularly abundant, especially in the shallower cores (1, 2 and 3).

Many of the rock fragments are too small to be identified andconsist merely of chlorite, sericite or clay, and quartz. Claystone and chloritic siltstone, however, can be detected, although fragments tentatively regarded as siltstone could equally well be fragments of volcanic groundmass. Grains of chlorite and opaques are common, and their somewhat indefinite boundaries give all the specimens a fairly characteristic appearance in thin section.

In spite of the strong similarity between the six specimens, it is possible to detect certain distinctive features.

In cores 1, 2 and 3 the matrix-framework ratio is low and the rocks are poorly cemented. In core 6 however, the framework forms only about half the rock, and both cores 9 and 10 are markedly argillaceous.

Sodic plagioclase is a prominent constituent in cores 1, 2, 3, 6 and 9, but is absent from core 10, even though in other respects the rock is similar to the shallower cores.

All of the specimens from Beachport No. 1 are fairly similar except that the specimens below core 6 are markedly more argillaceous. Another lithological difference is observed above core 6 as cores 1, 2 and 3 have little matrix and are poorly cemented.

Colourless sphene of the same variety as that found in Geltwood Beach and Kalangadoo is present in cores 3 and 6. Apatite is unusually common in the heavy mineral suites. Some grains are euhedral, and it is possible that they are derived directly from a granitic rock. Tourmaline is again either absent, or present only in a small quantity.

In addition to the above distinctions, the cores may be grouped as follows on the basis of clay mineral content.

.... Cores 9 and 10 have dominant kaolin, whereas smectite is absent or accessory.

.... All five types of clays are accessory in core 6.

.... Smectite is dominant in cores 1, 2 and 3.

<u>O.D.N.L. Penola No. 1 (Figure 6)</u>

The specimens from Penola No. 1 are mostly lithic greywackes and siltstones, but feldspar is not much less common among the framework grains than rock fragments. Potassic feldspar and sodic plagioclase are both present. The rock fragments are mostly claystone, but core 11 contains fragments of pilotaxitic volcanic rock, and other cores may also contain fragments of volcanic rock without the pilotaxitic texture. Alteration of biotite to chlorite is common to all specimens.

Microcline is present in cores 20 and 21, but not in the shallower cores. Both these cores are also distinct from the others in that they contain calcite and have well-sorted frameworks. However, cores 20 and 21 are different from each other because the quartz in core 21 has undergone secondary enlargement, whereas the quartz in core 20 has not.

The cores from Penola No. 1 are all fairly similar as in Beachport No. 1. However, microcline is present in cores 20 and 21, but absent in the shallower cores, although untwinned potassic feldspar is ubiquitous. This suggests that granitic material was exposed in the source area only during deposition of the sequence which includes cores 20 and 21. These specimens are also distinct from the shallower cores in that they have well sorted frameworks and contain much calcite in the matrix. This lithological break is paralleled in the heavy mineral suites by an abundance of garnet in cores 20 and 21, suggesting a provenance different from that of the shallower cores.

Fresh sphene is present in cores 3 and 11, comparable with the upper part of the Otway Group in the other wells. In addition, the abundance of apatite in most cores except the deepest, suggests a provenance similar to that of the Beachport sediments. Tourmaline is present in slightly greater quantity than in Kalangadoo or Beachport, but in cores 3 and 8 it is probably authigenic.

The clay mineral assemblages in the cores from this well are not as diverse as in the other wells but the following grouping of cores is possible:-

.... In core 21, kaolin is dominant and smectite is absent.

.... Smectite is dominant in cores 3, 8, 11, 14, 17 and20.

RESULTS OF SORTING, SPHERICITY AND ROUNDNESS DETERMINATIONS

The sorting, sphericity and roundness characteristics of the samples do not show sufficient variation to form a basis for subdivision or correlation of sequences between the wells. However, the similarity of these characteristics in all the samples suggests that all the sediments were deposited in a similar environment.

There is little published data on deducing environments of deposition from framework properties, but the observations of one author (Sahu 1964) suggests that the characteristics of the Gambier Embayment sediments examined, conform to either deposition in a shallow marine environment, or deposition by turbidity currents. — what a load of rubbish.

TRACE ELEMENT DISTRIBUTION

Generally, the concentration of trace elements in the samples from all of the wells is noticeably low (Figs. 2 - 6). Kalangadoo No. 1 has consistently lower concentrations than the other wells.

Comparison of the trace element determinations with published data would indicate that the sediments examined were not deposited in open marine conditions.

In general, the trace elements appear to be distributed randomly and do not characterize the sedimentary units distinguished from clay mineralogy.

However, although the trace elements are not suitable for correlation purposes, the patterns of distribution of some of the elements may be useful environmental indicators; especially when more reference points are available.

In this regard, phosphorus has a relatively high concentration below core 23 in Mt. Salt No. 1, coinciding with the more marine part of The Upper Cretaceous Sequence. Thus, as high phosphorus content may indicate an oceanic environment in the vicinity of upwelling currents, it is probably an environmental indicator in Mt. Salt. A similar high phosphorus content is found in core 8 from a marine sequence in Geltwood Beach No. 1, however, the high concentrations of phosphorus in the lower part of Geltwood Beach No. 1 and in the upper part of Beachport No. 1 do not delineate known marine sequences.

Chromium follows another pattern in Beachport No. 1. Here, high chromium is associated with dominant kaolin in the two lower cores, but as this association is not reproduced in the other wells it probably has a local environmental significance not defined by the present well distribution.

Similarly, the increase in silver, molybdenum, strontium, and significant decrease in manganese and vanadium below core 23 in Geltwood Beach No. 1 coincides with dominant illite in the clay minerals, but this association again is not reproduced in the other wells.

In addition, the high vanadium and zinc content of core 9 from Mt. Salt No. 1 is possibly related to the distinctive type of marine environment under which the transgressive Bahgallah Formation was deposited.

Other anomalous concentrations are indicated by the spectrographic analyses, but more statistical evidence is required to relate these to a particular environment or lithological unit.

CORRELATIONS SUGGESTED BY THE SEDIMENTARY STUDIES

Too few results are available yet to claim that subdivision of the stratigraphic column and regional correlation of units by means of the above investigations alone, is established. However, the zonation of the heavy minerals is distinctive and the correlations shown in figure 7 based on the distribution of apatite, sphene, epidote and garnet, are quite positive.

The sudden disappearance of this heavy mineral group must represent a significant change in provenance which incidentally, parallels a change in lithology from the lithic greywackes of the Otway Group to the sandstones with markedly fewer rock fragments of the Paaratte Formation.

In Geltwood Beach No. 1 and Kalangadoo No. 1, however, the apatite, sphene, garnet, epidote group is not present in the upper several hundred feet of the Otway Group. This distribution helps to delineate a unit in the upper part of the Otway Group which, in addition to the restricted heavy mineral assemblage, has markedly fewer igneous fragments, and markedly less fresh plagioclase than the remainder of the Otway Group. The lithological change is also marked on the electric logs in Geltwood Beach No. 1 at least, by the very pronounced shale-break on the spontaneous potential curve at 3990 feet (Figure 11). As the stratigraphic boundary between the Otway Group and the Paaratte Formation is placed at 3680 feet (Bureau of Mineral Resources, Geology and Geophysics, (ED.) 1965), it is possible on the basis of heavy mineral, petrographic, and E-log characteristics, to recognise a lithological unit between 3680 feet and 3990 feet in Geltwood Beach No. 1 Well. Evans (1966 p. 25) found in this interval, an abundant microplankton assemblage belonging to the Ascodinium parvum zone, which he considers to be equivalent in age to the top of the Waarre Formation.

The equivalent unit represented by cores 2 and 3 in Kalangadoo No. 1 is not as well-defined. Prominent breaks on the sonic, and electric logs at 2494 feet mark the top of the Otway Group, but no marked electric log break between cores 3 and 4 parallels the marked change in heavy mineral content, as in Geltwood Beach No. 1. (Figure 11). Itmay be significant, however, that the resistivity decreases gradually to a base level at 2960 feet, in Kalangadoo No. 1, in the same way that the resistivity decreases to a consistent level at 3990 feet in Geltwood Beach No. 1.

Also similarly to Geltwood Beach No. 1, the unit at the top of the Otway Group in Kalangadoo No. 1 contains a much lower percentage of rock fragments and fresh feldspar than the remainder of the Otway Group. This sequence in Kalangadoo No. 1 is also related to the sequence represented by core 8 in Geltwood Beach No. 1, Both are distinguished by the presence of microplankton (Harris 1964, 1965), which indicate a marine influence.

In both wells the greater proportion of rock fragments as well as the generally smaller grain size of the sandstones at the top of the Otway Group distinguish this sequence from the overlying Upper Cretaceous sequence.

The heavy mineral unit as defined above is not recognised in Penola No. 1 or Beachport No. 1, possibly because all the cores examined come from well below the top of the Otway Group and contain the apatite, sphene, epidote, garnet heavy mineral suite. However, the uppermost core from Beachport No. 1 was cut less than 190 feet below the top of the Otway Group, so the unit lacking these heavy minerals must be either very thin or not represented.

Representatives of the apatite, sphene, garnet, epidote group of heavy minerals are very scarce or wholly lacking in the cores from Mt. Salt No. 1. Consequently, in the absence of more than an accessory amount of rock fragments, it is considered unlikely that the Otway Group was encountered in this well.

Apart from the use of the group, apatite, sphene, garnet, epidote, as a whole for subdivision of the sedimentary sequence, the distribution of sphene plus epidote may be used for broad correlation of a sequence within the Otway Group. The distribution (figure 9) of these two minerals in the five wells studied indicates that sphene and epidote are confined to the upper part of the Otway Group, corresponding approximately to the distribution of Dettman's Paradoxa assemblage. The distribution of sphene plus epidote also approximates the distribution of smectite, with the notable exception of Penola No. 1 (figure 10). Other methods of correlation discussed below support inter-well correlation of this sequence.

Generally the heavy mineral suites in the Upper Cretaceous and Tertiary sequences are too similar for subdivision or correlation with the present number of reference points. One exception, however, is core 9 from Mt. Salt No. 1. This core not only exhibits the distinctive lithology of the Bahgallah Formation, but the heavy mineral fraction consists predominantly of siderite.

Other subdivisions of the individual well sequences are indicated, but the above correlations are selected because they suggest a consistent pattern of distribution of the heavy minerals which closely relates to the provenance of the sediment. Where erosion of the source rock and deposition is rapid, a greywacke with a wide range of heavy minerals results, (Otway Group). On the other hand, less rapid erosion or more prolonged transport, result in more mature quartz sandstones which contain only the more resistent heavy minerals, (Paaratte Formation, and the Lower Tertiary).

The clay minerals, perhaps because of sensitivity to environment of deposition and post-depositional alteration, are not always distributed consistently from well to well, although zonation within each well remains positive. Mt. Salt No. 1 shows especially significant clay mineral zones (figure 10). Below core 9 (corresponding to the Paaratte Formation), kaolin becomes the dominant clay mineral with accessory chlorite, whereas in the Lower Tertiary sequence above core 9, smectite becomes equally, or more abundant than kaolin, and chlorite is absent. The clay fraction of core 9 itself, is unique because it is monomineralic, consisting of the clay mineral greenalite.

This distribution of clay minerals accurately follows, and probably delineates the Paaratte Formation (below core 9), the Bahgallah Formation (core 9) and the Lower Tertiary (above core 9). Apart from the Paaratte Formation, theseunits are either not present or not cored in the other wells so direct comparisons are generally not possible.

However, the Paaratte Formation in Mt. Salt No. 1, Geltwood Beach No. 1, and Kalangadoo No. 1 may be compared. Kaolin generally dominates the clay minerals in all of the cores from this sequence, except core 7 in Geltwood Beach. Consequently dominant kaolin appears to be a feature of the Upper Cretaceous sequence which distinguishes it from the Lower Tertiary sediments above, and the Otway Group below. However, the almost complete absence in Geltwood Beach No. 1 of chlorite, which is present in all of the cores from the Upper Cretaceous sequence in Mt. Salt No. 1 and Kalangadoo No. 1, leaves an unexplained inconsistency.

Chlorite is also ~~most~~ almost ubiquitous in the Otway Group cores, but the predominance of smectite over kaolin in the clay mineral assemblage distinguishes this sequence. However, smectite dominates only in the upper part of the Otway Group and illite or kaolin dominates below core 21 in the Geltwood Beach No. 1, core 9 in Kalangadoo No. 1, core 6 in Beachport, and core 20 in Penola No. 1 (Figure 10).

The above distribution of smectite, is, except for Penola No. 1, very similar to the distribution of sphene plus epidote (figure 9), thus supporting inter-well correlation of that part of the sequence which includes these two minerals.

Consequently kaolin and smectite appear to have a consistent distribution in relation to heavy mineral distribution and stratigraphic boundaries.

It is especially significant that smectite and kaolin form the basis for correlation, as these two minerals according to Grim (1953), require completely different weathering and depositional environments for their formation. Kaolin for example, may form from any constituents, especially acid igneous rocks, if the alkalies are removed, or if the environment is acid and the temperature is moderate. Under more alkaline conditions, especially in areas of basic igneous rocks, where magnesia is retained, smectite will be the alteration product.

The anomalous or inconsistent distribution of clay minerals such as chlorite may be due to local variations in environment of deposition or diagenesis.

Trace elements also appear to be controlled mainly by depositional environments and therefore, are not suitable for correlation. However, more reference points may show that the more marine part of the Upper Cretaceous sequence and the transgressive marine Bahgallah Formation, may be delineated by such environmentally controlled elements as phosphate and vanadium.

CONCLUSIONS

Generally, the petrographic investigations indicate that both igneous and sedimentary rocks were present in the source area. The igneous rocks probably ranged from granite to acid volcanics with some basic igneous rocks.

Heavy mineral and clay mineral analyses indicate that the heavy mineral and clay mineral distributions are generally consistent with the litho-stratigraphic boundaries previously established.

The heavy mineral assemblages in particular, are closely related to the provenance of the sediment and consequently define lithological changes such as that between the lithic greywackes of the Otway Group and the quartzitic sandstones of the Paaratte Formation and Lower Tertiary. Where the percentage of rock fragments is reduced within the Otway Group itself, the less resistent heavy minerals are reduced also. Consequently although the distribution of the apatite, sphene, garnet, epidote group delineates the lithological and stratigraphic boundary between the Otway Group and the Paaratte Formation in some areas, elsewhere the heavy mineral break occurs at the base of a unit near the top of the Otway Group, which probably had a provenance more akin to that of the Paaratte Formation.

The clay mineral assemblages are not distributed as consistently as the heavy mineral assemblages, due to sensitivity to differing weathering and depositional environments, as well as post-sedimentary diagenesis. However, two of the clay minerals which require completely different weathering and depositional environments, appear to predominatein distinctive stratigraphic intervals. In this regard kaolin is dominant within the Paaratte Formation, whereas smectite is dominant in the upper part of the Otway Group, corresponding closely to the distribution of sphene and epidote. The lower part of the Otway Group is characterized by dominant kaolin plus illite and the absence of sphene.

Spectrographic analyses, on the other hand, indicate that the trace element concentrations are influenced predominantly by environment of deposition and are not suitable for regional correlation.

Finally, the sphericity, roundness, and sorting measurements show very little systematic difference which can be related to other properties of the sediments. Comparison of values obtained with those determined for sediments of distinctive environments elsewhere, suggest that the Gambier Embayment sediments are all shallow marine.

INTEGRATION OF THE RESULTS OF THE SEDIMENTARY STUDY WITH ELECTRIC LOG INTERPRETATION AND OTHER STRATIGRAPHIC INFORMATION

It is proposed in this section to discuss other sedimentary parameters of the Otway Group, and to integrate these with the petrological results, in order to define sequences that can be correlated from well to well.

Otway Group

The Otway Group extends in the subsurface from the northern boundary of the Gambier Embayment continuously to the edge of the continental shelf. Only one well has penetrated the sequence in South Australia, proving a thickness of 4,271 feet at Kalangadoo. However, seismic information indicates thicknesses ranging from several hundred feet on the southern part of the Padthaway Ridge to as much as 10,000 feet in the Penola and Robe Troughs. Geltwood Beach No. 1 proved a thickness in excess of 8,600 feet south of the Beachport-Kalangadoo High.

There are no outcrops of the Otway Group in South Australia but cuttings and core examinations indicate, within certain limits, a remarkable degree of lithological uniformity. The sediments, as described in the previous section, consist of green to grey lithic or feldspathic greywacke and green to grey siltstone and mudstone. These lithologies are commonly finely interbedded, but thicker beds showing cross bedding, occasional graded bedding, slump structures, and scouring are also known. The sediments are commonly carbonaceous with some coal beds and in situ carbonised plant roots. Igneous rock fragments (commonly volcanic), feldspar, and quartz are the main detrital components.

Although the overall lithology of the Otway Group appears very uniform it is possible to make broad distinctions based on cuttings and core examinations, which are supported by heavy and clay mineral zones, and delineated by electric log or seismic characteristics.

In this regard, it is noteworthy that coal beds and the more carbonaceous horizons (figure 11) are mostly confined in each well to an interval below the boundary between Dettman's Speciosus and Paradoxa assemblages. This floral boundary in turn is closely related to a prominent change in spontaneous potential log characteristics (figure 11). Taking the

Kalangadoo No. 1 well as an example, it can be seen that a marked change in S.P. log characteristics takes place at 5290 feet. Between 5290 feet and 4740 feet a transition zone separates the complex relief abom, and the generally low relief with occasional pronounced negative kicks below.

Examinations of the cuttings samples indicates a much higher percentage of sandstone (impossible to measure accurately) above 5290 feet. In addition, the cuttings abom 4740 feet are generally low in carbonaceous material, whereas below 4740 feet and especially below 5290 feet, carbonaceous shales locally grade into coal bands and beds. These lithological differences, although difficult to measure quantitatively, are quite marked over this interval.

The dipmeter survey (figure 11) gives further significance to this interval, indicating dip variations complementary to the S.P. log character changes. Above about 4740 feet the dip and direction of dip varies, but is predominantly 2 - 8 degrees to the southwest. Between 4740 feet and 5290 feet, the dip varies markedly in a pattern suggestive of cross-bedding. Beneath 5290 feet the direction of dip changes to the south, becoming very consistent in both azimuth and dip-angle, especially below 5700 feet. This same sequence of events is followed even more positively in Heathfield No. 1 where the dip direction across the equivalent interval changes from northeast at 3900 feet, to a variable dip in a probable cross-bedded zone, and finally to a definite southwest dip below 4480 feet. Also, as in Kalangadoo, the dips below theunconformit are remarkably regular both in angle and direction of dip.

Dipmeter logs were not run in any of the other wells in South Australia except Mt. Salt No. 1, so direct correlations are not possible. However, the S.P. log exhibits a change in character similar to that described for Kalangadoo No. 1, between 2705 feet and 3210 feet in Penola No. 1, at about (?) 3770 feet in Beachport No. 1, and less positively at about 9000 feet in Geltwood Beach No. 1 (figure 11). It is possible, however, that the reduced relief in Geltwood Beach No. 1 reflects increased compaction and diagenesis of the sediments below 9000 feet.

The same generalisations with regard to lithology as in Kalangadoo No. 1 well are noted in the cuttings from each of the remaining wells. It is also significant that the change in S.P. log characteristics in each well, takes place consistently within several hundred feet of the boundary between Dettman's Paradoxa and Speciosus assemblages. The only exception is in Geltwood Beach No. 1 well where Evans (1966) places this boundary about 3500 feet above the S.P. log boundary.

Reference to the previous section shows marked agreement of the heavy mineral zones with the above subdivision. Sphene and epidote are found in each well, wholly in those cores taken above the S.P. log boundary (figure 11). In Geltwood Beach No. 1, it is noteworthy that epidote is found as low as core 21, in support of the suggested change in S.P. log characteristics at about 9000 feet.

Clay minerals on the other hand, follow this subdivision of the sequence in a general way only. Smectite dominates throughout the interval above the S.P. log boundary in Geltwood

Beach No. 1 and Kalangadoo No. 1, but dominates only down to core 6 in Beachport No. 1, whereas in Penola 1, smectite is dominant down to core 20, 1000 feet below the equivalent interval in the other wells.

Despite the exceptions outlined above, it is considered that a good basis exists for correlation across the Gambier Embayment of the three sequences described in the Kalangadoo No. 1 well. These sequences in brief are:-

6765' - 5290' Characterized by low relief on the S.P. log, but punctuated by discrete and pronounced negative "kicks". These features indicate a high percentage of argillaceous sediment with local developments of sandy facies: - cuttings examinations support this interpretation. The heavy minerals, sphene and epidote, are absent from this sequence even though they are common in the sediments above 5290'. Kaolin plus illite are the dominant clay minerals, whereas smectite is dominant above 5290'. With the exception of core 7, coal and carbonaceous shale are confined to this sequence. Finally, the dipmeter survey indicates consistent angle and direction of dip of the beds to 5290 feet, above which the average direction of dip swings from south to southwest.

5290' - 4740' Defined by dipmeter survey as a unit with highly variable angles and directions of dip, indicative of cross bedding, in marked contrast to the sequence below and also in contrast to the

5290' - 4740' (Contd.) sequence above 4740 feet. The direction of dip above 5290 feet is mainly to the southwest, in contrast to the south to south of southwest dip below that depth. This sequence is also defined on the S.P. log as a transition zone between tho low relief below 5290 feet and the complex high relief above 4740 feet. This sequence cannot be differentiated from the sediments above 4740 feet on the basis of heavy and clay mineral assemblages, although the presence of coal indicates affinities with the sediments below 5290 feet.

4740' - 2494' This sequence is conspicuous on the S.P. log due to the relatively high and complex relief above 4740 feet. Cuttings examinations indicate that this represents a much bigger percentage of sandstone, mainly thin interbeds and laminations than in the sequence below 5290 feet. The dip-meter survey shows considerable dip variations which could be due to local cross-bedding - (? small scale) within this unit. The predominant dip is to the southwest in conformity with the underlying sequence.

4740' - 2494' Sphene, epidote, and dominant smectite characterize this sequence, but coal is absent and carbonaceous material is generally less abundant in the cuttings from this interval than from the underlying sequences. The top of the sequence at 2494 feet is marked on the electric

4740' - 2494' (Contd.) logs by a sharp increase in resistivity, and a negative shift of the spontaneous potential.

Cores 2 and 3 from the uppermost part of the 4740' - 2494' interval lack the apatite, sphene, garnet, epidote group of minerals, suggesting a different provenance for this part of the sequence. In addition, the thinly laminated and thin-bedded aspect of these sediments together with the presence of micro-plankton in core 2, also distinguishes the interval between 2494 feet and ?2960 feet (figure 11).

For the purpose of simplifying subsequent discussion, the symbols a, b, c and d are given to the above sequences as follows:-

Unit d -	represents	interval	2484' - ?3960'	in	Kalangadoo	No. 1
Unit c -	"	"	?2960' - 4740'	"	"	"
Unit b -	"	"	4740' - 5290'	"	"	"
Unit a -	"	"	5290' - 6765'	"	"	"

The sequences as defined above, are correlated on the basis of the above criteria, with equivalent sequences in Penola No. 1, Beachport No. 1, Robe bore, Comaum bore, and Geltwood Beach No. 1, as shown in figure 11. It is realised that these criteria do not constitute a basis for a formal subdivision of the Otway Group, however, the above units appear to have a consistent group of characteristics which strongly suggest correlation from well to well. In this regard Leslie (1965 p. 20) describes an identical broad lithologic sequence from the Otway Range area and recognises equivalent sequences in several wells. He also noted that the dipmeter survey in Ferguson's Hill No. 1 suggests an unconformity at the top of the lower dark grey mudstone and well bedded, fine-grained sandstone sequence; as is the case in Kalangadoo No. 1.

In addition, Evans (1966 plate 4A) places the boundary between the Speciosus and Paradoxa assemblages about 200 feet below an unconformity in Ferguson's Hill No. 1, which would indicate that the sequences recognised by Leslie (1965) are of much the same age as the equivalent sequences in Kalangadoo No. 1.

In addition to the above correlations the Otway Group can be subdivided into two major units on the basis of a seismic unconformity (Rochow 1967). This unconformity is present in the seismic time section at a depth of about 4100 feet at Penola No. 1 Well, corresponding approximately to a change in angle of dip in cores from that well (Ludbrook 1963). There is, however, no noticeable change in lithological characteristics associated with this boundary so identification of the two units on this basis only, is impossible at this stage. However, the distribution of the seismic unconformity suggests that the lower sequence does not persist over basement highs such as the Kalangadoo High. Moreover, the Stylosus assemblage which although not present at all in Kalangadoo No. 1, characterizes the sequence 400 feet below the unconformity at Penola No. 1 Well. Consequently, the sequences described in Kalangadoo No. 1 probably represent the sediments above the seismic unconformity.

The two major sequences into which the seismic unconformity divides the Otway Group are referred to informally as the Otway Group - upper unit, and the Otway Group - lower unit. The lower unit has a restricted distribution which is partly sedimentary and partly erosional. The greatest thickness of the lower unit probably exceeds 6000 feet in the axial part of the Robe and Penola Troughs. Interpretations of the depth to basement in the offshore seismic sections (Haematite Explorations 1965) indicate that the Otway Group - lower unit, perhaps with a conformable sequence of older sediments underneath, may be as much as 13000 feet thick. The lower part of this sequence in the offshore section of the Robe Trough is faulted against basement near the axis of the trough and the remaining section wedges out with local faulting against basement along the northern margin of the embayment. Wedge-out of this unit along the northern flank of the Penola Trough and especially up the flanks of local basement highs is pronounced. However, the Otway Group - lower unit undergoes progressive truncation to the south over the Kalangadoo-Beachport High and the original area of deposition in this direction is unknown.

The Otway Group - upper unit, on the other hand, extends right across the Gambier Embayment and is markedly less affected than the lower unit by the basic structures such as marginal faulting and basement highs. North of the Penola Trough, the upper unit is progressively eroded and truncated toward the Padthaway Ridge. Within the Robe and Penola Troughs and on the Beachport-Kalangadoo high the thickness remains relatively constant, varying from 3000 to 4500 feet. However, the thickness increases to at least 8600 feet at Geltwood Beach, south of the Beachport High. Other control points are not available south of the Beachport-Kalangadoo high, but seismic data indicates that regional uplift along the continental margin has resulted in truncation of the sequence in this area.

Sand-shale ratios calculated for the Otway Group-upper unit as a whole, in the several wells are consistent at about 0.2.

SUMMARY OF OTWAY GROUP SEDIMENTATION

The Lower Cretaceous sediments of the Gambier Embayment may be conveniently divided into two units on the basis of a seismic unconformity. The upper unit has a widespread distribution and is probably continuous with the Otway Group in other areas of the Otway Basin, but the lower unit appears to be confined to negative areas such as the Robe and Penola Troughs. Although the two units are separated by an unconformity, it is convenient to include them both in the Otway Group at this stage, because the limited well control indicates a marked similarity in lithology.

The upper unit of the Otway Group may be further subdivided in Kalangadoo No. 1 Well into four sequences on the basis of various sedimentary characteristics. The lower sequence (unit a) either rests unconformably on the Otway Group - lower unit or on basement, and is noticeably less sandy than the overlying sediments. Coal beds are almost wholly confined to unit a indicating perhaps a less marine environment of deposition.

Unit b is cross-bedded and more sandy, with a south-westerly dip, in contrast to the southerly dip of the unit below. This sequence probably represents rejuvenation of the sedimentary processes with the development of deltaic deposits in the northern part of the Gambier Embayment.

The sequence conformably above the cross-bedded unit (unit c) also has a relatively high proportion of sandstone and is distinctive because of the presence of the heavy minerals, sphene and epidote, and the general absence of coal. (The notable exception being in Robertson No. 1). Microplankton near the top of the Otway Group in unit d may indicate an increasing trend to marine conditions above the coal-bearing sequence. However, the microplankton occur within a sequence which is in some ways petrologically distinct from the remainder of the Otway Group, so the increased marineness may be confined to this unit.

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12.2.1968

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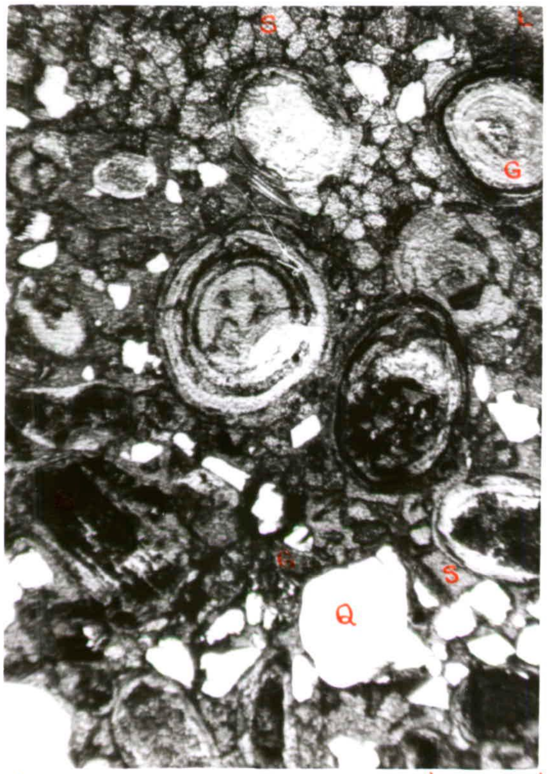
PLATE I

A. Mt. Salt No. 1, Core 9, TS15665, PPL, x 100
Bahgallah Formation. Oolitic sandstone with a ferruginous cement. The oolites and cement are both composed of greenalite (G), and many oolites have brown cores and concentric bands which are presumed to be oxidised greenalite.
The quartz fragments (Q) are unsorted and generally angular, though the larger grains are subrounded. Lithic fragments (L) are of ferruginous material, and are angular to subangular with a coating of greenalite.
Biotite flakes (B) are subrounded, probably by chemical action.
Siderite (S) forms the matrix in pebble-like areas and occurs as a mosaic of uniform grain-size. Scattered siderite grains are present throughout the greenalite matrix.

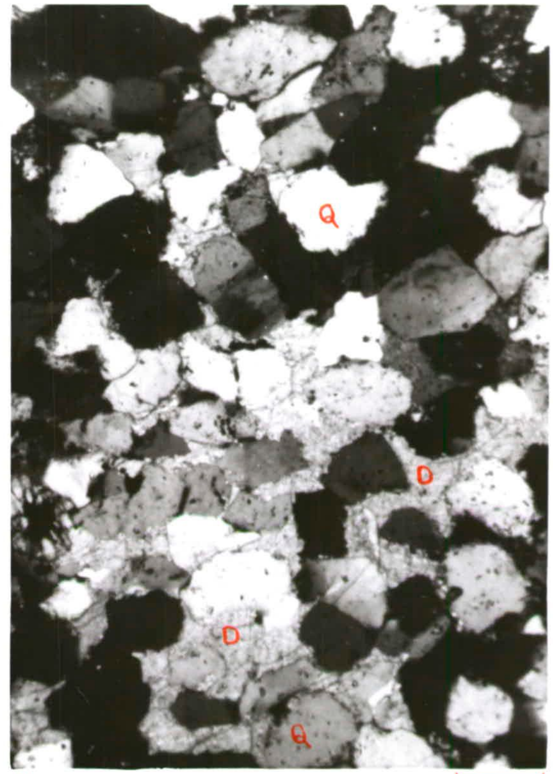
B. Mt. Salt No. 1, Core 31, TS15674, XN, x40
Upper Cretaceous dolomitic sandstone. Well sorted, angular to subrounded quartz grains (Q) form a mosaic in which sparry dolomite (D) is present as a patchy cement. Some quartz grains have secondary overgrowths.

C. Geltwood Beach No. 1, Core 8, TS16113, XN, x 100
Argillaceous and chloritic greywacke. Quartz (Q) is the dominant framework component, and occurs as angular to subangular grains with a moderately uniform grain-size.
Claystone fragments (Cl) and green chloritic and glauconitic grains are numerous. Plagioclase and alkali feldspar fragments (F), contorted mica flakes (M) and carbonaceous matter are moderately abundant. The matrix consists of fine quartz and clay.

D. Geltwood Beach No. 1, Core 9, TS16114, XN, x 100
Greywacke, in which the grain size of the framework components is relatively uniform. The quartz (Q) and feldspar (F) grains are angular to subangular. The plagioclase is particularly fresh and is a more prominent constituent than in the greywacke of Core 8, TS 16113. Numerous very fine-grained igneous rock fragments (RF) are present. Other framework components are claystone fragments, rounded green chloritic grains, contorted mica flakes and ferruginous and opaque mineral grains. The matrix is mainly clay, fine quartz and micas.



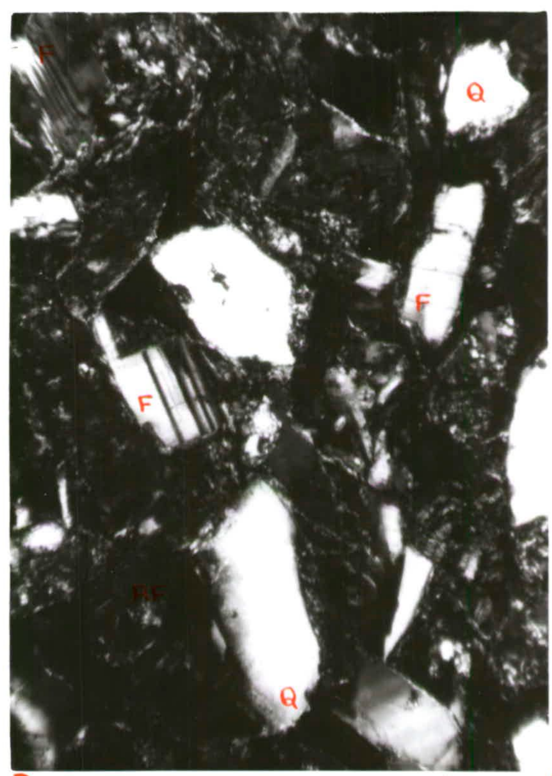
A 0·10 mm



B 0·20mm

PLATE I.

C 0·10 mm



D 0·10 mm

PLATE 2

Fig. A

Sample taken from Core 12 (Otway Gp.), ODNL Kalangadoo No. 1. The section is perpendicular to the bedding of a siltstone with a grain-size of 0.02 to 0.06mm. Dark grey carbonaceous matter emphasizes the small scale current bedding. Note the small dislocation of the bedding along a plane, dipping at 60°.

Fig. B

Core 25 (Upper Cretaceous), ODNL Mt. Salt No. 1. The sediment is a carbonaceous fine quartz sandstone with a clayey, possibly kaolinitic, matrix. The main features of this specimen are the irregular or lenticular nature of the bedding, and the common presence of sand "rafts" which cut across the bedding.

Fig. C

Sample taken from Core 9 (Bahgallah Fm.), ODNL Mt. Salt No. 1. The section is parallel to the bedding. The specimen is a distinctive dark green oolitic sandstone. Quartz and rock fragments form the coarse grains which are unsorted and range up to 3mm. in diameter. The coarse grains are commonly rounded, but the smaller grainsizes are subangular to subrounded.

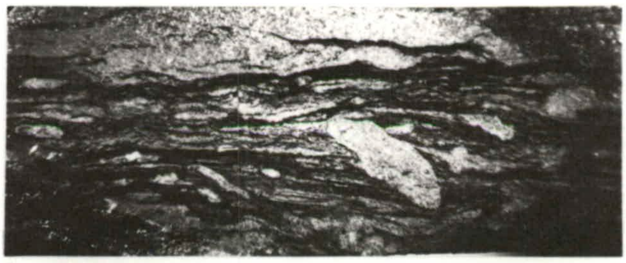
The fine dark grains in the photo are formed from greenalite, the same material as the groundmass. Brown material which forms the nucleus of some oolites and also forms concentric bands is probably weathered greenalite.

Fig. D

Core 18, BPNL Geltwood Beach No. 1. The section is cut perpendicular to the bedding planes. The sediment is a fine grained greywacke with concentrations of dark carbonaceous material in many of the laminations. Note the approximately parallel bedding in the lower third of the photo and the well developed foresets with long bottomsets near the top of the photo. These bear a striking resemblance to sedimentary structures in flood deposits, illustrated by McKee, Crosby, and Berryhill (1967, p. 838 photo b).

A

0 2
Cms.



B

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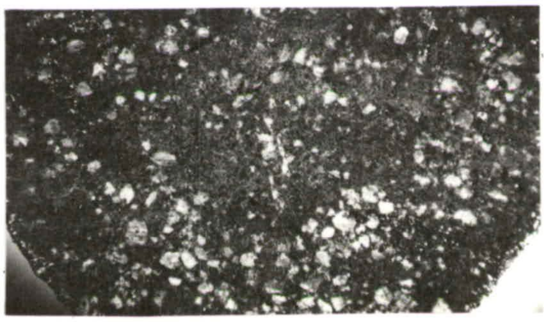

C

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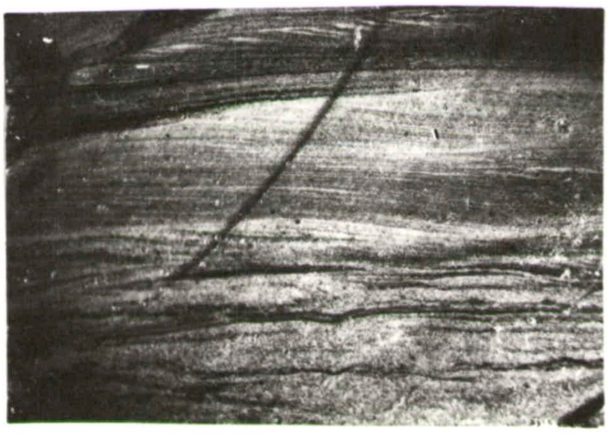
Cms.



D

0 2
Cms.

PLATE 2

STRATIGRAPHIC SCALE

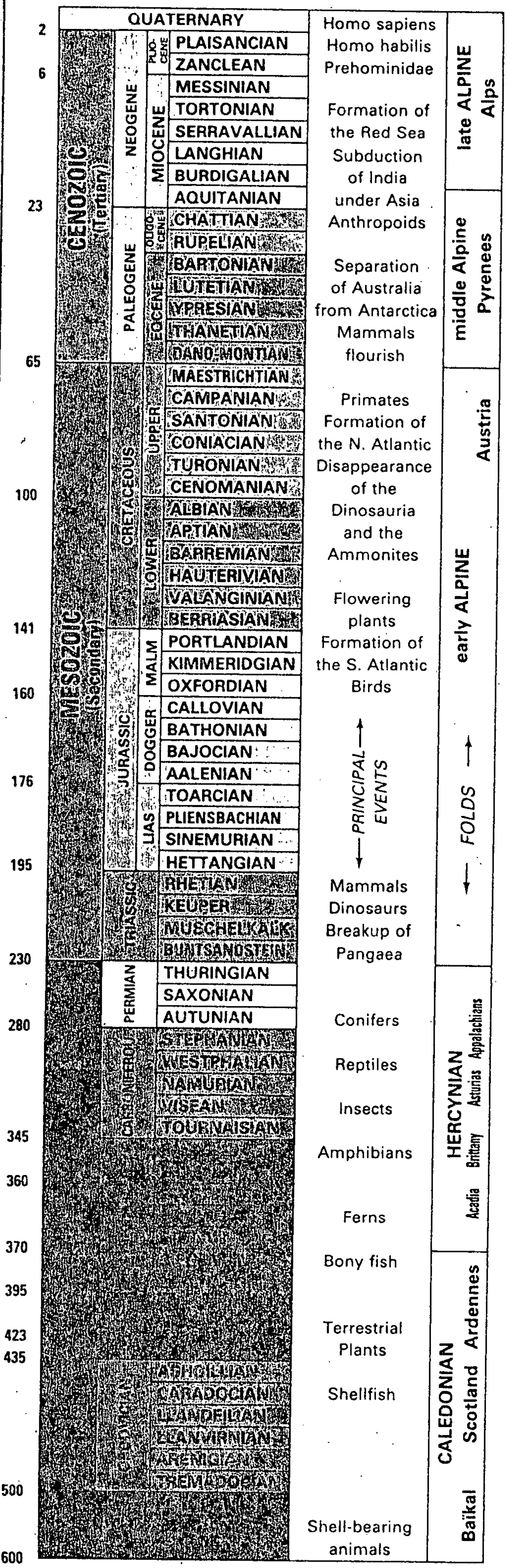


FIGURE 1 - MISSING

THE MINERALOGY, PETROGRAPHY AND TRACE ELEMENT DISTRIBUTION IN CORES FROM B.P.N.L. GELTWOOD BEACH NO.1

OTWAY BASIN FIG. 2. L67-104/4

THE MINERALOGY, PETROGRAPHY AND TRACE ELEMENT DISTRIBUTION IN CORES FROM O.D.N.L. MT. SALT NO.1 WELL

OTWAY BASIN FIG. 3

L67-102/4

THE MINERALOGY, PETROGRAPHY AND TRACE ELEMENT DISTRIBUTION IN CORES FROM A.O.D.A.N.L. KALANGADOO NO.1 WELL

OTWAY BASIN FIG. 4

L67-101/4

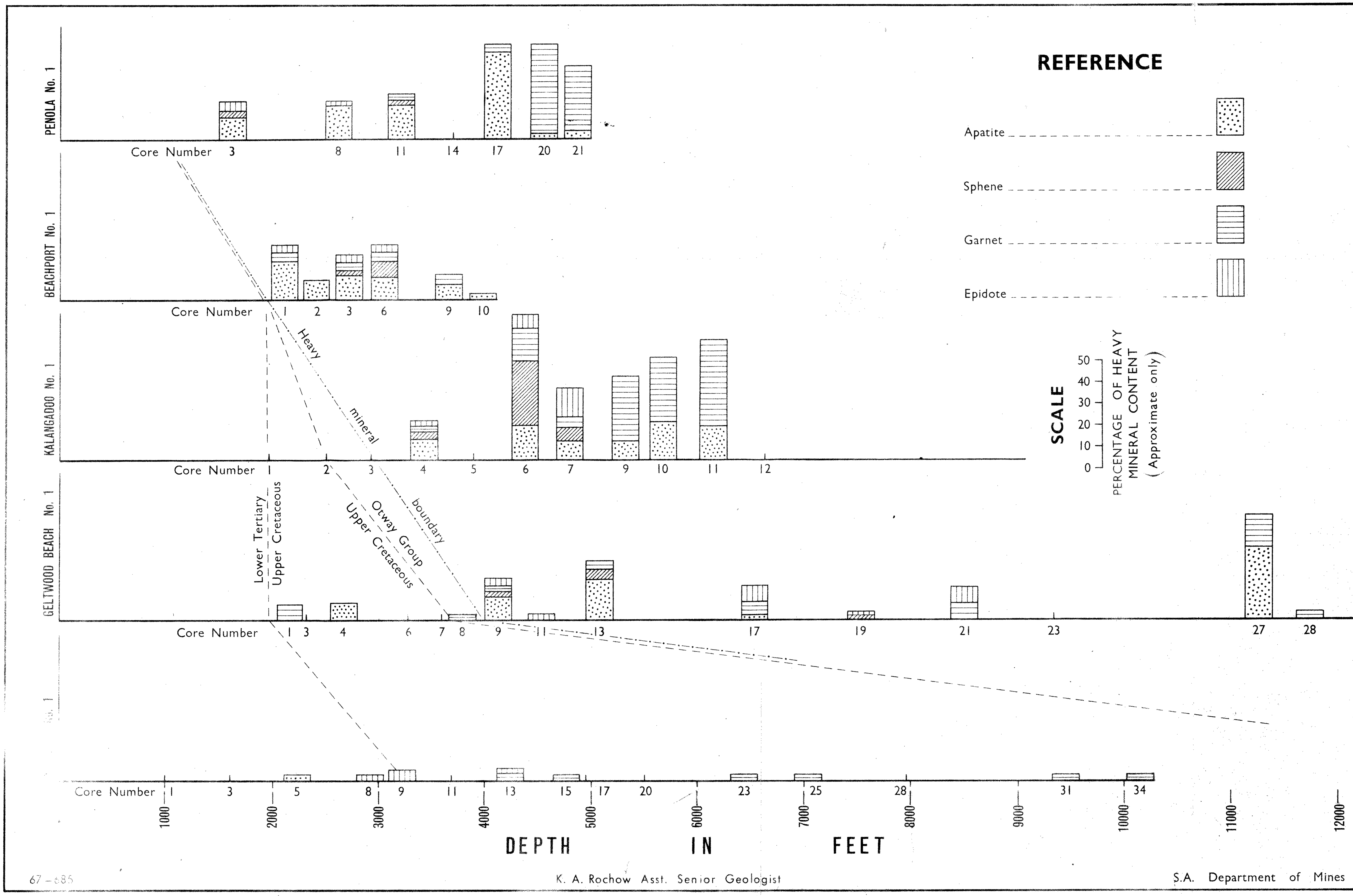
THE MINERALOGY, PETROGRAPHY AND TRACE ELEMENT DISTRIBUTION IN CORES FROM S.E.O.S. BEACHPORT NO. 1 WELL

OTWAY BASIN FIG. 5. L67-100/4

THE MINERALOGY, PETROGRAPHY, AND TRACE ELEMENT DISTRIBUTION IN CORES FROM O.D.N.L. PENOLA NO. 1

OTWAY BASIN FIG. 6

L67-103/4



Reduce to 5 inches

CONCENTRATION OF A[illegible]E, SPHENE, GARNET, EPIDOTE, IN CORES FROM 5 O[illegible] WELLS

OTWAY BASIN FIG. 7.

M.L. 67-685/4
2.10.67

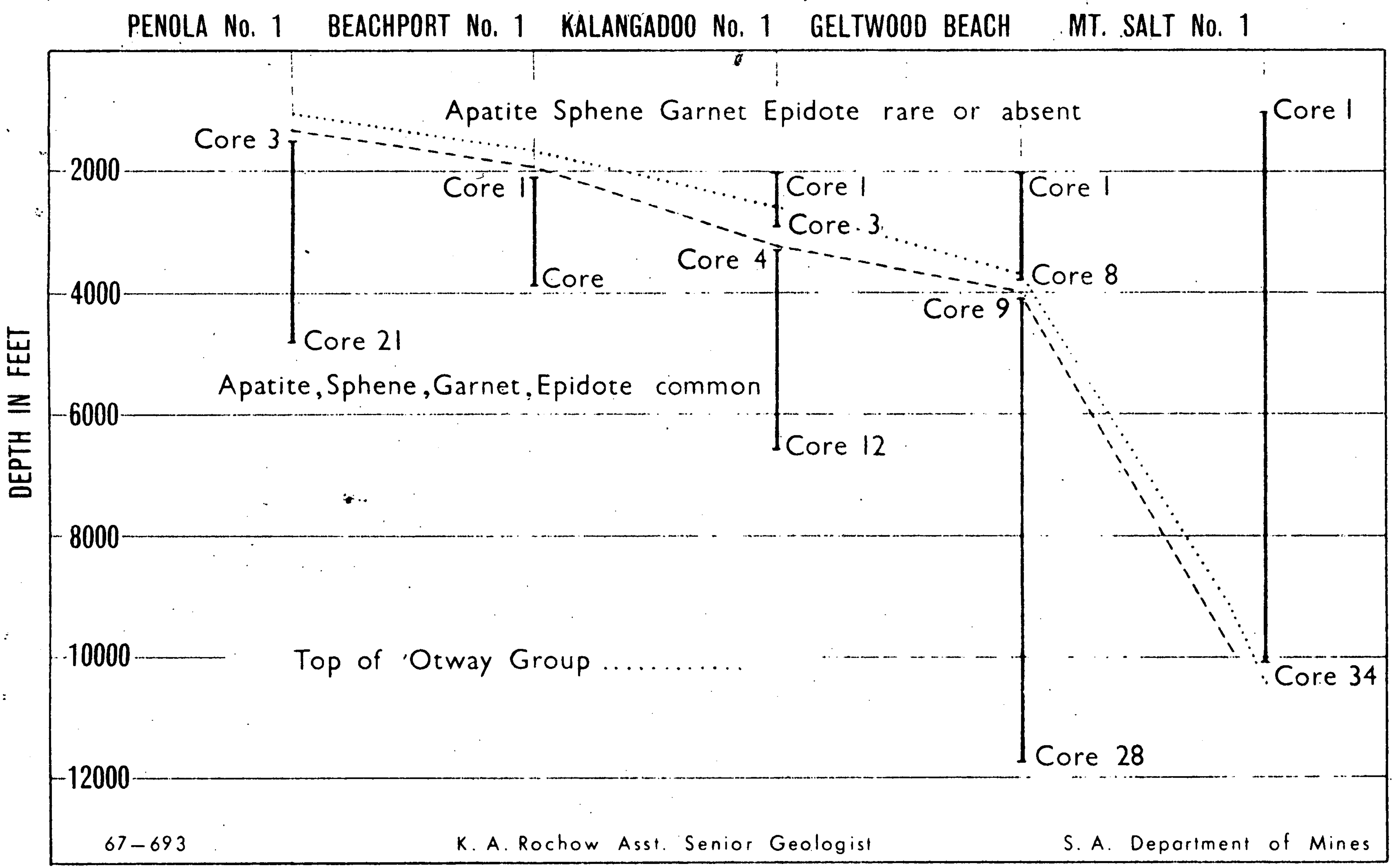


FIG.8. DISTRIBUTION OF APATITE, SPHENE, GARNET, AND EPIDOTE

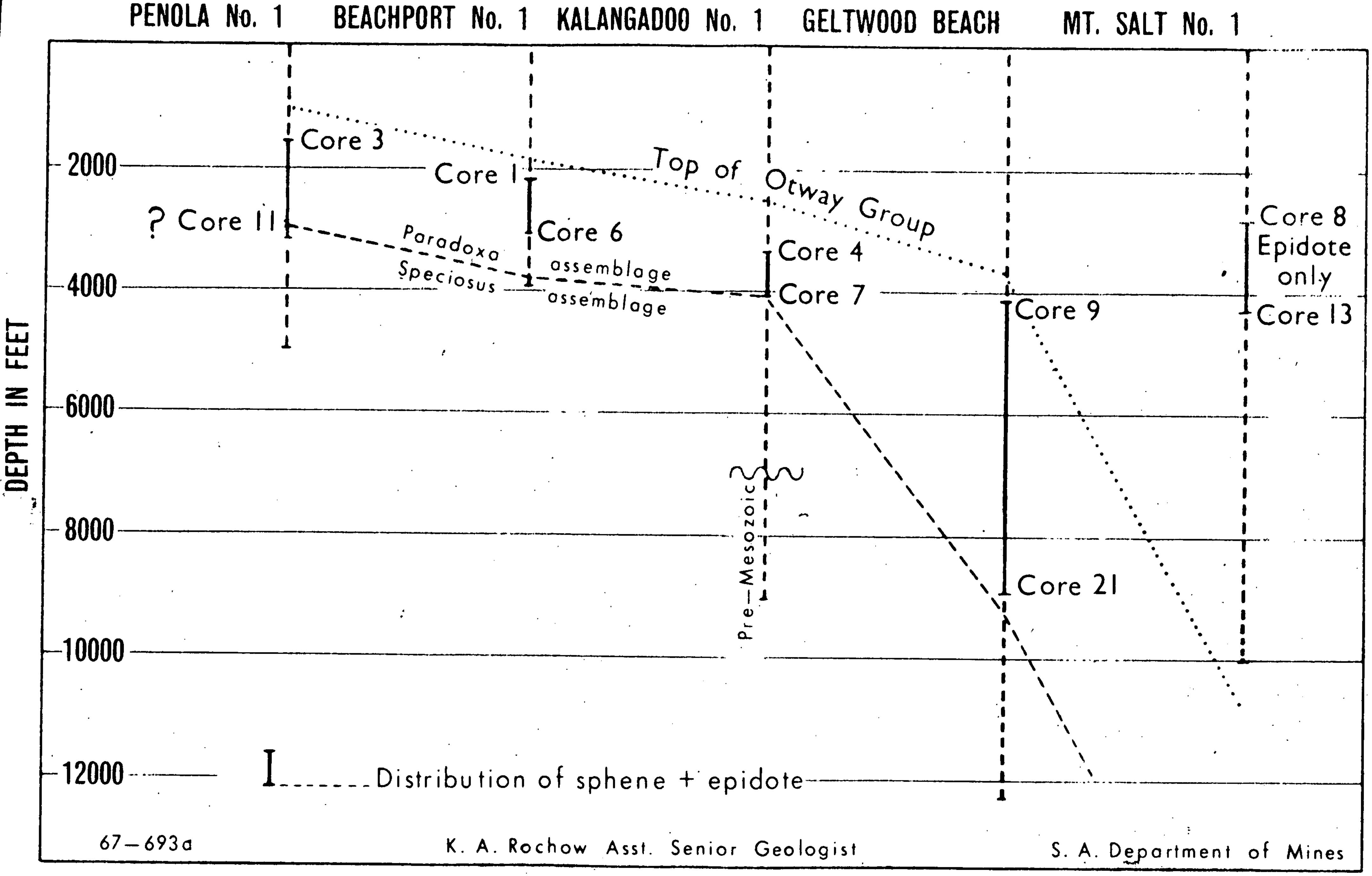


FIG. 9 DISTRIBUTION OF SPHENE AND EPIDOTE

OTWAY BASIN

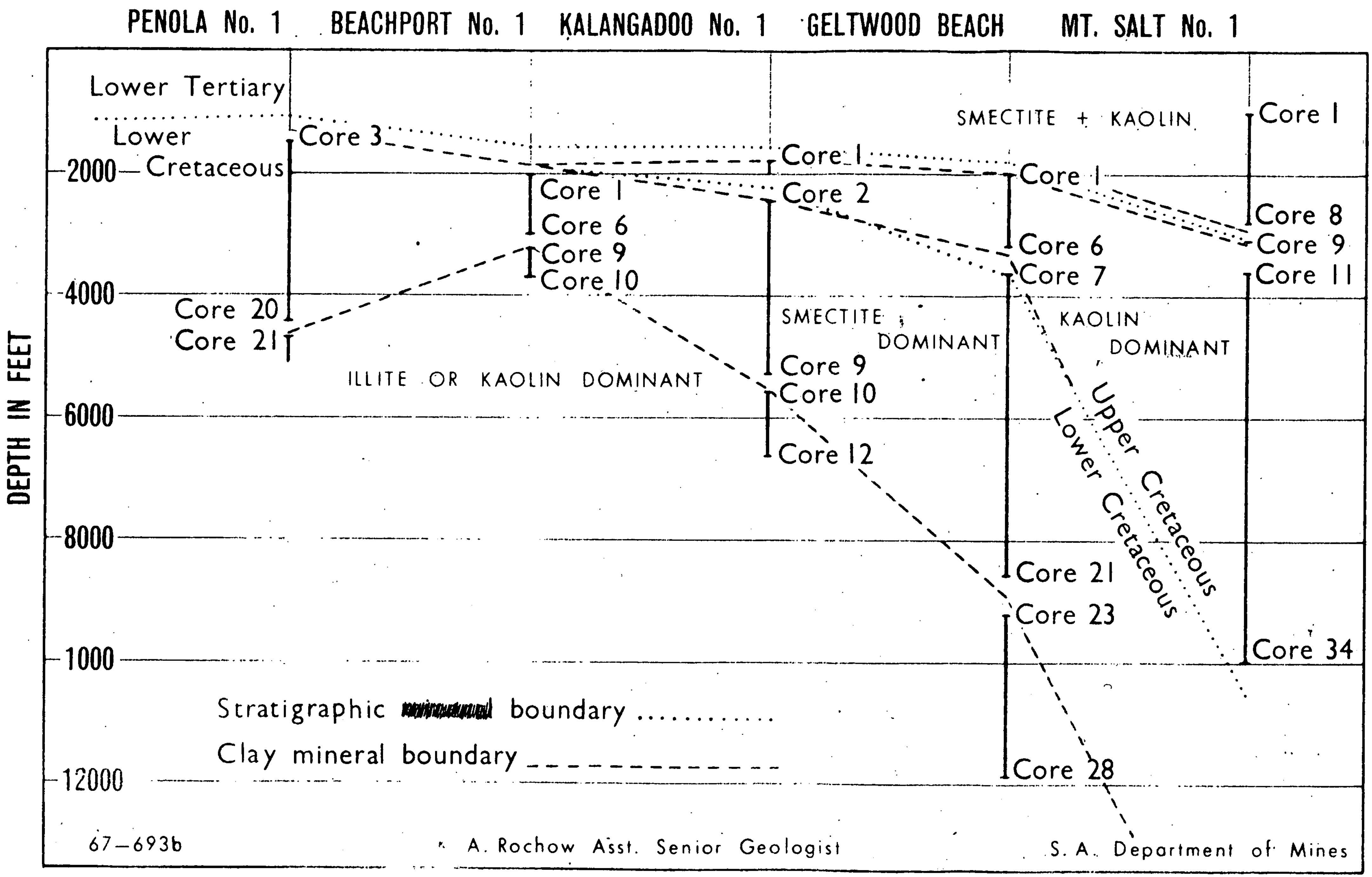


FIG.10. CORRELAT SEQUENCES BASED ON CLAY MINERAL ASSEMBLAGES

FIG. 11

WELL LOGS SHOWING CORRELATIONS OF SEQUENCES WITHIN THE OTWAY GROUP

Actual size

DIPMETER SURVEY
A.O.D.A.N.L. KALANGADOO NO.1

FIG. 12. OTWAY BASIN

ML L67-92/4