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In Australia’s Northern Territory
FORMATION EVALUATION STUDY -
ARUMBERA SANDSTONE,
PANCONTINENTAL WALLABY NO. 1 WELL,
AMADEUS BASIN, NORTHERN TERRITORY,
AUSTRALIA

Report Prepared For:

Mr. J.D. Gorter
Senior Geologist
PanContinental Petroleum Ltd.
20 Bond Street
Sydney NSW 2000
Australia

November 25, 1981
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SUMMARY

Arumbera Sandstones examined in this study are feldspathic litharenites. Monocrystalline quartz is the dominant detrital grain. Polycrystalline quartz, orthoclase, chert, and metamorphic rock fragments are other important constituents. Detrital clay is present in all sandstone samples, occurring as pedogenic clay rims on grains.

Arumbera Sandstones are fine grained (0.25 mm). The sands vary widely in terms of sorting (poorly to well sorted).

The sands are characterized by a primary intergranular pore system. This pore system is partially occluded by anhydrite and silica cement. Only one sample (6823.7 ft) contains measurable quantities of authigenic clay cement (1%).

Arumbera Sandstones will be susceptible to formation damage from the following mechanisms:

1) Precipitation of fluosilicic salts during HF acidization.

2) Precipitation of Fe(OH)₃ gels during HCl acidization (very minor).

Arumbera Sandstones may be safely drilled with a fresh water based mud system. Mud clean-up acidization, if required, may proceed with a mud dispersal agent consisting of 12% HCl plus a nonionic or anionic surfactant and a non-emulsifying surfactant. HF should not be employed in acidification of these sands.

Arumbera Sandstones will not respond to a matrix acid stimulation. If stimulation is attempted, we recommend hydraulic fracturing as the most effective technique. An N₂ foam frac should prove effective.

Richard K. Vessell, Ph.D
Chief Geologist

David K. Davies, Ph.D
President
Certified Professional Geologist No. 4188
INTRODUCTION

This report comprises a portion of an ongoing study by PanContinental Petroleum Ltd. of potentially productive Proterozoic-Early Cambrian Arumbera Sandstones. The study was initiated in order to obtain information concerning the reservoir quality and fluid sensitivity of the sands.

Specifically, the following items have been examined:

1) The textural and compositional characteristics of Arumbera Sandstones.

2) The origin, nature, and distribution of porosity in the Sandstones.

3) The nature, distribution, and abundance of clay in Arumbera Sandstones.

4) The mineralogy and distribution of cements in Arumbera Sandstones.

5) The susceptibility of Arumbera Sandstones to formation damage from drilling or completion fluids.

6) The composition of drilling and completion fluids which will produce the least formation damage.

ANALYTICAL METHOD

1) Petrographic Analysis

All samples employed in this study were obtained from conventional core pieces made available by PanContinental Petroleum (Table 1). Portions of samples used for petrographic analysis were impregnated with blue epoxy resin, slabbled, mounted on a glass slide, and ground to a thickness of +30 microns. This rock thin section was analyzed using the petrographic microscope. All thin sections were stained with Alizarin Red "S" stain to facilitate distinction of calcite from dolomite. Where the presence of ferroan cements was suspected, the thin section was also stained with potassium ferricyanide. Petrographic analysis of thin sections yielded the following data:

a. Grain size -- Grain size is determined in thin section by measuring the long diameter of randomly selected grains. The mean of 100 measurements per thin section is used as the mean grain size for each sample.
b. **Sorting** -- Sorting of each sand sample is evaluated using two techniques: 1) visual comparison of the sample with standard charts prepared by Beard and Weyl (1973, Bull. Am. Assoc. Petrol. Geol.) and 2) the ratio of the length of the largest grain to the mean length of all grains.

c. **Sand-Silt-Clay Percentages** -- The relative percentage abundance of sand-silt-clay size components in each thin section is estimated. These estimates do not include the total amount of clay in the sample. Some clay minerals are contained in sand-sized clay balls and altered rock fragments. The presence of clay balls and altered igneous and metamorphic rock fragments may increase the actual percentage of clay in the rock. The percentage of clay as reported in our tables can be used as an indicator of depositional energy.

d. **Bulk Composition** -- The bulk composition of each sample is determined through point counting, +1 percent, for all components larger than clay size.

e. **Porosity Origin** -- Visual examination of thin sections enables determination of the type of porosity (primary intergranular or secondary dissolution porosity). It also enables description of the morphology of the pore system and pore throats. Qualitative estimates of porosity-permeability can also be made using thin sections of adequate samples.

f. **Diagenetic History** -- Petrographic analysis allows determination of the diagenetic history of the rock. The diagenetic history is responsible for the ultimate porosity and permeability of any reservoir. Determination of the diagenetic history enables us to determine the major and minor causes of porosity-permeability reduction or enhancement.

g. **Percent Solubles** -- Petrographic analysis enables quantitative determination of the volumetric abundance (+1%) of acid soluble components in the sand. More importantly, it enables a determination to be made as to what percentage of the soluble material lies in the pore throats, and how much occurs as discrete grains. This is significant in the design of matrix acid or acid-frac jobs.
2) X-Ray Diffraction Analysis

The composition of the fine fraction (less than 5 micron size fraction) of the sands was determined by X-ray diffraction. The fine fraction of each sample was separated from the sands, settled onto glass plates and analyzed in air dried and glycolated states. This form of X-ray analysis yields reliable (+3%) results of the composition of clays in a sand. Unfortunately, it does not enable the analyst to determine whether these clays are dispersed, structural, or laminated in origin. In order to determine which of these clays occur in the pores ("dispersed clays") it is necessary to undertake scanning electron microscope analysis.

3. Scanning Electron Microscope Analysis

The pore systems of four (4) selected samples from the Arumbera Sandstone were analyzed using a scanning electron microscope. The microscope used is fitted with an energy dispersive X-ray system, which allows for chemical analyses of the pore fill minerals while they are being visually examined. Photographs of selected, representative pores are presented in this report.

GENERAL INFORMATION

Three (3) copies of this report have been forwarded to Mr. J.D. Gorter of PanContinental Petroleum Ltd. David K. Davies and Associates retain one (1) copy for future consultation with authorized personnel on details related to this study. All thin sections and original X-ray diffraction patterns are stored at the laboratories of David K. Davies and Associates, Houston, Texas, and are available for study at any time. All data and interpretations are considered confidential and the sole proprietorship of PanContinental Petroleum Ltd.
## TABLE 1

**LIST OF SAMPLES AND ANALYSES PERFORMED**

PanContinental Wallaby No. 1

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Depth (Ft)</th>
<th>Thin Section</th>
<th>X-Ray</th>
<th>SEM</th>
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<td>6818.9</td>
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<td>X</td>
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<td>D-503-002</td>
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<td>D-503-003</td>
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<td>D-503-004</td>
<td>6823.8</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

*(All from base Arumker III unit)*
COMPOSITIONAL AND TEXTURAL PROPERTIES OF ARUMBERA SANDSTONES

General - The compositional and textural properties of the Arumbera Sandstone were determined through petrographic analysis of thin sections prepared from core samples. Mean grain size and bulk sediment composition were obtained by point counting 100 grains on each section. Sorting was visually estimated employing standard charts prepared for a range of grain sizes. The compositional and textural properties of Arumbera Sandstones are presented in Table 2.

Composition - Arumbera Sandstones examined in this study are feldspathic litharenites. Quartz grains comprise the bulk of the detrital fraction of these sandstones (56-67%). Monocrystalline quartz grains are dominant (48-63%). Polycrystalline quartz grains are less abundant (4-12%). Quartz grains are well rounded and are generally ellipsoidal to spherical in shape.

Feldspars comprise 9 to 23 percent of the detrital fraction. Most of these feldspars are orthoclase. A few feldspars display dissolution features; others have a fresh appearance.

Rock fragments comprise a significant proportion of the detrital fraction. Polycrystalline quartz (4-12%), chert (Tr-2%), and metamorphic rock fragments (2-3%) are the most important types.

Detrital clay is present in all of the sandstone samples examined in this study. Detrital clay matrix occurs as a grain coating in significant quantities (0-12%). Clay matrix is volumetrically more important toward the top of the sequence and generally lacking from the base of the sand interval. This matrix occurs as pedogenic (soil) clay rims on detrital grains. The pedogenic rims consist of illitic clay and iron oxide.

Texture - Arumbera Sandstones are fine grained (0.24-0.25 mm). The average grain size of sands cored in this well is 0.25 mm. Grain size displays little variation from base to top of the cored section.

The sandstones vary widely in terms of sorting characteristics. Sands from the lower portion of the cored interval are well sorted. These sands contain little detrital clay matrix. Sands from the upper portion of the interval are poorly sorted.
## Table 2

**Thin Section Analysis**

**WELL WALLABY 1 (CORE NO. 2)  **

**FORMATION** ARUMBERA SANDSTONE

**DEPTH** 6818.75-6823.67 ft

<table>
<thead>
<tr>
<th>Depth (Ft)</th>
<th>Mean Grain Size (mm)</th>
<th>Overall Sorting</th>
<th>Monocrystalline Quartz</th>
<th>Polycrystalline Quartz</th>
<th>K-Feldspar</th>
<th>Plagioclase Feldspar</th>
<th>Chert</th>
<th>Igneous RF's</th>
<th>Metamorphic RF's</th>
<th>Sandstone Fragments</th>
<th>Clay Balls</th>
<th>Shale Fragments</th>
<th>Plant Remains</th>
<th>Carbonate Fragments</th>
<th>Shell Fragments</th>
<th>Glaucolite</th>
<th>Heavy Minerals</th>
<th>Others</th>
<th>Detrital Clay Matrix</th>
<th>Authigenic Clay</th>
<th>Silica</th>
<th>Calcite</th>
<th>Dolomite</th>
<th>Siderite</th>
<th>Anhydrite</th>
<th>Pyrite</th>
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<th>Total Clay Minerals</th>
<th>Total Carbonates</th>
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<td>Average</td>
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</table>

*Clay plus iron oxide

MX = Depositional matrix (fines deposited simultaneously with the sand grains). RF's = Rock Fragments.
RESERVOIR QUALITY OF ARUMBERA SANDSTONES

Pore System Morphology - Thin section photographs presented on the following pages display the pore system morphology of Arumbera Sandstones (Figure 1). The pores which occur in this sand interval are dominantly primary intergranular pores. A few large irregular pores of secondary origin have also formed as a result of the partial dissolution of chemically unstable grains in the sand (primarily feldspars).

Many of the primary pores visible in thin section are partially occluded by anhydrite cement and silica overgrowths. Open primary porosity appears to have formed through dissolution of anhydrite. This anhydrite cement, precipitated prior to silica cementation of the sand, excluded development of silica overgrowths in the pores. Later, dissolution of anhydrite resulted in exhumation of some original primary porosity.

Diagenesis - Petrographic and scanning electron microscope examination of Arumbera Sandstones indicates that the sands have undergone extensive post depositional alteration. Changes in composition have occurred in response to variations in pressure, temperature, and geochemical environment.

Diagenesis has resulted in both a decrease in primary porosity and permeability and an enhancement of porosity through generation of secondary porosity. Diagenesis involved three processes:

1) Precipitation of authigenic cement
2) Compaction
3) Secondary porosity generation

Arumbera Sandstones examined in this study have been cemented by a variety of minerals including silica, authigenic feldspar, calcite, anhydrite and authigenic clay. Silica cement occurs as quartz overgrowths with euhedral terminations on detrital quartz grains (Figure 2). Authigenic feldspar occurs in minor quantities as a pore lining and as overgrowths on detrital feldspar grains (Figure 2). Dolomite and anhydrite occur as large poikilotopic patches occluding primary porosity (Figure 2). Authigenic clays and pyrite occur as pore fills. In spite of the cementation, some primary porosity remains open in the sands.

Authigenic silica is the most important sandstone cement (1-12%). Authigenic clay (0-1%), anhydrite (2-10%) and dolomite (0-2%) also occur in significant quantities.
These photos display the pore system morphology of Arumbera Sandstones. Primary porosity (blue) is largely occluded by anhydrite cement (white in plane light, bright colors in crossed nicols).

Some primary porosity has been exhumed through dissolution of anhydrite (photo E). The resulting secondary porosity is distributed in a patchy or laminated fashion.
FIGUE 2

CEMENTATION OF ARUMBERA SANDSTONES

Wallaby No. 1 Well

<table>
<thead>
<tr>
<th>Photo</th>
<th>Depth (Ft)</th>
<th>Illumination</th>
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<tbody>
<tr>
<td>A</td>
<td>6818.75</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>6820.25</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>6822.00</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>6823.67</td>
<td>2</td>
</tr>
</tbody>
</table>

Photo Scale - Red dot = 0.03 mm
Illumination - 1 = Plane polarized light
2 = Crossed nicols

Photo A - This photo displays development of pedogenic clay rims (brown) around detrital grains (white). Note open primary pore in the center of the photo (blue).

Photo B - This photo shows three generations of cement. Note small, euhedral quartz overgrowths on grains at upper left; feldspar overgrowths on feldspar grain (grey-center); and anhydrite pore fill (dominantly blue).

Photo C - Dolomite cement (pink-center) and anhydrite (blue) cement this portion of the sandstone.

Photo D - Feldspar grain in the center of this photo displays feldspar overgrowths. Some porosity is also filled by anhydrite (yellow).
A further reduction in primary porosity occurred as a result of compaction of the sandstones. Burial compaction has resulted in a loss of approximately 10 percent of the original sandstone pore volume through a rearrangement of grain packing.

Porosity enhancement has occurred as a result of dissolution of anhydrite cement and some detrital grains. Anhydrite cement was precipitated in many primary pores early in burial. The presence of anhydrite in some zones precluded development of silica overgrowths in the pores. Dissolution of anhydrite in the subsurface resulted in exhumation of some of the primary pore system.

The diagenetic processes outlined above have occurred in a sequential fashion. The order of these events may be inferred from textural relationships of cements.

**Early Diagenesis** -

Stage 1) Development of pedogenic clay rims on detrital grains.

Stage 2) Precipitation of anhydrite cement in some portions of the sand.

Stage 3) Shallow burial and grain rotation resulting in tighter packing.

Stage 4) Early development of syntaxial quartz overgrowths on detrital quartz grains. Silica cement largely filled pores not occluded by anhydrite.

Stage 5) Dolomite cementation.

**Late Diagenesis** -

Stage 6) Development of secondary porosity. Primary pore network partially exhumed through dissolution of pore filling anhydrite.

Stage 7) Leaching and partial dissolution of some feldspar grains.

Stage 8) Development of feldspar overgrowths on some detrital feldspar grains.

Stage 9) Precipitation of authigenic clays.
NATURE, DISTRIBUTION, AND ABUNDANCE OF CLAYS

Sandstones examined in this study contain 1 to 12 percent total clay (Table 2). The clay occurs as detrital and authigenic clay.

Detrital clay, occurring as pedogenic grain rims, comprises the bulk of the clay fraction of samples examined in this study. Only one sample 6823.7 ft contains measurable quantities of authigenic clay (1%).

The results of X-ray diffraction analyses of the less than 5 micron size fraction of Arumbera Sandstones are presented in Table 3. These analyses indicate that illite is the major clay variety in the sands. Minor quantities of kaolinite and chlorite are also detected.

X-ray analyses also detect the presence of quartz, K-feldspar, dolomite, gypsum, anhydrite, and halite.
### TABLE 3

Semiquantitative X-ray diffraction analyses of the Arumbera Sandstone.
PanContinental Wallaby No. 1 Well.

<table>
<thead>
<tr>
<th>Depth (Ft)</th>
<th>6818.9</th>
<th>6820.2</th>
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<td>Anhydrite</td>
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<td>Halite</td>
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<td>D503-003</td>
<td>D503-004</td>
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</tbody>
</table>
CLAYS AND PETROPHYSICS

Precipitation of clay minerals in the pores and pore throats of Arumbera Sandstones will affect the S.P., resistivity, and porosity logging response of the sands.

a) **Resistivity** - Due to the presence of fibrous illite within the rock pore system, these sands will display excess conductivity. This is a result of the presence of exchange cations, adsorbed on clay surfaces. This plus the high clay particle surface area available for current flow, will result in resistivity variations and may cause zones containing abundant pore fill clay to appear to have higher water saturations than are actually the case.

b) **S.P.** - The presence of clays may also have an affect on the S.P. response of the sands. The presence of the clay in pores and pore throats will decrease permeability and suppress S.P. response.
FORMATION SENSITIVITY TO FLUIDS

Arumbera Sandstones examined in this study will be susceptible to formation damage from the following mechanisms:

1) Precipitation of fluosilicic salts during HF acidization.

2) Precipitation of Fe(OH)₃ gels (very minor) during HCl acidization.

HF Acid Sensitivity

Problem - Analyses of Arumbera Sandstones indicate the presence of anhydrite and some halite in the reservoir. If HF acid is used in the stimulation of these sandstones, the HF acid will spend on silicate grains and fluosilicic acid will be formed. This fluosilicic acid, when mixed with fluids rich in Ca⁺⁺ and Na⁺ may form gelatinous solids:

\[
\begin{align*}
H_2SiF_6 + 2NaCl & \rightarrow Na_2SiF_6 + 2HCl \\
H_2SiF_6 + CaCl_2 & \rightarrow CaSiF_6 + 2HCl
\end{align*}
\]

Further, if HF is allowed to spend, gelatinous silica may be reprecipitated from solution:

\[
H_2SiF_2 + 2H_2O \rightarrow 6H^+ + F^- + SiO_2
\]

Solution - A pad of HCl or NH₄Cl may be run ahead of any HF bearing fluid in order to flush salt solutions from the zone to be acidized. Otherwise avoid use of HF in this sand.

HCl Acid Sensitivity

Problem - Chlorite clay and pyrite present in the rock system are iron-rich cements. Iron present in these cements occurs both as Fe⁺⁺ and Fe⁺⁺⁺. This iron will be liberated from the clay by partial dissolution of the chlorite and pyrite.

The danger exists that ferric iron liberated by partial dissolution of chlorite and pyrite will be reprecipitated as a gelatinous ferric hydroxide gel as the acid solution spends (system pH raised above 1.5).

\[
Fe^{+++} + 3 OH^- \rightarrow Fe(OH)_3
\]
This ferric hydroxide compound is an inorganic gelatinous polymer containing quantities of bound water. Formation of ferric hydroxide gel will block sandstone pore throats resulting in damage to reservoir permeability.

**Solution** - Acetic and citric acid are weak iron sequestering agents which inhibit the precipitation of dissolved iron for extended periods of time. When these acids are blended with HCl acid, ferric ions are tied up (sequestered) forming water soluble complex ions. Hence, should chlorite clay with ferric iron occur as a pore fill cement, citic or acetic acid should be added to HCl placed in contact with the formation. This acid solution should be removed from the formation before it spends.
RECOMMENDATIONS

Drilling - Arumbera Sandstones are devoid of expandable layer clay. The sands may be safely drilled with a fresh water based mud system. Consideration may be given to the use of a low solids mud system in this zone in order to avoid forcing drilling mud solids into sandstone pore throats.

Perforating - Arumbera Sandstones will not be susceptible to formation damage from migrating fines. They may be safely perforated with a large differential in favor of the well bore.

Clean-up - Should a mud clean-up acidization be attempted we recommend use of a mud dispersal agent consisting of the following components:

1) 12% HCl
2) A non-ionic or anionic surfactant
3) A non-emulsifying surfactant

HF should not be used in the clean-up of these sands.

Clay Stabilization - There appears to be no need to employ a clay stabilizing compound in these sandstones.

Stimulation - Arumbera Sandstones will not respond significantly to a matrix acid stimulation. The sands contain little acid soluble cement.

Should stimulation be attempted, hydraulic fracturing will be the most effective technique. Fracturing will interconnect groups of pores previously isolated by silica and anhydrite cement. We recommend use of 2-3% KCl foamed with N₂.
SCANNING ELECTRON MICROGRAPH SCALE

The micron marker indicates the photograph scale by displaying a system of bars and dots which correspond to the viewing and photographing magnification. The relative distance represented by the micron marker and the bar length for a set magnification is as follows:

<table>
<thead>
<tr>
<th>Magnification</th>
<th>Marker display</th>
<th>Relative distance (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100,000x</td>
<td></td>
<td>0.1 (1000Å)</td>
</tr>
<tr>
<td>10,000-70,000x</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>1,000-7,000x</td>
<td></td>
<td>10.0</td>
</tr>
<tr>
<td>100-700x</td>
<td></td>
<td>100.0</td>
</tr>
<tr>
<td>15-70x</td>
<td></td>
<td>1000.0 (1 mm)</td>
</tr>
</tbody>
</table>

Note 1: The above table can be read as follows: The first dot is read as "1", and all other dots are read as "0". For instance, if two dots are displayed, it indicates that the length of the bar corresponds to "1", "0" μm (=10 μm). If no dots appear at all, it indicates that the relative distance is 0.1 μm.

Note 2: The magnification of the image displayed on the viewing CRT is approx. 1.2 times that indicated on the magnification indicator. However, since the length of the micron bar corresponds to this ratio, the micron marker can be read as displayed.
### SCANNING ELECTRON MICROGRAPHS

**OF THE**

**ARUMBERA SANDSTONE**

PanContinental Wallaby No. 1

6818.9 Ft

<table>
<thead>
<tr>
<th>Photograph</th>
<th>Magnification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9390</td>
<td>70x</td>
<td>This low magnification survey view of the sample displays well developed sandstone porosity.</td>
</tr>
<tr>
<td>9391</td>
<td>1500x</td>
<td>High magnification view of a sandstone pore lined by illite fibers (I).</td>
</tr>
<tr>
<td>9392</td>
<td>1000x</td>
<td>Sandstone pores are partially occluded by quartz overgrowths (Q) and illite (I).</td>
</tr>
<tr>
<td>9393</td>
<td>1000x</td>
<td>This photo displays a secondary pore with grain residue. The pore is lined in part by fibrous illite.</td>
</tr>
</tbody>
</table>
SCANNING ELECTRON MICROGRAPHS
OF THE
ARUMBERA SANDSTONE
PanContinental Wallaby No. 1
6820.2 Ft

<table>
<thead>
<tr>
<th>Photograph</th>
<th>Magnification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9394</td>
<td>70x</td>
<td>Survey view of sample. Intergranular porosity is open and well interconnected.</td>
</tr>
<tr>
<td>9395</td>
<td>700x</td>
<td>High magnification view of a pore, possibly of dissolution origin, lined and partially filled by fibrous illite (I).</td>
</tr>
<tr>
<td>9396</td>
<td>1500x</td>
<td>This photo displays a primary intergranular pore partially occluded by silica overgrowths (S). Remaining porosity is lined by illite (I).</td>
</tr>
<tr>
<td>9397</td>
<td>2000x</td>
<td>High magnification view of an illitic grain coating. Illite also bridges a pore throat.</td>
</tr>
</tbody>
</table>
SCANNING ELECTRON MICROGRAPHS

OF THE

ARUMBERA SANDSTONE

PanContinental Wallaby No. 1

6822 Ft

<table>
<thead>
<tr>
<th>Photograph</th>
<th>Magnification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9398</td>
<td>70x</td>
<td>General view of sample displaying a pore system of open primary pores.</td>
</tr>
<tr>
<td>9399</td>
<td>1000x</td>
<td>This photo displays the residue of a partially dissolved grain.</td>
</tr>
<tr>
<td>9400</td>
<td>700x</td>
<td>High magnification view of a sandstone pore partially occluded by silica cement (S) and fibrous illite (I).</td>
</tr>
<tr>
<td>9401</td>
<td>1500x</td>
<td>View of a sandstone pore partially occluded by silica cement (S) and lined by illite (I).</td>
</tr>
</tbody>
</table>
### SCANNING ELECTRON MICROGRAPHS

**OF THE**

**ARUMBERA SANDSTONE**

PanContinental Wallaby No. 1

6823.7 Ft

<table>
<thead>
<tr>
<th>Photograph</th>
<th>Magnification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9402</td>
<td>70x</td>
<td>This low magnification view of the sample displays the pore system morphology of the sand. This sample has less porosity than other sands examined in this study.</td>
</tr>
<tr>
<td>9403</td>
<td>1500x</td>
<td>Some of the primary porosity of sands examined in this study is occluded by anhydrite cement (A).</td>
</tr>
<tr>
<td>9405</td>
<td>1000x</td>
<td>View of a secondary pore created by dissolution of a feldspar grain (F).</td>
</tr>
<tr>
<td>9406</td>
<td>700x</td>
<td>Pore filled by anhydrite cement (A).</td>
</tr>
</tbody>
</table>
APPENDIX

Brief Description of Rock Analyses Performed in Fluid Sensitivity Studies

1. Petrographic Analysis

Portions of samples used for petrographic analysis are impregnated with blue epoxy resin, slabbed, mounted on a glass slide, and ground to a thickness of +30 microns. This rock thin section is analyzed using the petrographic microscope. All thin sections are routinely stained with Alizarin Red "S" stain to facilitate distinction of calcite from dolomite. Where the presence of ferroan cements is suspected, the thin section is also stained with potassium ferricyanide. Petrographic analysis of thin sections yields the following data:

a. Grain Size -- Grain size is determined in thin section by measuring the long diameter of randomly selected grains. The mean of 50 measurements per thin section is used as the mean grain size for each sample.

b. Sorting -- Sorting of each sand sample is evaluated using two techniques: 1) visual comparison of the sample with standard charts prepared by Beard and Weyl (1973, Bull. Am. Assoc. Petrol. Geol.) and 2) the ratio of the length of the largest grain to the mean length of all grains.

c. Sand-Silt-Clay Percentages -- The relative percentage abundance of sand-silt-clay size components in each thin section is estimated. These estimates do not include the total amount of clay in the sample. Some clay minerals are contained in sand-sized clay balls and altered rock fragments. The presence of clay balls and altered igneous and metamorphic rock fragments may increase the actual percentage of clay in the rock. The percentage of clay as reported in our tables can be used as an indicator of depositional energy.

d. Bulk Composition -- The bulk composition of each sample is determined through point counting +200 grains on each thin section. The technique yields the bulk composition of the rock to an accuracy of +1 percent, for all components larger than clay size.

e. Porosity Origin -- Visual examination of thin sections enables determination of the type of porosity (primary intergranular or secondary dissolution porosity). It also enables description of the morphology of the pore system and pore throats. Qualitative estimates of porosity-permeability can also be made using thin sections of adequate samples.

f. Diagenetic History -- Petrographic analysis allows determination of the diagenetic history of the rock. The diagenetic history is responsible for the ultimate porosity and permeability of any reservoir. Determination of the diagenetic history enables us to determine the major and minor causes of porosity-permeability reduction or enhancement.

g. Percent Solubles -- Petrographic analysis enables quantitative determination of the volumetric abundance (+1%) of acid soluble components in the sand. More importantly, it enables a determination to be made as to what percentage of the soluble material lies in the pore throats, and how much occurs as discrete grains. This is significant in the design of matrix acid or acid-frac jobs.

2. X-Ray Diffraction Analysis (Fine Fraction Only)

Portions of samples used for X-ray diffraction analysis are disaggregated either manually or using ultrasonic vibrations. The fine-grained fraction of the sample is separated following disaggregation and sedimented onto a glass slide. (The exact size of the fine fraction used in this analysis depends upon the wishes of the client. Generally we use the less than 5 micron size fraction). The fine fraction is then analyzed using an X-ray diffractometer. Each sample is analyzed twice: 1) in air-dried and 2) glycolated states. This analysis enables a determination of the mineralogy of the fine grained components of the rock, particularly the clays. Glycolation is an essential step in this analysis because it is the only method to determine accurately the presence of swelling clays.
The abundance of individual components in the fine fraction, as analyzed by this technique, is accurate to ±3 to 5 percent. X-ray diffraction does not distinguish whether the clay sized components originated from pore-linings, pore-fills, shale laminae, clay balls, altered rock fragments, or as contaminant from drilling muds. (Indeed, X-ray analysis sometimes demonstrates the presence of significant quantities of barite, halite, KCl, and smectite from the mud system). Thus, although X-ray diffraction is the best method of distinguishing the composition of clay minerals in a sample, it cannot be used to determine the location or origin of these clays. To do this, it is necessary to undertake scanning electron microscope analysis.

3. Scanning Electron Microscope Analysis

Portions of samples used for scanning electron microscope analysis are broken to present a fresh, uncontaminated surface. The sample is then mounted on an aluminum stud and coated with a light dusting of gold. This coating material is used to improve the quality of the SEM photographs and to prevent surface charging of the sample. Each sample is then placed in the SEM and scanned for approximately one hour. Diagenetic minerals of interest in the pores are photographed at varying magnifications. The scanning electron microscope used is fitted with an energy dispersive X-ray system. This enables the observer to X-ray the diagenetic minerals as they are being observed on the SEM. This form of X-ray analysis yields qualitative estimates of the elemental composition of the minerals and allows for preliminary determinations of mineralogy.

SEM analysis is invaluable in the examination of pores, pore throats, and pore walls. It enables determinations of the diagenetic minerals in the pores and pore throats, as well as details of pore geometry.

Sample Requirements

These analyses can be undertaken on washed or unwashed cuttings samples, sidewall cores, conventional cores, and plugs which have been used for porosity-permeability analysis. Results from conventional cores and core plugs are the most reliable. Sidewall coring often results in fracturing of individual grains, changes in grain-to-grain relationships, and contamination with drilling mud. Sidewall cores can be used for petrographic, X-ray, and scanning electron microscope analysis as long as these problems are understood. When cuttings samples are used, careful selection of chips is important to avoid misrepresentation by cavings. In our laboratory, selection is undertaken by a geologist using a binocular microscope and electric logs (if provided by client). Cuttings samples are generally the tightest, most cemented portions of any reservoir. Analysis of cuttings samples generally results in an overestimation of the amount and number of cements in any sample.

Adequate sample size is important. The sample should be approximately 1 cubic inch (or 1 teaspoonful of representative cuttings). The analyses can be performed on much smaller samples, if necessary, with some loss of reliability. At least three samples should be selected from each interval. In formations thicker than 50 feet, one sample every 10 or 15 feet is sufficient for analysis of diagenesis and fluid sensitivity. For reliable interpretation of depositional environment, samples should be collected every 5 to 10 feet throughout each interval of interest.

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