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A PETROGRAPHIC STUDY OF THE PACOOTA SANDSTONE, AMADEUS BASIN, NORTHERN TERRITORY

by

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ONSHORE

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CONTENTS

SUMMARY

Arenites of the Pacoota Sandstone are predominantly fine grained, moderate-well sorted and quartz rich. Feldspar is the other main detrital mineral present, but other constituents occurring in some of the samples include glauconite, phosphatic shell fragments, haematite and manganese oxides. Clay content is usually very low except in some of the surface samples where weathering has decomposed all feldspars and micas to kaolinite. Evidence from subsurface samples indicates that weathering may have removed carbonate and sulphate cements from many of the samples.

Only three carbonate rocks were included in the suite of samples. Two of the carbonates are relatively fine grained micritic wackestones with a very high terrigenous content while the other rock is a shelly, glauconitic grainstone, now extensively recrystallized and cemented by sparry calcite.

Of the five mudrocks examined only one was a subsurface sample unaffected by weathering. It contained abundant illite and mica with at least some of the illite being authigenic in origin. Weathering of mudrocks results in the formation of kaolinite.

Evidence from subsurface samples indicates a very complex history for the arenites. The single most important diagenetic change is cementation by quartz overgrowths which are widespread and have almost totally cemented many samples. Feldspar overgrowth development, as well as dolomite and anhydrite cementation are also significant processes, although weathering has obliterated much of the evidence of these other cements in surface samples.

With the exception of very small amounts of porosity due to incomplete quartz overgrowth development, most of the porosity in the Pacoota Sandstone is secondary due to dissolution of some feldspar grains and also carbonate and sulphate cements. However, the high porosities in some surface samples are due to removal of feldspars and cements by weathering and not diagenetic dissolution.

1. INTRODUCTION

This study of the Pacoota Sandstone was carried out in accordance with the brief provided on 18th December, 1985 (see Appendix 1).

A total of 61 thin-sections was examined in this study and one sample was analysed by X-ray diffraction methods. Eighteen of the thin-sections were prepared as part of this project; the rest had been prepared earlier and were supplied with the samples.

The majority of samples used in this study were arenites with only three carbonate rocks and five mudrocks included. Most of the samples came from outcrop sections but a small number were subsurface samples from the P3B subunit in the Mereenie Field. All subunits of the Pacoota Sandstone (P1-P4) were represented in the surface samples.

2. ANALYTICAL PROGRAM

2.1 Thin-section Analysis

In accordance with the brief, 18 thin sections (2 carbonates, 16 arenites) were prepared. Each rock was impregnated with blue dyed epoxy resin. Half of each thin-section of the carbonates was stained with Alizarin red S to identify calcite and half of each arenite thin-section was stained with sodium cobaltinitrite to distinguish potash feldspar.

Twenty-two samples were analysed by point counting 300 points in each thin-section to provide detailed data for use in the construction of compositional plots.

Fifteen thin-sections were examined to provide answers to 10 specific questions listed in the brief.

In order to determine paragenetic sequences for the three rock groups (arenites, argillites, carbonates), all thin-sections were examined. For those samples not previously analysed by point counting, estimates of composition were made in some cases or else rapid point counts of 100 grains were made to provide basic compositional data.

No grain size analyses were carried out on any of the thin-sections but the average grain size was estimated from thin-section.

2.2 X-ray Diffraction Analysis

Only one sample was analysed by XRD. This was a mudrock from which an orientated clay mount was prepared by crushing some of the sample in distilled water and drying the slurry on a glass disc. The sample was scanned first in air dried condition and then after treatment with ethylene glycol. After inspection of the diffractograms no additional analyses were carried out.

PETROGRAPHY

3.1 Thin-section Analysis

Twenty-two samples were analysed by point counting for parameters which could be directly utilized in the following plots :

(i) Q-F-R plots (Folk, 1974);
(ii) four-variable quartz plots (Basu et al, 1975);
(iii) Q-F-L plots (Dickinson and Suczek, 1979);
(iv) Qm-F-Lt plots (Dickinson and Suczek, 1979);
(v) Qp-Lv-Ls plots (Dickinson and Suczek, 1979);
(vi) Qm-P-K plots (Dickinson and Suczek, 1979).

The point count analysis results are listed in Table 1.

Samp. No.	Sub Unit	QM<5	Qm>5	Qp<3	Qp>3	Cht	Srf	Kfel	Pla	Mic	H-M	Opq	Anh	Car	Clay	Vpor
4A	P3B	54.7	8.0	1.5	1.2	-	-	10.4	-	0.3	-	1.8	-	-	5.2	17.0
17	P3B	74.3	10.7	2.7	1.7	-	-	2.3	-	-	0.3	-	-	-	0.3	7.7
18	P3B	61.0	6.0	4.0	2.3	-	-	-	-	-	-	-	-	-	15.7	11.0
19	P3A	75.3	8.7	4.3	2.3	-	-	-	-	-	-	-	-	-	0.7	8.7
28	P1	58.6	14.6	6.2	9.9	-	0.9	1.6	-	-	-	-	-	-	-	8.3
29	P1	63.0	10.3	6.3	4.0	-	-	3.7	-	-	0.7	-	-	-	9.7	2.3
30	P1	68.0	14.7	7.7	4.7	-	-	3.0	-	-	-	-	-	-	-	2.0
31	P1	64.0	10.7	3.7	0.7	-	-	19.3	1.0	-	-	-	-	-	0.3	0.3
32	P1	73.7	8.0	6.3	-	-	-	11.7	-	-	0.3	-	-	-	-	-
33	P1	81.7	5.3	4.3	0.7	-	-	0.3	-	-	-	-	-	-	0.3	7.3
34	P1	63.1	6.6	4.2	0.7	-	-	20.9	-	-	-	-	-	-	2.6	2.0
35	P1	67.7	5.0	2.0	-	-	-	20.7	1.3	0.3	-	-	-	-	-	3.0
36	P1	77.3	10.7	6.3	1.0	-	-	1.7	-	-	-	-	-	-	0.3	2.7
37	P1	77.7	8.0	3.3	1.0	-	-	-	-	-	-	-	-	-	1.0	9.0
60	P1	77.7	5.3	5.3	2.0	-	-	-	-	-	-	-	-	-	1.3	8.3
70	P3B	66.8	14.8	6.5	1.7	-	-	3.9	-	0.3	0.3	1.7	-	-	2.0	2.0
71	P3B	79.7	3.4	3.8	1.3	-	-	10.3	-	-	-	-	-	-	0.3	1.3
85/3	P3B	61.3	11.6	4.1	0.7	0.3	-	9.2	1.2	-	0.3	0.3	3.2	1.9	0.6	5.2
85/4	P3B	69.6	13.6	5.0	1.0	-	-	7.2	0.7	0.3	-	-	-	1.3	1.0	0.3
85/5	P3B	17.3	0.7	-	-	-	-	29.7	0.7	7.7	3.7	4.0	-	-	36.3	-
85/6	P3B	60.5	13.2	4.3	0.7	-	-	17.8	1.0	0.3	-	-	-	2.3	-	-
209	P3B	52.0	2.0	4.3	15.1	3.0	-	0.6	0.3	1.0	3.3	-	-	-	3.6	14.8

Qm<5 = monocrystalline quartz with <5deg undulosity Qm>5 = monocrystalline quartz with >5deg undulosity Qp<3 = polycrystalline quartz consisting of 2-3 grains Qp>3 = polycrystalline quartz consisting of >3 grains (metamorphic quartz) Cht = chert Srf = other sedimentary rock fragment types Kfel = potash feldspar Pla = plagioclase Mic = mica H-M = non-opaque heavy minerals Opq = opaques Anh = anhydrite Car = carbonate Vpor = visible porosity

TABLE 1. THIN-SECTION ANALYSES

The data indicate that in general the sandstones have a very low clay content which in some cases did not even register in the point count analyses. In some samples the recognition of clay is made difficult by the presence of haematite or limonite as grain coatings or pore fillings as the iron oxides often obscure any clay.

In several samples (e.g. 28, 60) large, often elongated secondary pores are present which may be in excess of 3mm long. No trace remains of the contents of these pores but it is likely that most were shale clasts.

Sample 85/5 is a coarse siltstone which contains abundant mica as well as illite and chlorite which may be in part of detrital origin but which also appear to be diagenetic decomposition products of mica. Because there is a continuum of grain size from large, obvious mica flakes, the majority of which are biotite, down to clay sized illite, the quantitative distinction between detrital mica and clays is impossible to determine with any reliability.

In sample 85/3 the 1% of polycrystalline metamorphic quartz also includes 0.3% (1 grain) of a quartz-mica metamorphic rock fragment. In sample 209 the 3% of chert includes 2% of silicified grains showing remnant oolitic structure.

3.2 Answers to Specific Questions

In section 3(d) of the brief, 10 specific questions were listed concerning various samples. Answers to these questions are given below :

(i) Sample 2 is primarily a sandstone consisting mostly of rounded quartz grains which make up 60% of the rock. Manganese oxides occur mainly as an intergranular cement which is irregularly distributed through the rock.

In some places the patches of manganese appear too large to be only an intergranular pore filling, while in other places sand grains appear to have acted as nuclei for manganese to precipitate in concentric layers producing an oolitic structure. Oolitic structured manganese makes up less than one quarter of the total manganese which amounts to 33% of the rock. It seems likely that the manganese oxides were deposited synchronously with the sand grains. While some of the manganese has precipitated in an oolitic form, the majority has formed as a structureless precipitate which in some places was sufficiently abundant to cause the quartz grains to be suspended in manganese with no grain to grain contact occurring.

(ii) The dark grains in sample 5 are patches of haematite which occur as pore fillings which precede quartz overgrowths. The haematite may possibly have been derived from detrital grains of ilmenite, magnetite or haematite. In sample 85/4 the black minerals are well rounded grains of detrital tourmaline.

(iii) The sparse pebbles in sample 3A were not encountered in the thin-section. Those pebbles visible in the rock appear to be chert and metaquartzite. In thin-section the largest grains within the sandstone are all fragments of metaquartzite. Sample 209 contains pebbles composed of a variety of silicic rocks including metaquartzite, chert, haematitic jaspilite, and silicified oolite.

(iv) Sample 52 was originally a clean quartzose sandstone cemented by quartz overgrowths but the rock has since been metamorphosed to the point where partial recrystallization of quartz has begun. The small amounts of original clay or mica are now represented by fine grained muscovite and biotite. Although recrystallization is well advanced, the outlines of the original well rounded quartz grains (average grain size 0.5mm) are still visible beneath the now partly recrystallized overgrowths. A well defined preferred orientation of secondary mica crystals indicates that the metamorphic event was accompanied by significant stress and was not purely a thermal (contact) event.

Sample 215A is a metaquartzite derived from a highly quartzose sandstone which contained only minor amounts of feldspar which has now been weathered out of the rock. Little secondary mica is present indicating a very low original clay content. This rock is more extensively recrystallized than sample 52.

Sample 215B is also a metaquartzite. It is very similar to sample 215A and it was originally a very clean quartzose sandstone containing little feldspar or clay. The rock has several well defined laminae which are rich in heavy minerals. These heavy minerals include rounded grains of tourmaline and zircon as well as secondary rutile which has probably developed from detrital ilmenite.

(v) Sample 56 is a quartzose sandstone which has a fairly uniformly distributed system of intergranular pores. A few of the pores are large and appear to be secondary as a result of feldspar dissolution. The bulk of the intergranular pores are smaller and could possibly be of primary origin. However, the irregular surfaces of some of the grains bordering the pores suggests that at least some of these pores may be secondary and may have originated by the dissolution of an earlier carbonate or sulphate cement.

(vi) Sample 59 contains fragments which are composed of laminated phosphatic material (collophane). While the internal structure of the fragments appears to be lamellar, to what extent the original structure has been modified by diagenesis is unclear. Interpretation of the fragments is complicated by the fact that none of the fragments are of intact fossils; all are broken, generally rounded and presumably have been transported. Most of the fragments are straight or slightly curved in section and some indication of crenulated or slightly ribbed surfaces were noted in a few examples. In view of the shape and composition of the fragments, they are considered most likely to be from shells of inarticulate brachiopods.

(vii) The red areas in sample 78 consist of loose, earthy haematite which is mostly confined to isolated secondary pores within an otherwise tightly quartz overgrowth cemented sandstone. It is likely that the secondary pores originally contained a cement such as siderite or ferroan dolomite, which has since been oxidized during weathering.

(viii) Sample 85/3 is a quartzo-feldspathic sandstone which also contains numerous heavy mineral grains. The rock is cemented by quartz overgrowths and also by irregularly distributed anhydrite and carbonate. The carbonate is not siderite, but is ferroan dolomite or ankerite which is often flecked with fine grained haematite. Larger patches of haematite occur within heavy mineral-rich laminae where the haematite appears to have developed, along with some secondary rutile or anatase, from detrital ilmenite which occurs along with tourmaline and zircon grains.

(ix) Sample 85/5 is a micaceous and clay-rich siltstone in which mica content (mostly biotite) was measured at 7.7% by point counting. The clay in this sample appears to be predominantly illite, at least some of which has probably developed from the degradation of mica during burial. It is likely that the original mica content of the sediment when deposited was considerably higher than the 7.7% now indicated.

(x) In samples 201A and 201B silica cementation is concentrated within the coarser grained layers in both samples. These layers were deposited as clean quartz sands with little or no clay. The average grain size of the sands is 0.4mm (medium sand). As a result of the lack of clay, quartz overgrowth cementation has been almost complete. The less cemented zones are finer grained with average grain sizes around 0.12mm (fine sand) and significant amounts of clay and mica were deposited in these finer sediments. As a result, many grains are clay coated and in some places pores are completely filled by illite, which is in part detrital and in part due to mica decomposition. The presence of the illite as a pore filling and grain coating has severely inhibited quartz overgrowth cementation. Overgrowths are only poorly developed within the fine grained laminae. Instead, grain suturing due to pressure solution is more common in these zones.

3.3 Carbonate Petrography

Three carbonate-rich samples were included in the suite of samples studied. Alizarin red S staining indicated that all are calcitic. Two of the samples (300, 85/2) are from the P2 subunit and have a very high terrigenous component and in many respects are better described as calcareous arenites rather than carbonates. Sample 1, from the P1 subunit, has only a low terrigenous content.

Sample 1. Fossiliferous, glauconitic grainstone

This rock is composed mainly of coarsely crystalline calcite which is stained with iron oxides as a result of weathering. Some of the iron oxide patches probably represent oxidized pyrite. The rock also contains 5-7% glauconite pellets up to 1mm long, as well as 1-2% quartz.

The original depositional fabric of this rock is almost impossible to determine because of the extent of recrystallization which has occurred. Allochems are visible in the rock but they are usually little more than ghost outlines marked by poorly defined micrite envelopes. The allochems are mostly elongated, slightly curved shell fragments up to 3mm long which are probably of predominantly brachiopod origin. A small number of irregularly shaped to approximately rounded grains partly replaced by glauconite resemble fragments of dasycladacean algae.

The shape of the allochems can only be defined where micrite envelopes have developed around the grains and these envelopes are usually incomplete. They do, however, indicate that the majority of the allochems are transported, worn and rounded fragments rather than being intact, in-situ shells.

The rock appears to have been deposited in a current or wave affected shallow marine environment as a well washed, shelly, glauconitic grainstone containing little mud. The large, well rounded glauconite pellets are interpreted to have developed concurrently with the deposition of the allochems. The only finer grained material deposited may have been a few peloids or intraclasts which are now represented by patches of neomorphic spar with crystal sizes around 0.08mm compared with 0.25mm crystal sizes for most of the rock.

The clean porous character of the original sediment has enabled the later development of an extensive sparry calcite cement to produce a glauconitic biosparite (in the terminology of Folk).

A paragenetic sequence for this rock is interpreted as follows:

(i) Development of micrite envelopes and algal boring of allochems (syndepositional or very early, shallow burial under marine conditions).

(ii) Formation of authigenic pyrite particularly associated with earlier formed glauconite.

(iii) Cementation by sparry calcite cement (subaerial or freshwater diagenesis) to eliminate all intergranular porosity.

(iv) Recrystallization of allochems and possibly some fine grained peloids or intraclasts to produce neomorphic spar and microspar.

(v) Alteration of pyrite to haematite/limonite (in part probably a weathering process).

Sample 300 Glauconitic, terrigenous wackestone

Although this sample is highly calcareous, it is better described as a calcareous, glauconitic arenite, rather than a carbonate as much of the framework of the rock consists of terrigenous material. Although carbonate makes up more than 50% of the rock, at least some of that carbonate appears to have replaced unstable terrigenous grains such as feldspars or lithic grains. In this rock, apart from some areas where carbonate mud appears to have been introduced by bioturbation, most of the carbonate occurs as a cement and replacement mineral rather than as either a carbonate mud matrix (micrite) or as carbonate allochems.

The composition of the sample is estimated as follows:

55-60%	carbonate (sparry calcite + some microspar)
20-25%	quartz
5-10%	feldspar (predominantly potash feldspar)
1-2%	mica
2-3%	sedimentary rock fragments (shale clasts)
3-5%	clay
3-5%	glauconite
1-2%	opaques (haematite/limonite)
<1%	non-opaque heavy minerals
1-2%	visible porosity

Apart from one or two extensively recrystallized fragments which may have been skeletal particles, virtually no carbonate allochems are evident in the rock although a few phosphatic shell fragments are present. There is nevertheless evidence of bioturbation, with some finer grained parts of the rock probably representing original carbonate mud which has since been variably recrystallized to microspar. The bulk of the calcite, however, is a coarser grained sparry cement which does not appear to be recrystallized micrite. This sparry calcite has replaced many terrigenous grains such as feldspars to varying degrees. Some laminae within the original sediment appear to have been shaly and some shale clasts are also present but the bulk of this sample appears to have originated as a well sorted, very fine-fine grained terrigenous sand. Finer grained, micritic and shaly laminae were interbedded with the sand and parts of these laminae have become incorporated in the sand as a result of bioturbation. The rock was later cemented and partly replaced by calcite and the micrite has recrystallized to microspar.

The description of the rock as a wackestone is strictly only applicable to those sections of the sample which were obviously micritic.

Sample 85/2 Glauconitic, terrigenous wackestone

This sample is broadly similar to sample 300 in that it has a high terrigenous content of fine and very fine sand, but it contains slightly more carbonate than sample 300 and its texture is also more variable. As with the previous sample, carbonate allochems are extremely rare but micrite is more abundant. The rock is irregularly laminated and shows evidence of bioturbation which has disrupted some of the laminae. In addition, some features of the sample suggest that it may have been affected by slumping or redeposition as there are large clasts of very fine sandstone up to 15mm long surrounded by predominantly micritic sediment. The clasts are glauconitic, quartzo-feldspathic sandstones which are extensively cemented by quartz overgrowths. The larger clasts are almost completely devoid of carbonate although some of the smaller clasts contain carbonate as a replacement mineral particularly around the margins of the clasts. Shale clasts up to 2.5mm long also occur within several laminae.

The sample appears to be part of an interbedded sequence of sandy and shaly clastics and muddy, glauconitic carbonates with the laminae having been partly disturbed and intermixed as a result of bioturbation and possibly slumping.

The bulk of the rock is carbonate rich and consists of fine-medium grained calcite microspar and spar developed mostly by recrystallization of micrite in what was originally a mud-supported, mixed carbonate and clastic sediment. The average composition of the rock is estimated as follows :

55-65%	carbonate (mainly calcite microspar and spar from micrite recrystallization)
12-17%	quartz
5-10%	feldspar (mainly potash feldspar)
10-15%	sedimentary rock fragments (very fine sandstone and shale clasts)
1-2%	clay
5-8%	glauconite
1-2%	mica
2-3%	visible porosity

In addition to the recrystallization of micrite to microspar, there has also been a significant amount of replacement of terrigenous constituents by sparry calcite. The rock contains a small amount of porosity and although the pores are isolated they are often large and vuggy being up to 2.5mm long. In some cases these pores may mark where shell fragments have been dissolved but for the majority of the secondary pores, the nature of the dissolved material cannot be determined.

A paragenetic sequence of post burial changes for samples 300 and 85/2 is interpreted as follows :

(i) Formation of glauconite, much of which may be early diagenetic rather than syndepositional.

(ii) Recrystallization of micrite and rare shell fragments to calcite microspar and spar.

(iii) Development of quartz and minor feldspar overgrowth cements within terrigenous clasts.

(iv) Partial replacement of terrigenous clasts by calcite.

It was difficult to establish the age relationship between diagenesis of the carbonate and clastic components of the rock. It is possible that recrystallization of carbonates and the replacement of clastic grains by carbonate could have been complete before quartz overgrowth development occurred.

3.4 Argillite Petrography

Of all the samples examined in thin-section in this study, only three are sufficiently fine grained to be described as argillites. In addition, one fine grained sample was provided for analysis by X-ray diffraction methods. Two other samples were listed in the brief as mudrocks. Sample 84 is a bioturbated laminated very fine sandstone with some shaly intercalations and sample 85 is a fine to very fine grained ferruginous sandstone which will not be discussed in this section.

Sample 85/5

This is the only subsurface fine grained sample and it was listed in the brief as an arenite. It is actually a coarse siltstone with an average grain size of 0.05mm which is only slightly below the coarse silt/very fine sand boundary. The composition of this rock was determined by point counting (see Table 1). The rock is very rich in feldspar which is almost exclusively of potash type. Feldspar is more abundant than quartz in this rock. Significant amounts of mica, particularly biotite, are also present as well as non-opaque heavy minerals, mostly zircon.

The rock is rich in clay which fills all intergranular spaces between quartz and feldspar grains. The clay appears to be mainly illite which is in part detrital but at least some of the clay has developed by decomposition of mica to illite and minor chlorite.

The sample also contains several thin lenses in which haematite is abundant and occurs between the quartz and feldspar grains in place of illite clay. The haematite-rich zones appear to have originally been patches where dense pyrite cement was present.

Sample 3

This is an extensively weathered surface sample which is composed almost entirely of earthy haematite and limonite except on one edge of the thin-section where a very fine sandstone lamination is present. Apart from the iron oxides which constitute around 80% of the rock, there are small amounts of quartz (10-15%) and kaolinite clay (5-10%) which has formed from weathered mica crystals.

Sample 86

Sample 86 is also an extensively weathered mudrock but one in which little iron oxide is present. The rock appears to have been micaceous when originally deposited but weathering has converted all the mica to clays, predominantly kaolinite. Much of the fine grained illite in the rock also appears to have converted to kaolinite during weathering. The only opaque mineral present is fine grained leucoxene which together with a small amount of secondary anatase is probably a decomposition product of biotite mica.

The composition of the rock is estimated as follows :

5-10%	quartz
85-95%	clays (mainly kaolinite, lesser illite)
2-3%	leucoxene + anatase

Sample 84

This is a laminated but extensively bioturbated fine-very fine grained sandstone with interbedded shaly laminae. Bioturbation has severely disrupted the bedding so that the shaly laminae have been partly intermixed with the more sandy layers. The composition of the cleaner, sandy layers is estimated as follows :

60-80%	quartz
8-12%	feldspar (mainly potash feldspar)
<1%	mica
<1%	heavy minerals (tourmaline, zircon)
1-2%	opaques (haematite)
4-8%	clay
3-5%	visible porosity (secondary porosity due to feldspar, dissolution)

Quartz overgrowths are well developed in the more quartzose sandy layers but decrease as clay content increases.

The most fine grained and least quartzose of the shaly layers consists almost entirely of clay and opaques (haematite) with mica, quartz and feldspar collectively constituting less than 10% of the shaly layers. The dominant clay mineral appears to be illite. Haematite content is highly variable and ranges in the shales from below 10% to above 70% with clay content varying inversely.

Between the two extremes of relatively pure sands and shales are a variety of laminae which consist of mixtures of the two types to produce tight, muddy sands containing variable amounts of opaques. The haematite grains are of very consistent grain size which is around 20um. The grains occur as equant to roughly spherical crystals and appear to have originated as pyrite.

Sample 200

This sample was analysed by X-ray diffraction analysis to determine its clay mineralogy. The analysis results show that kaolinite is the dominant clay mineral with illite also present in significant amounts. The kaolinite is a well crystallized variety producing sharp, well defined basal reflections. The 10Å illite peak showed a slight change in shape but not position following treatment with ethylene glycol. This suggests that the illite contains a very small interstratified smectite component probably not exceeding 5%.

Apart from a very small amount of quartz in the sample, the only other mineral present is represented by a broad, ill-defined, low amplitude peak in the 14-20Å range. On glycolation this peak changed character slightly to produce a maximum at 19Å which is a wider lattice spacing than that normally expected for glycolated smectites (17Å).

This mineral is tentatively interpreted as some form of mixed layer clay, possibly a chlorite-smectite, but this cannot be verified as no other peaks were recognizable which could be assigned to this mineral to assist its identification.

It appears that this sample is generally similar to sample 86 with the kaolinite being a product of weathering of what was originally an illite/mica-rich mudrock. This conclusion is supported by the appearance of the sample in hand specimen where it takes the form of small fragments of weathered, white, laminated, almost "chalky" mudrock.

Paragenetic Sequence

Determination of a general paragenetic sequence for the argillites is hampered by their fine grain size and the abundance of clay minerals which require XRD analysis for positive identification. In addition, later weathering of surface samples further complicates their interpretation. The type of diagenetic changes, other than pure compaction, which have affected the mudrocks include :

(i) Growth of authigenic pyrite.

(ii) Decomposition of detrital micas to clays such as illite, and possibly illite-smectite and chlorite.

(iii) Oxidation of pyrite to haematite.

These processes are similar to those operating in the arenites and can often be more readily identified in the arenites because of the coarser grain size of the framework in these rocks.

3.5 Petrography and Diagenesis of Arenites

The great majority of samples examined in this study are arenites. In addition to the 21 arenites which were analyzed by point counting of 300 points per sample, an additional 27 arenite samples were examined and their general composition was determined by point counting 100 grains in each thin-section. In these brief analyses no discrimination of different quartz types was undertaken. The average grain size of the sands was also estimated from thin-section. The results are listed in Table 2. Discussions of petrology and diagenetic history are based on an examination of all the arenite thin-sections from this study as well as some observations from earlier studies of the Pacoota Sandstone in the Mereenie Field.

It was considered desirable to draw on observations from previous studies as the samples provided for this study include only 4 subsurface samples. Interpretation of the diagenetic history in the surface samples is complicated by mineralogical changes resulting from severe weathering which has affected many of the sample. Dissolution processes involving the removal of carbonate and sulphate cements and also feldspar grains may occur under both diagenetic and weathering conditions. The subsurface samples provide a more reliable record of diagenetic changes as the overprint of recent weathering is absent.

Some of the processes which are considered to have occurred during weathering include the dissolution of carbonate and sulphate cements and the dissolution/decomposition of feldspars to give either secondary pores or kaolinitic clays. Leaching of clays such as illite or chlorite to produce kaolinite, and the introduction of minerals to the pore system from percolating near-surface groundwaters have also occurred during weathering. Minerals introduced in this way include limonite (goethite), clays (particularly kaolinite), and opaline silica. Although kaolinite formation can also be a widespread diagenetic process, there are some textural differences between diagenetic and weathering kaolinites with features of the latter being well illustrated in some of the weathered surface samples.

Sample Number	Sub Unit	AvGS (mm)	Quartz	Chert	Feldspar	Rock Fragments	Mica	Non-opaque Heavy Minerals	Manganese Oxides	Haematite	Limonite	Opal	Collophane	Anhydrite	Carbonate	Glauconite	Clay	Visible Porosity
2	P1	0.30	59	-	1	-	-	-	33	-	-	-	-	-	-	-	-	7
4	P2	0.20	62	-	3	1	-	-	-	26	-	-	1	-	-	8	-	-
5	P1	0.20	83	-	-	-	-	1	-	3	-	-	-	-	-	-	2	11
7	P4	0.30	84	-	-	-	-	-	-	-	2	-	-	-	-	-	3	11
8	P4	0.10	59	1	-	-	-	1	-	-	1	-	-	-	-	-	22	17
9	P4	0.18	90	-	-	-	-	1	-	-	-	-	-	-	-	-	2	8
10	P4	0.18	77	-	-	-	-	1	-	-	-	2	-	-	-	-	7	14
11	P4	0.45	77	-	-	-	1	-	-	-	6	-	-	-	-	-	3	13
12	P4	0.20	89	-	-	-	-	1	-	-	-	-	-	-	-	-	4	7
13	P4	0.19	76	1	-	-	-	1	-	-	8	-	-	-	-	-	-	15
14	P4	0.25	88	1	-	-	-	1	-	-	-	-	-	-	-	-	4	6
16	P3B	0.12	59	-	-	-	-	1	-	-	-	-	-	-	-	-	31	10
20	P3A	0.25	89	-	-	-	-	1	-	-	-	-	-	-	-	-	10	1
21	P3A	0.20	96	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4
22	P3A	0.20	84	-	-	-	-	-	-	-	3	-	-	-	-	-	1	12
23	P3A	0.15	86	-	-	-	-	-	-	-	3	3	-	-	-	-	2	6
26	P3A	0.25	96	-	-	-	-	-	-	-	2	-	-	-	-	-	-	2
56	P3A	0.30	90	-	-	-	-	1	-	-	-	7	-	-	-	-	1	2
57	P2	0.23	70	1	3	-	-	-	-	1	-	-	3	-	-	21	-	1
59	P1	0.40	72	-	3	1	-	-	-	-	5	-	10	-	-	-	7	2
75	P3A	0.20	82	-	13	-	-	1	-	4	-	-	-	-	-	-	1	-
78	P3A	0.22	94	-	-	-	-	1	-	2	-	-	-	-	-	-	-	3
81	P2	0.20	69	-	4	-	-	-	-	11	-	-	-	-	-	15	-	1
201A	P1	0.18	85	-	-	-	-	1	-	-	-	-	-	-	-	-	3	12
201B	P1	0.18	78	-	1	-	-	1	-	-	-	-	-	-	-	-	5	15
207	P1	0.09	59	-	4	-	-	1	-	-	20	-	-	-	-	-	3	13

TABLE 2. GENERAL COMPOSITIONAL DATA FOR PACOOTA ARENITES

The effects of weathering in the Pacoota Sandstone are easily underestimated because of the highly siliceous and well cemented character of the formation. Nevertheless, weathering has been sufficiently severe in many samples to totally remove any unstable grains, notably feldspars by either completely leaching them from the rocks or else converting them to kaolinite clays. The susceptibility to weathering does not appear to have been uniform in all the surface samples however and some still contain significant amounts of minerals such as feldspars and glauconite which could have been expected to decompose during prolonged weathering. Leaving aside a factor which cannot be assessed in this study, i.e. the location and possible variation of surface exposures with respect to their susceptibility to weathering, it would appear that with minor exceptions, those surface samples which contain the most feldspar are the finer grained sands with average grain sizes below 0.2mm (fine sand). A similar trend has been noted in earlier studied subsurface samples from the Mereenie Field.

Texture

Estimates of average grain size indicate that the Pacoota Sandstone samples fall within a relatively narrow grain size range. Thirty-two of the 48 arenites are fine sands, 8 are very fine sands and 8 are medium sands. Sorting also appears to be relatively good with most samples estimated to be moderately or well sorted. Poorer sorting usually occurs where the sandstones are obviously laminated, with individual laminae differing in their average grain size.

Although most sandstones are now extensively cemented, preservation of original grain outlines beneath quartz overgrowth cements indicates that they were deposited as very clean sands with a high proportion of well rounded grains.

Composition

The arenites of the Pacoota Sandstone are invariably highly quartzose with the quartz mostly consisting of monocrystalline grains with non-undulose or only slightly undulose extinction.

The rocks are often relatively rich in feldspar which consists almost entirely of potash varieties including microcline, orthoclase and perthite. In the subsurface samples this feldspar is often exceptionally fresh in appearance even though the grains are often well rounded. By contrast, lithic fragments are rare in the Pacoota Sandstone.

Small amounts of mica are often present and the majority of sandstones also contain a few grains of non-opaque heavy minerals. These heavy minerals are most commonly well rounded grains of tourmaline and zircon but occasional grains of rutile, sphene and anatase were also noted.

The most common opaque mineral in the sandstones is haematite. In some cases haematite appears to have developed from the decomposition of detrital iron-bearing heavy minerals (possibly ilmenite, magnetite) but more commonly haematite seems to have formed by oxidation of diagenetic minerals such as pyrite, ferroan carbonate cements, or glauconite.

Hydrated iron oxides (limonite, goethite) are present in many of the surface samples as a result of the weathering of other iron-bearing minerals such as ferroan carbonates.

None of the surface samples now contains any carbonate or sulphate but carbonates (particularly ferroan dolomite) and anhydrite are present in the subsurface samples and these minerals were frequently encountered in other subsurface Pacoota samples previously studied. Textural characteristics of some of the surface samples indicate that they were almost certainly once cemented by carbonates and/or sulphates to varying degrees.

Clay content is often extremely low in the arenites, even to the extent that it fails to register in the point count analysis. Only in some of the most fine grained sands close to the silt boundary does clay content increase significantly. Previous studies of subsurface Pacoota samples indicate that illite and chlorite are the two clays usually encountered and kaolinite is absent. It therefore appears likely that the kaolinite which can be seen in many of the thin-sections of surface samples and which also features prominently in the XRD analysis of sample 200, is a product of surface weathering and is neither a detrital nor a diagenetic clay. Minerals which appear to have decomposed to kaolinite include feldspars, micas and illite clay.

Visible porosity is variable in the arenites used in this study. Visible porosity is a measure of those pores which are large enough to be resolved under the optical microscope. This excludes microporosity which is interstitial between pore filling clay minerals. However, the very low clay content in many of the sandstones and consequent very low microporosity means that visible porosities may closely approach measured core porosities.

Most of the porosity in the Pacoota Sandstone appears to be of secondary origin except in a few places where small, remnant primary pores remain due to incomplete quartz overgrowth cement development. In the surface samples much of the porosity, which is often quite high, is the result of weathering out of minerals such as feldspars, cements, shale clasts or even shell fragments under near surface conditions and not during diagenesis. In this way, the effects of weathering mask any diagenetically induced dissolution porosity formation, but it seems unlikely that many of the surface samples were significantly porous prior to being exposed to surface weathering.

An examination of the three subsurface arenites from the Mereenie Field indicates that in only one (sample 86/3) is there any significant porosity (5.2%). The pores are irregularly distributed and include some large and often isolated secondary pores which are the result of feldspar dissolution. The remaining pores appear to be due to the dissolution of dolomite and anhydrite cements which now have a patchy distribution through the rock.

An examination of the 10 most porous surface samples with visible porosities ranging from 12% to 23%, all of which come from the P4 or P3B subunits, suggests that most of the porosity is weathering induced. In samples 15 and 17 the porosity appears to be almost exclusively due to removal of feldspars by weathering. Samples 4A, 8, 10 and 22 have also lost feldspars during weathering but they may also have lost some carbonate/anhydrite cement. In samples 11, 13, 18, 209 the porosity is due to very limited development of quartz overgrowths on rounded quartz grains. From previous studies of subsurface samples, this suggests that these samples were most likely anhydrite, or possibly carbonate cemented. Less common causes of porosity retention, which have been noted previously, are the coating of grains by haematite or authigenic chlorite clays.

Diagenesis

Cementation of the Pacoota Sandstone is the most widespread and important diagenetic change and it commonly results in almost total loss of porosity from sands which when originally deposited must have been extremely clean and porous.

Silica cementation in the form of quartz overgrowths is the most common type of cement. In the cleaner, more quartzose sands, e.g. sample 36, overgrowth cementation is virtually complete with all primary pores eliminated by overgrowths and only isolated secondary pores remaining.

Feldspar overgrowths are also common in the Pacoota Sandstone and contribute to the cementation of the rocks. In some of the very feldspathic sands such as sample 31 a combination of quartz and feldspar overgrowths has totally eliminated all intergranular porosity leaving only one or two isolated, elongated pores resulting from dissolution of shell fragments.

Other cements frequently encountered in the Pacoota Sandstone in the subsurface are carbonates and sulphates. The sulphate cement is usually anhydrite and this is present in all three subsurface arenites (85/3, 85/4, 85/6) although in only trace amounts in the latter two samples. Previous studies of the Pacoota Sandstone in the Mereenie Field have shown anhydrite to be widespread although it is usually present in amounts not exceeding 5% in the sandstones.

Carbonate cements are also common in the subsurface Pacoota samples. The most frequently encountered carbonate is a ferroan dolomite which is flecked with very fine grained haematite. This carbonate is present in all three of the subsurface arenites examined in this study. Previous studies have shown that calcite and siderite are also occasionally present in the Pacoota Sandstone. No carbonates were present in any of the surface samples from this study but as noted previously there are strong indications that carbonate and/or sulphate cements were originally present in many of the sands.

A number of minerals other than those cements described above also occur as authigenic minerals in the formation. Several of these minerals may be syndepositional but they may also have continued to form under early burial conditions. Such minerals as glauconite and manganese oxides may fall into this category.

Haematite is an important authigenic mineral in the Pacoota Sandstone. In many places, the haematite has clearly developed by oxidation of original authigenic pyrite which occurred as pore filling cement, as disseminated fine grained crystals in muddy sands (e.g. sample 84) or associated with glauconite and sometimes phosphatic shell fragments. Apart from these situations where haematite has clearly formed from pyrite, haematite also occurs as pore linings and grain coatings. Its origin here is less clear but it may possibly have formed by dissolution and oxidation of ferroan carbonate cements.

The oxidation of pyrite and possibly carbonates and glauconite to haematite has occurred during diagenesis and is not simply a weathering process as haematite is common in subsurface samples. The conversion of ferrous to ferric iron during burial suggests a significant change in pore fluid characteristics at some stage of the burial history with oxygenated pore fluids passing through the rock.

Authigenic clay minerals are also present in the Pacoota Sandstone although clay content in most of the arenites is low. Clays are most abundant in sample 85/5 where the clay appears in thin-section to be predominantly illite with a smaller amount of chlorite also present. A significant proportion of this clay appears to have developed by the degradation of detrital mica, a process which has been observed in earlier studies of the Pacoota Sandstone. The kaolinitic clays visible in many surface samples appear to be weathering products and have not formed during diagenesis.

Grain suturing and microstylolite formation due to pressure solution is uncommon in the Pacoota Sandstone. This process is mainly confined to those samples which contain appreciable amounts of decomposing mica or illite clays which can be seen lining the microstylolite seams. A small amount of grain suturing is also evident in some samples (e.g. 11) where quartz overgrowths are insignificant and the rock texture suggests that the rock was probably cemented by sulphate or carbonate.

The other important type of dissolution which occurs in the Pacoota Sandstone involves the removal of framework feldspar grains and carbonate or sulphate cements to form secondary porosity. These processes can be identified in the subsurface samples, particularly 85/3 and have also been described in other arenites from the Mereenie Field, but as previously discussed, the dissolution effects associated with weathering of the surface samples makes any diagenetic dissolution processes difficult to recognize.

An additional complication in the interpretation of secondary porosity development due to carbonate or sulphate cement removal is that later quartz overgrowth development partly obscures the evidence of dissolution.

Paragenetic Sequence

The full sequence of diagenetic changes in the Pacoota Sandstone is naturally not reflected in each sample but from an examination of all samples the general order of diagenetic changes can be determined.

The first processes to occur are those which were syndepositional but which may have continued into the early stages of burial. The formation of glauconite and manganese oxides probably falls into this category.

The interpreted sequence of diagenetic changes is shown diagrammatically in Figure 1.

The relatively late stage of diagenetic origin for the widespread quartz overgrowth cements is based on the following observations :

(i) Overgrowth development is inhibited by a variety of other diagenetic events such as the presence of authigenic clays and other cements which must therefore precede overgrowth development.

```
GLAUCONITE FORMATION       ---

MANGANESE OXIDE            ----
PRECIPITATION

AUTHIGENIC PYRITE            -----
FORMATION

FELDSPAR OVERGROWTH              ------
FORMATION

ANHYDRITE CEMENTATION                  ------

DOLOMITE CEMENTATION                    --------

AUTHIGENIC CLAY                               --------?
FORMATION

GRAIN SUTURING                                  --------

HAEMATITE FORMATION BY                   ?-?--------
OXIDATION OF PYRITE ETC.

SECONDARY POROSITY FROM                         ----------
ANHYDRITE, DOLOMITE DISSOL.

QUARTZ OVERGROWTH                                      --------
CEMENTATION

SECONDARY POROSITY FROM                           ?-?-?---------
FELDSPAR DISSOLUTION

                              EARLY-------BURIAL HISTORY------LATE
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FIGURE 1. PARAGENETIC SEQUENCE

(ii) In places where anhydrite and dolomite cements are sufficiently abundant to fully enclose quartz grains, these quartz grains show no overgrowth development indicating an early origin for carbonate/sulphate cements relative to quartz overgrowths.

(iii) That quartz overgrowth development may have accompanied dissolution of carbonate/sulphate cements is suggested by the presence of small remnant crystals of anhydrite and dolomite which have become enclosed by quartz overgrowths.

It appears that anhydrite may in some places precede dolomite formation as there are indications that the dolomite sometimes occurs as an isomorphous replacement of anhydrite.

Evidence to show that feldspar overgrowths developed before carbonate/sulphate cements occurs in the situation described in (ii) above where framework quartz and feldspar grains are fully enclosed by carbonate or sulphate cements. Although quartz overgrowths have not yet developed in this situation, feldspar overgrowths are present on many grains indicating their early diagenetic origin.

The early diagenetic development of feldspar overgrowths and anhydrite which probably originated as gypsum, suggests that formation waters were of relatively high salinity and the combination of anhydrite and dolomite possibly suggests an evaporitic influence at an early stage of the burial history. However, a simple evaporitic origin for the dolomite and anhydrite is unlikely. The Pacoota Sandstone consists mostly of well reounded and relatively well sorted sands which together with evidence of fossil debris and bioturbation suggests deposition in a shallow marine environment. Such an environment would have near normal salinity rather than the hypersalinity required to produce direct precipitation of evaporitic minerals from seawater.

There is nevertheless some petrological evidence to suggest that the climate may have been arid during deposition of the Pacoota Sandstone. The clean, clay-free, well sorted and well rounded character of many of the sands indicates a prolonged transportation history prior to deposition. Despite this, the sandstones, particularly in the subsurface, are often rich in feldspar, much of which is exceptionally fresh. This indicates a very much reduced rate of chemical weathering activity which is consistent with an arid climate.

A possible model to explain the nature of cementation in the Pacoota Sandstone, which was suggested in an earlier study of the formation in the Mereenie Field (Martin, 1983), is that the evaporite minerals formed during early burial at shallow depths in a desert or nearshore sabkha environment within the zone of influence of a fluctuating water table. Evaporation and concentration of brine may occur where the water table intersects the land surface and the salinity of the pore waters and the water table level may fluctuate in response to periodic influxes of freshwaters separated by periods of drought. This environment of fluctuating salinity has been termed the "schizohaline environment" by Folk and Land (1975) and is probably more likely to be represented by inland desert sabkhas rather than nearshore, supratidal sabkhas where periodic water influxes are likely to be of seawater. One of the difficulties which may be overcome by the schizohaline model is that the dolomite formed in normal sabkha diagenesis is usually fine grained, non-stoichiometric protodolomite. However, given fluctuating salinity, growth of coarsely crystalline, well ordered dolomite is favoured during low salinity periods when dilution of formation brine could achieve a suitable Mg:Ca ratio and salinity combination to allow precipitation. Gypsum would precipitate during times of high salinity. It is also possible that some of the haematite may have formed under these conditions by oxidation of pyrite although haematite formation may also have occurred later in response to an influx of fresh, oxygenated waters to the aquifer sand.

4. CONCLUSIONS

1. Arenites of the Pacoota Sandstone are mostly fine grained, moderately to well sorted and are highly quartzose with the quartz consisting mostly of monocrystalline grains with little or no extinction undulosity.

2. Feldspar is the other main framework constituent. It consists mainly of potash varieties including microcline, orthoclase and perthite. In many of the surface samples weathering has either totally removed feldspar or else it has been converted to kaolinite clay.

3. Apart from quartz and sometimes feldspar, the majority of surface arenites contain little else other than a few grains of heavy minerals, usually tourmaline and zircon.

4. The subsurface arenites contain both anhydrite and dolomite as patchy cements, and the texture of some of the surface samples suggests that prior to weathering, they may also have been cemented by carbonates or sulphates.

5. Of the three carbonate rocks included in the suite, one is a highly recrystallized, glauconitic grainstone composed mainly of recrystallized shell fragments cemented by sparry calcite. The other two carbonate rocks are finer grained, bioturbated, glauconitic wackestones with a terrigenous content of fine sand which makes up only slightly less than 50% of the rocks. Few carbonate allochems are present and the carbonate occurs as recrystallized micrite and sparry calcite cement with the calcite also partly replacing many terrigenous grains.

6. Illite is the dominant mineral in the argillites in the subsurface where it is both detrital and authigenic, forming from the decomposition of mica. Surface weathering of micas, illite and probably feldspar has produced kaolinite in the surface argillites.

7. The arenites have a complex diagenetic history which commences with processes such as glauconite formation and manganese oxide precipitation which are likely to be syndepositional or very early burial, through phases of cementation by feldspar overgrowths, anhydrite, dolomite and finally quartz overgrowths. Cementation has resulted in the total loss of primary porosity from almost all samples.

8. Other significant diagenetic processes include the oxidation of iron-bearing minerals such as pyrite to haematite, and the dissolution of some feldspar grains and also anhydrite and dolomite cements to form secondary porosity. In many of the surface samples these diagenetic dissolution processes are masked by weathering-induced dissolution and decomposition processes.

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APPENDIX 1. STUDY BRIEF

INSTRUCTIONS FOR PETROGRAPHIC AND X-RAY DIFFRACTION ANALYSES

1. PREPARATION OF THIN SECTIONS

One standard oversized thin section (22mm x 38mm) is to be prepared from each of the following samples:

3A
4A
5
60
75
85/2
85/3
85/4
85/5
85/6
207
209
211
215A
215B
300

Two standard oversized thin sections are to be prepared from sample number 201.

All samples are to be impregnated with blue plastic (epoxy type), n = 1.54, under vacuum prior to sectioning. Thin sections are to be mounted with colored (light green ?) epoxy, n = 1.54, and cut to standard thickness (0.03mm). One half of each thin section of sandstone is to be stained with Sodium Cobaltinitrate, and one half of each thin section of limestone or dolostone is to be stained with Alizarin Red S.

The stratigraphic orientation of each sample cut perpendicular to bedding is to be indicated on the thin section.

2. X-RAY DIFFRACTION ANALYSES

The composition of sample number 200 is to be determined by X-ray diffraction. The analysis is to be conducted on an oriented grain mount scanned from 2° to 35° 2θ. Smectite group minerals are to be identified by glycolation, and kaolinite is to be distinguished from chlorite by heating.

3. PETROGRAPHIC ANALYSES

a) The composition of the following samples is to be determined by point-counting:

<u>P1</u>

28
29
30
31
32
33
34
35
36
37
60

P3B

17	85/3
18	85/4
19	85/5
70	85/6
71	209
4A	

Compositional data will be used for the construction of:

i) Q-F-R plots (Folk, 1974);
ii) four-variable quartz plots (Basu et al., 1975);
iii) Q-F-L plots (Dickinson and Suczek, 1979);
iv) Qm-F-Lt plots (Dickinson and Suczek, 1979);
v) Qp-Lv-Ls plots (Dickinson and Suczek, 1979); and
vi) Qm-P-K plots (Dickinson and Suczek, 1979).

b) A paragenetic sequence is to be determined for each rock type (arenites, argillites, and carbonates). The sequence is to be determined by examination of all samples.

c) Each of the carbonate samples are to be described and classified. Dunham's (1962) classification of carbonate rocks is to be used to describe depositional texture. Crystal size, carbonate grain type and abundance, carbonate composition, organic and inorganic sedimentary structures, size and abundance of terrigenous material, and degree of textural alteration are to be included in rock names as modifiers of depositional texture.

d) Appropriate petrographic analyses are to be conducted to determine:

1. If sample number 2 is a manganese-rich arenite or an oolitic ironstone,

2. The mineralogy of the black grains in sample numbers 5 and 85/4,

3. The lithology of the pebbles in sample numbers 3A and 209,

4. The lithology of sample numbers 52, 215A, and 215B,

5. If sample number 56 contains primary porosity,

6. The fossil assemblage in sample number 59,

7. The mineralogy of the red areas in sample number 78,

8. If sample number 85/3 contains siderite and hematite,

9. If sample number 85/5 contains biotite, and

10. The reason extensive silicification is confined to one horizon in sample numbers 201A and 201B.

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