Results of 1982 Field Program
McArthur River
Permits OP191/OP198
Northern Territory, Australia

ONSHORE

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Text

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AUSTRALIA

Results of 1982 Field Program
McArthur River Area
Permits O.P. 191/O.P. 198, Northern Territory

by

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Frontispiece Scenic hoodoo development within Hodgson Sandstone Member of Abner Sandstone Formation (Roper Group).

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1. INTRODUCTION

Petroleum Permits O.P. 191 and O.P. 198 are located in the McArthur River area of Northern Territory, Australia, to the southwest of the Gulf of Carpentaria and to the south of Arnhem Land, between latitudes 14° 50' south and 17° 25' south, and longitudes 134° 30' east and 136° 30' east. The Permits are onshore and cover a land area of 39,847 square kilometers (15,385 square miles) (Figure 1-1). Amoco Australia Petroleum Company holds a 50% interest in the Permits; the other 50% interest is held by Kennecott, who are owned by Sohio. Work obligations associated with the Permits are summarized in Enclosure 1-1.

The Permits extend over a portion of the McArthur River Basin, which is composed primarily of a thick sequence of middle to upper Proterozoic sedimentary rocks and has been stable since the late Proterozoic. Minor amounts of Cambrian and Mesozoic sediments locally cover the Proterozoic; they are invariably horizontal to sub-horizontal and attest to the structural stability of the area. Proterozoic sediments are not usually considered to be a viable target for petroleum exploration, mainly because of problems associated with their great age. Where they are not metamorphosed, they have usually undergone severe structural and diagenetic alteration, such that no reservoir potential remains. In addition, the relative paucity of diverse biological activity during the Proterozoic Eon suggests that less hydrocarbon source-rocks exist than in more recent sediments. Those that do exist have usually suffered severe thermal alteration, and have long since expelled their hydrocarbons. In the McArthur River area, however, the Proterozoic section is not only unmetamorphosed, but also appears to have undergone only mild structural and thermal alteration. In addition, hydrocarbon shows have been reported in the area. The objective of the 1981 and 1982 field programs was to investigate the Proterozoic sediments in the area in order to determine whether they represent a viable objective for petroleum exploration.

In the area covered by the Permits, the Proterozoic sedimentary section consists of three groups, the Tawallah Group, the McArthur Group and the Roper Group, but hydrocarbon potential is apparently confined to the McArthur and Roper Groups. Numerous shows of hydrocarbon and bitumen have been reported from these two groups.

Deposition of the McArthur Group was, in part, structurally controlled, as these sediments are largely confined to a linear, fault-bounded graben known as the Batten Trough. Although the Batten Trough, which is oriented roughly north-south, has several features representative of aulacogens, it also has many features strongly suggestive of an origin as a wrench-fault basin. Deposition of the overlying Roper Group shows little structural control, and these sediments were apparently laid down as broad progradational sheets. Some folding and faulting is evident in both the McArthur and Roper Groups.

During 1981 a field party of four Amoco geologists conducted a program of shallow corehole drilling and reconnaissance-scale field mapping. These investigations were designed to verify the occurrence of hydrocarbons in the Proterozoic section, to establish the basic structural and stratigraphic framework of the area, and to acquire source and reservoir rock samples from the maximum number of formations. The program was a qualified success, as it did verify the presence of hydrocarbon in the area, and a simple model of structure and stratigraphy of the area was constructed. In addition, samples from both outcrop and coreholes yielded encouraging results for both source rock and reservoir properties. It subsequently became apparent, however, that the shallow coreholes frequently did not penetrate the zone of weathering, and that the samples therefore might not be representative of true subsurface conditions. It was equally apparent that additional field mapping was necessary to add required information on lateral and vertical facies trends, structural history, paleogeography, etc.

The 1982 field program, the results of which this report documents, was designed to follow-up the 1981 work and to acquire this needed information. A field party of two to four geologists conducted concurrent corehole drilling and field mapping programs. The drilling program ran from approximately April 15, 1982 to August 10, 1982. Eight coreholes, with depths ranging from 221 meters to 592 meters, were drilled in a variety of locations (Enclosure 1-2) and tested a number of stratigraphic units. A Longyear 44 rig (Plate 1-3) with a depth capability of 900 meters was used to drill below the weathered zone, which can be as much as 100 meters thick in this area. Total metrage for the eight holes was 3687 meters, with excellent core recovery throughout most of the operation. All cores were logged in the field, and the coreholes were logged with gamma-ray, spontaneous-potential and single-electrode resistance tools, when possible.

Selected samples from the cores were shipped to Amoco Production Company Research Center, Tulsa, Oklahoma, for laboratory analysis. A total of 135 samples were chosen for organic geochemical analysis; of these, 58 samples contained sufficient organic carbon to warrant full thermal evolution analysis. In addition, 131 core samples were plugged at the Research Center and "farmed-out" for reservoir analysis. U.S. Testing Labs performed porosity, horizontal air permeability and grain density tests on the plugs. Mineralogy, Inc. performed X-ray diffraction analyses on these samples, and standard thin-section petrography and scanning electron microscopy were performed in-house.

The field mapping phase of the study concentrated on acquiring information on facies trends, paleo-currents, environment of deposition, unit thicknesses and structural control of deposition. The results have been incorporated into this report and are presented in the appropriate sections. A total of 365 outcrop samples were taken during the mapping program (Enclosure 1-2) and shipped to Tulsa. They have been used to help evaluate facies changes, environment of deposition and the effects of weathering. Because of the ubiquitous and extreme effects of weathering on reservoir properties, the outcrop samples are unreliable indicators of subsurface reservoir quality, and only a few have been quantitatively analyzed.

Geological field work during this phase of the 1982 program included:

1. Reconnaissance-scale mapping and sampling of the St. Vidgeon-Towns area, in the northwestern portion of O.P. 198 (Enclosure 8-3).

2. Study of facies variations in the upper McArthur and Roper Groups (Section 8).

3. Investigation of northwest-trending apparent growth-faults.

4. Detailed mapping in the vicinity of the eight corehole sites (Enclosures 6-1 through 6-6).

5. Examination of faults in the St. Vidgeon area and their relationship to fold deformation (Section 7).

6. Regional reconnaissance of en echelon folds (Section 7).

7. Geologic mapping in the vicinity of the 1982 seismic test lines.

8. Investigation of a paleokarst developed in the Kookaburra Creek Formation (Section 8).

2. SUMMARY

Amoco Australia Petroleum Company Ltd. holds a 50% interest in permits O.P. 191 and O.P. 198, which cover an area of 15,385 square miles (39,847 square kilometres) on the Gulf of Carpentaria coast of Northern Territory, Australia. The other 50% interest is held by Kennecott, who are owned by Sohio. Geologically, the licenses are located over a portion of the Proterozoic-age McArthur Basin.

The three unmetamorphosed Proterozoic rock-groups recognized in this area are, from oldest to youngest, the Tawallah, McArthur and Roper Groups. Tawallah Group sediments consist of volcanics, clastics, and a few carbonates. In general, these rocks are highly fractured. Possible evidence, in the form of chlorite-lined fractures, exists for local low-grade metamorphism along some faults.

The overlying McArthur Group consists of dolomites, black shales and occasional sandstones and conglomerates. Development of north-trending pull-apart basins by a northwest-trending right-lateral wrench system controlled deposition of McArthur Group sediments. An initial phase of downwarping resulted in the deposition of red beds, sabkhas, and shallow water carbonates (Mallapunyah through Teena Formations).

Following this, a series of high angle, north-trending normal faults formed. Relatively rapid subsidence of graben-like, pull-apart basins controlled deposition of deeper-water organic-rich mudrocks such as the Barney Creek and Lower Lynott Formations. Pulses of fault movement allowed formation of thick clastic wedges adjacent to these faults. The actual mode of basin formation appears to be alternating motion on faults and "graben" formation due to formation of two half-grabens. For instance, within the Batten Trough, deposition of the Barney Creek Formation was controlled by the Emu Fault, whereas the Tawallah Fault appears to have controlled clastic influx at the time of deposition of the Lynott Formation. Northwest-trending faults also exhibit growth during this phase of sedimentation though their cumulative effects on sedimentation are unclear.

The final phase of McArthur Group sedimentation involved deposition of shallow-water sediments (middle Lynott through Dungaminnie Formations). More quiescent conditions prevailed throughout this period; fault movement was sporadic and of lesser magnitude. Resultant deposition of shallow-water carbonates (stromatolitic, intraclastic, oolitic), thin shale units, siltstone and sandstone occurred. Numerous periods of emergence are evidenced by the presence of local paleokarsts within some of the carbonate units. Local uplifts resulted in deposition of the Mt. Birch Sandstone on the flanks of the Urapunga Tectonic Ridge, the Wearyan Shelf and possibly the Tawallah High.

Regional downwarping centered to the west, coupled with clastic deposition prograding from the west, constituted Roper Group sedimentation. Deposition of thick, clean quartz sheet-sandstones and variably-organic shales occurred. Possibly, growth along northwest-trending faults may have taken place at this time.

Subsequent to deposition of the Roper Group, reactivation of north-trending normal faults through dextral transcurrent motion caused the formation of *en echelon* folds. Later sinistral transcurrent motion along the northwest-trending wrench faults appears also to have formed some *en echelon* folds.

Subsequent to the Proterozoic there seems to have been little significant tectonic activity in the area, although organic geochemistry and petrography indicate that the Proterozoic rocks have at some stage been buried quite deeply. Flat-lying Cambrian and Mesozoic cover is occasionally found, and may represent the few remnants of what was a substantial thickness of cover.

Hydrocarbon generation and migration have occurred within the McArthur River area, and, perhaps more significantly, the presence of live hydrocarbon shows in several of the 1982 coreholes indicates that these hydrocarbons may exist in volatile, recoverable form. None of the coreholes was located to test for structurally-trapped hydrocarbon; the degree of preservation may be expected to be much higher in traps where the hydrocarbon is protected from degradation. The possibility also exists that in oil-saturated reservoirs the extensive diagenetic effects observed in most reservoir samples were inhibited. This is based on the early timing of oil migration inferred from petrographic analysis. Therefore, although most porosity-permeability tests showed poor reservoir quality, the actual conditions in an oil-saturated reservoir may be much better. The other elements necessary for trapping large accumulations of hydrocarbons are also present. There are numerous shales and claystones throughout the sequence that would form ideal seals, and several unconformities that may have performed in the same manner. Numerous folds and faults are observed in the area and are interpreted to form abundant structural traps throughout the sequence. In addition, deposition of many of the units is considered to be fault-controlled, and strong lateral facies changes associated with these faults are observed in outcrop, and are expected to provide stratigraphic trap plays at depth.

Based on these observations and the data compiled in this report, the McArthur River area, although certainly a high risk area, presents viable hydrocarbon exploration targets which merit further exploration.

3. RECOMMENDATIONS

1. Follow up the 1982 field program with a seismic program which concentrates on the most prospective areas of O.P. 191 and O.P. 198. These areas are:

   A. The Broadmere Anticline, located in the western portion of O.P. 191, north of the Mallapunyah Fault.

   B. The St. Vidgeon area, located in the northwestern portion of O.P. 198.

   C. The Cox River area, located in the southwestern corner of O.P. 198.

   A full discussion of these areas and their prospectivity is presented in Section 11.

2. Perform geologic mapping and limited sampling along the 1983 seismic trails to fully evaluate and interpret the 1983 seismic data.

3. Integrate the results presented in this report with results of the 1983 seismic program in order to:

   A. Demonstrate the drillable structures/prospects within the seismic program areas, and assign a priority rating based on probability of success, potential reservoir volume, and the anticipated value of the geological data that would be obtained by drilling.

B. Determine whether the combined results warrant continued exploration, or if the area should be dropped. If the former, choose and evaluate potential drill-sites each programmed to approximately 8,000-10,000 feet (2,438 - 3,048 metres) in depth. Assess the relative merits of drilling slim-hole wells or conventional exploratory wells to this depth. Acquire Australian partner/partners to obtain the required 50% Australian interest, and to reduce Amoco interest to 25%. Drill one or more exploratory wells.

4. If further exploratory work is warranted:

A. Evaluate the feasibility of conducting further fieldwork and drilling shallow (600 to 800 metre) coreholes in the northwestern corner of O.P. 198, in order to examine facies variations, source quality and reservoir quality of the McArthur Group in the St. Vidgeon area.

B. Conduct additional detailed facies studies of the Barney Creek, Yalco, Stretton and Cobanbirini Formations, and any other formations considered critical to the generation, migration and entrapment of hydrocarbon in the Permit areas.

5. Cut additional plugs from the cores to further evaluate reservoir rock characteristics. Slab the core and ship one slab to Tulsa Core Facility for storage and further sedimentological work.

6. Continue the interpretation of gravity and airphoto data.

4. CONCLUSIONS

The McArthur Basin consists primarily of middle to upper Proterozoic sediments. Three major groups are defined; the Tawallah Group, the McArthur Group and the Roper Group. The maximum cumulative stratigraphic thickness of all three groups is 16,000 meters, although the total thickness is probably much less in any given locality. Primary prospectivity lies in the McArthur and Roper Groups, which form the upper 10,000 meters of described section.

Three major depocenters are recognized in the McArthur River area. The Batten and Broadmere Troughs are linear, fault-bounded grabens within which thick sequences of dolomitic sediments of the McArthur Group were deposited. A gentle downwarp was centered west of Bauhinia Downs on the Bauhinia shelf during Roper Group time, forming the other major depocenter. In each area the estimated total thickness of Proterozoic sediments is in excess of 5,000 meters.

1. We consider that the area displays ample evidence that hydrocarbons were generated in the geologic past, and that reservoir rock quality, nature of sealing units, structural history and the timing of hydrocarbon emplacement could have contributed to the trapping and preservation of accumulations of hydrocarbons.

2. The following prospective areas and possible traps have been identified:

A. A large anticline in the western portion of O.P. 191.

B. *En echelon* folds in the western and northwestern portions of the permits.

C. Structural and stratigraphic traps adjacent to growth faults, such as the Emu and Tawallah Faults.

D. Anticlines within the Batten Trough.

E. Stratigraphic traps within Roper Group clastics and McArthur Group carbonates and clastics.

The western portion of the permits is considered more highly prospective, because more of the sedimentary section is preserved there. In addition, Roper Group clastics are thicker and there are numerous anticlines at surface. Other areas are still considered prospective although the preserved sedimentary sequence is often thinner. Also, rather rugged terrain in some areas precludes the use of Vibroseis trucks as a seismic source.

3. Several formations from both Roper and McArthur Groups have source rock potential, based on both 1981 and 1982 results. The Barney Creek Formation in the middle McArthur Group is believed to have the greatest source potential, although it was untested by the 1982 corehole drilling program. A total of 37 samples were analyzed from a variety of coreholes prior to 1982 and indicated an average total

organic carbon (TOC) content of 1.5 weight percent, typically in the peak-oil stage of thermal maturity. The Yalco Formation appears to have the best source rock potential of the units tested by the 1982 corehole program, averaging 1.6 weight percent TOC with oil-prone, algal, organic material in an early-peak to peak-oil stage of thermal maturity. The Lansen Creek shale, encountered in Coreholes 82-1 and 82-8, displays good to fair source rock potential, averaging 0.7 weight percent TOC. The thermal maturity of this unit varies between the two coreholes, with the samples from Corehole 82-1 showing peak oil to past-peak oil stage and those from Corehole 82-8 showing a pre-generation to early-peak oil stage of maturity. The Lynott Formation, encountered in Corehole 82-5, has fair to non-source quality, averaging approximately 0.4 weight percent TOC in an advanced stage of catagenesis. The Mainoru, Crawford and Dungaminnie Formations all have low TOC values in the non-source range. Of the other units not tested by the 1982 program, the Reward Dolomite and Corcoran Shale may have some source potential.

4. Adequate reservoir potential is expected to exist in the sub-surface in several formations. These are, in order of quality, the Hodgson Member of the Abner Formation (avg. Ø = 11.5%, avg. k = 266 md); the Bessie Creek Formation (avg. Ø = 9.6%, avg. k = 111 md); the Broadmere Sandstone Member of the Cobanbirini Formation (avg. Ø = 13.7%, avg. k = 53.2 md); the Stretton Formation (avg. Ø = 9.5%, avg. k = 27.0 md); the Yalco Formation (avg. Ø = 7.1%, avg. k = 137.1 md); and the Looking Glass and Balbirini Formations with fair to poor reservoir potential. Conglomeratic facies developed in some of these

clastic units as a result of growth faulting are also potential reservoirs.

5. No adequate reservoir potential is expected to exist in the sub-surface in several formations. These are the Limmen Sandstone, Mainoru Shale, Dungaminnie Formation, Crawford Sandstone, Lynott Shale, and the Jalboi and Arnold Members of the Abner Formation.

6. Within the quartz arenites (Abner, Bessie Creek and Cobanbirini Formations) porosity and permeability have been diagenetically reduced. These diagenetic processes are, in their approximate order of importance, deposition of authigenic quartz overgrowths, deposition of authigenic illite and chlorite, deposition of authigenic hematite, pressure solution of quartz, and deposition of authigenic kaolinite. Bitumen is locally observed in the Broadmere Sandstone Member of the Cobanbirini Formation. Where it is in contact with authigenic quartz and clays, the hydrocarbon appears to have inhibited the growth of these secondary minerals. An early timing of the migration of hydrocarbon is implied, with resulting preservation of reservoir quality from diagenetic effects in an oil-saturated reservoir.

7. Within the dolomitic McArthur Group units (Yalco, Stretton, Looking Glass and Balbirini Formations) porosity and permeability were frequently enhanced by the formation of vuggy porosity, possibly in vadose weathering zones. Subsequently, they were reduced by the deposition of quartz and silica, followed by sparry dolomite, in pore spaces. Bitumen is locally observed in the Yalco, Stretton and

Balbirini Formations. Where it is in contact with secondary quartz and dolomite crystals, the hydrocarbon shows evidence of having migrated into the formations after the deposition of secondary quartz and silica, and either before or concurrently with the formation of sparry dolomite. Oil-saturated reservoirs within these units may therefore have been protected from the diagenetic reduction of reservoir quality resulting from the deposition of secondary dolomite.

8. Surficial weathering typically enhances porosity and permeability of outcrops of both dolomites and quartz arenites, making them generally unrepresentative of subsurface conditions. However, surface outcrop characteristics, such as weathering style, resistance to erosion, friability etc., appear to be qualitatively indicative of subsurface reservoir properties. The enhancement of porosity and permeability in quartz arenites occurs through the conversion of illite and chlorite to kaolinite, removal of hematite, minor removal of quartz and the dissolution of lithics and feldspars. The enhancement of porosity in dolomitic units occurs through the preferential dissolution of slightly more soluble material, and frequently is localized along fractures.

9. Numerous shales, and possibly also unconformities, could act as seals above potential reservoir units. There are numerous possibilities for both structural and stratigraphic hydrocarbon trapping.

10. A large graben-like feature paralleling the Batten Trough has been identified by E. Wicherts, in the western portion of O.P. 191, and has

been informally named the Broadmere Trough. Fieldwork completed in 1981 confirmed the presence of upper McArthur Group sediments on the eastern flanks of the feature. Preliminary interpretation of 1982 test seismic data in the area indicates the presence of these units at depth within the basin. A similar McArthur Group sequence to that present in the Batten Trough is anticipated to occur at depth. The Broadmere Trough is interpreted to represent a pull-apart basin. A large anticline, with estimated closure on the order of 110 square kilometers occurs within it and is presently considered to be a primary exploration target. Gravity data appear to indicate that this structure is present at depth. Late left-lateral movement along the Mallapunyah Fault apparently caused the folding.

11. The presence of a major east-west ridge, or hingeline, in the southwestern corner of O.P. 198 is indicated by gravity data and surface geologic data. McArthur Group sediments undergo facies changes across this feature, which is also the northern limit of the Broadmere Trough.

12. The presence of an emergent McArthur Group paleohigh, to the east of Corehole 82-4, is indicated by gravity and core data. Clastic sediments shed off this high are a potential exploration target.

13. The existence of a large east-west trending basin in the northwestern corner of O.P. 198, of probable McArthur Group age, is indicated by gravity data. This had previously been interpreted to be a basement high. A major tectonic ridge, the Urapunga Fault Zone, forms the

northern boundary of this basin and highly influenced sedimentation within it.

14. The following aspects of faulting in the permit area have been noted:

A. Growth on northwest-trending faults caused changes in thickness and facies of contemporaneous sediments. Previously, growth had been recognized only on north-trending faults. These facies and thickness changes could result in stratigraphic or structural/stratigraphic traps.

B. Zones of silicification and mineralization have been recognized along various faults and may have resulted from zones of formerly higher heat-flow associated with the faults. Rock samples taken from the vicinity of such faults may therefore not be representative.

C. Faults in the northwestern portion of O.P. 198 (St. Vidgeon area) appear to be right-lateral, strike-slip faults with associated *en echelon* folding.

15. The following stratigraphic/sedimentary features are of note:

A. The distal turbidites encountered in the Middle Lynott Formation in Corehole 82-5 were probably deposited in response to vertical motion along the Tawallah Fault and are the distal equivalent of Middle Lynott conglomerates outcropping near the fault.

B. Corehole 82-6 established the eastern limit of the Stretton Formation conglomerate in the vicinity of Catfish Hole waterhole. Clastic units such as this, shed off northerly and northwesterly-trending growth faults, are good potential reservoirs.

C. Previously unmapped units of the Cobanbirini Formation in the western portion of O.P. 191 have been recognized and subdivided.

5. REGIONAL GEOLOGY

5.1 Geological Setting

The McArthur River Area is situated within the McArthur Basin, a sequence of unmetamorphosed Proterozoic sediments (Figures 1-1 and 7-1) which comprises a portion of a belt of Proterozoic rocks extending from Arnhem Land, Northern Territory to Mt. Isa, Queensland. These Proterozoic rocks are bounded and overlain by Mesozoic sediments of the Carpentaria Basin to the northeast, and by lower to middle Paleozoic sediments of the Georgina Basin to the south and southwest.

The McArthur Basin, an inferred linear, marine embayment (Plumb, et al., 1980), is bounded to the northwest by the Nanambu Complex and to the southeast by the Murphy Inlier, which existed as a tectonic-topographic expression throughout Carpentarian Time.

The Lawn Hill Platform, to the southeast of the Murphy Inlier, consists of a sequence of platform carbonates and basinal clastics, and represents a gradation into the Mount Isa Orogen, a probable former continental-margin belt (Plumb, et al., 1980). Right-lateral motion on a northwesterly-trending system of wrench faults is thought to have resulted in normal movement on a number of north-trending faults, with the consequent formation of a number of pull-apart basins. The component wrench faults include the Calvert, Mallapunyah and Bulman Faults (Figure 7-1). Within the McArthur Basin, a fault-bounded graben-like feature known as the Batten Trough apparently developed as a result of normal movement along the northerly-trending Emu and Tawallah Faults, which resulted from right-lateral displacement along the Mallapunyah Fault. A similar graben-like feature, indicated by gravity data, occurs to the west of the Four Archer's Fault (Enclosure 7-4) and has been informally named the Broadmere Trough.

A tectonic ridge, known as the Urapunga Tectonic Ridge (Enclosure 7-2) is oriented east-west in the northern part of O.P. 198 and acted as a major hingeline during the Carpentarian (McArthur Group).

Three distinct groups of sediments have been recognized within the McArthur Basin: (1) the Tawallah Group, consisting of lower Proterozoic sandstones, mudstones, volcanics, and minor carbonates, overlain by (2) the Carpentarian-age McArthur Group, composed of shallow-water carbonates, mudstones, clastics and minor volcanics, and (3) Roper Group sediments consisting of blanket sandstones, siltstones, shales, and minor carbonates, of Carpentarian to Adelaidian age. Composite maximum stratigraphic thickness within the Permits is about 16,000 metres, of which the McArthur and Roper Groups comprise the upper 10,000 metres.

Tawallah Group sedimentation apparently pre-dated formation of the Batten Trough, although north of the Urapunga Tectonic Ridge a graben-like feature existed. McArthur Group sedimentation was highly influenced through the formation of graben-like basins by pull-apart motion developed through right-lateral movement along the northwest-trending wrench system. Initial deposition of lower McArthur Group carbonates in gently downwarping troughs was superceded by initiation of normal movement along northerly-trending faults, such as the Emu and Tawallah Faults within the permit acreage. Alternating normal motion along these faults allowed development of the Batten Trough in a double half-graben manner. Resultant sediments deposited include organic mudrocks, turbidites, and minor carbonates. Cessation of fault movement, coupled with slower downwarp of the Batten Trough, allowed deposition of upper McArthur Group shallow water, high energy carbonates. Movement along the Urapunga Fault Zone allowed deposition of coarse clastic units.

A period of general uplift and erosion of unknown duration preceded general downwarp to the west and progradation of thick Roper Group clastic sediments from the west. A minimum of three transgressions followed by deposition of regressive clastic sequences occurred during this period (Enclosure 8-10).

Deformation of the sequence during the late Proterozoic resulted from initial right-lateral movement along the northerly-trending faults followed by reactivation of the northwest-trending wrench system by left-lateral movement. A number of *en echelon* domes and basins formed as a result.

Since the Proterozoic, minor marine transgressions deposited a sequence of very thin, undeformed, flat-lying Cambrian clastics and carbonates, Cretaceous clastics, and Tertiary carbonates. This thin veneer has been largely removed by persistent, severe, surficial weathering and erosion, and is preserved only locally. For instance, various Cenozoic lateritic profiles exist throughout the area and locally are continuing to form at present.

Proterozoic sediments in the Permit acreage are of interest for hydrocarbon exploration as they are unmetamorphosed, contain abundant potential source and reservoir rock horizons, and the area has remained essentially stable since the late Proterozoic.

5.2 Surficial Weathering

The effects of surface chemical weathering have profound consequences on the apparent reservoir and source quality of all formations exposed at the surface. These effects, which have acted to leach all mobile organic and inorganic constituents from surface exposures, have such extreme magnitude because of the great age of the sediments, long time-span of sub-aerial exposure, and the severe sub-tropical climate of the region. The principal conclusion from this section of the study is that surface samples provide reliable information only on the depositional fabric and the primary sedimentary structures, which are preserved despite weathering. We do not consider quantitative porosity, permeability or organic geochemical data from surface samples to be representative of that expected in the subsurface.

5.2.1. General Considerations

Two types of outcropping lithologies are of prime importance in our consideration of the effects of weathering; mature quartz arenites (potential reservoirs) of the Roper Group and organic shales (potential sources) of both Roper and McArthur Groups. In addition, weathering of dolomites may create zones of enhanced porosity, and is locally important.

The quartz arenites, principally of the Abner, Bessie Creek and Cobanbirini Formations, are seen in the unweathered subsurface to consist of more than 90 percent quartz with minor amounts of residual detrital feldspar, lithic grains, authigenic clays, iron oxides, pyrite, and locally hydrocarbon. Detrital quartz grains range from very fine to very coarse in size and are typically rounded to very well rounded. Most are monocrystalline and non-undulatory, indicating a probable plutonic or volcanic provenance, but strained and/or polycrystalline grains are locally abundant, typically in the Bessie Creek Formation. These types of grains are believed to derive from metamorphic terrains. Quartz overgrowths are ubiquitous, generally associated with minor suturing (pressure solution) of the primary grains.

The formation of overgrowths appears to have been the most important process acting to reduce porosity and permeability. Authigenic kaolinite, chlorite and illite are also present.

It has been known for many years that some minerals tend to weather faster than others. This weathering series, which is in general the reverse of the Bowen Reaction Series, is summarized in Tables 5-1 and 5-2.

Empirical evidence of this relationship was provided by Wahlstrom (1948) who studied a paleo-weathering profile over a Paleozoic granodiorite. The observations from this study are summarized in Figure 5-1 and Table 5-3. Note the decrease in silica caused by breakdown of silicate minerals other than quartz. Also note the large relative increase in Al_2O_3, Fe_2O_3, and K_2O due to the high stability of these species in the weathering environment. Both Al_2O_3 and K_2O are fixed in the profile by their inclusion in clay minerals, particularly illite.

When considering the weathering of mature quartz arenites such as those present in the Roper Group, the picture becomes a little clearer. Any unstable, mafic components have been weathered and converted to clay minerals and iron oxides during previous sedimentary cycles, and so the primary constituents of these sandstones are quartz grains, minor feldspar and rare labile rock fragments, plus authigenic minerals. Allogenic clays are rare or lacking. Figure 5-2 shows the types of weathering reactions that convert primary minerals on the left to weathering products on the right. Stability of the primary minerals increases from top to bottom.

Illite is fairly stable, but may be converted to kaolinite under acidic conditions with the accompanying formation of free silica which is typically removed from the system by surface runoff and potassium ions. Chlorite apparently undergoes a similar reaction, with the excess iron eventually forming stable iron oxides. Any remaining detrital feldspars will degrade to form gibbsite and/or kaolinite with release of free silica and potassium ion. Quartz, the most stable of all primary constituents, will be dissolved only if the amount of free silica in the groundwater falls below saturation levels. This tends not to occur easily for two reasons:

1) Circulating groundwaters tend to be acidic, favoring kaolinization and the release of free silica.

2) The solubility of silica becomes lower with lower Ph, causing a preference to deposit silica, rather than dissolve it (Figure 5-3).

The free silica created by all the above processes was apparently removed from the system by circulation of waters and was not re-precipitated. Precipitation of silica in a shallow, low temperature environment nearly always results in opaline material. One reason is that the solubility of amorphous silica rises extremely rapidly with increased temperature (Figure 5-10) and becomes correspondingly harder to precipitate. In consequence, low temperatures favor precipitation of an unordered phase (opal) while high temperatures favor precipitation of more ordered phases (quartz). The difficulty of precipitating crystalline quartz at surface conditions nearly always establishes opal solubility as the control on precipitating secondary silica. The euhedral faces on quartz overgrowths in Roper Group sediments and preservation of chalcedony cements in the deeper Yalco Formation indicate that the secondary quartz in the Roper Group sandstones did not originate as opal cements with later conversion to quartz.

Diagenetic history is fully discussed in Section 9 (Reservoir Properties).

These relationships are also summarized in Figure 5-4. Note that kaolinite is stable when free quartz in solution is saturated and the Ph lies between 7 and 4 (acidic conditions). Also note the extreme stability (non-solubility) of hematite at Ph greater than 2.

The general chemical composition of the major types of sedimentary rocks is summarized in Figure 5-5. Also shown is the chemical composition of weathering end-products, bauxite (gibbsite) and laterite, and the trend in the change in composition that surface weathering of sandstone causes (arrow). The less mature the sandstone, the higher the unweathered content of calcium and magnesium will be. The arrow shown is for a moderately mature quartz arenite with some feldspars and detrital clays present.

Within the McArthur Group, sediments are dominantly dolomite-rich and quartz-poor. As expected, they respond to surficial weathering very differently than do the quartz arenites of the Roper Group.

Evidence from outcrop suggests that solution of the dolomite framework of these rocks occurs in the shallow weathering zone, forming vugs and enlarging fractures. The process is confined to the vadose zone, which is typically characterized by large volumes of acidic water moving downward to the ground-water table. The process of solution, when carried forward to an extreme degree, results in continued enlargement of cavities to form caverns or zones of highly porous rock a few metres or tens of metres thick. The larger cavities, associated with weathering surfaces of long duration, are frequently filled with collapse breccia. These solution breccias are frequently seen in outcrop, and several have been observed in core as well.

Below the vadose zone, re-precipitation of carbonates frequently occurs (Chafetz, 1972). This process apparently accounts for the late-stage sparry dolomites commonly filling vugs and fractures. In addition, silica cements are frequently observed lining cavities in McArthur Group units (Appendix II). They usually appear to have been deposited as amorphous silica, and therefore were deposited in a very shallow environment. The silicification of weathering carbonates is a frequently reported process (Chafetz, 1972; Howell, 1931).

5.2.2. Climate

The climate of a region affects the degree and style of weathering. In general, laterites and bauxites result from weathering in areas with high annual rainfall and tropical climates, which produce silica undersaturation in the groundwater. The intense weathering, in addition to leaching silica, strips sodium and calcium from smectites and potassium from illite, leaving kaolinite or gibbsite. In moist, temperate climates, illite and/or smectite are preserved in soil profiles due to less-extreme weathering.

The formation of ferruginous horizons and crusts is associated with fluctuating water tables and seasonal rainfall. They result from transport of dissolved iron from actively weathering parent rock to the air-water interface. The strongly seasonal rainfall in the McArthur River area accounts for the prevalence of this type of weathering profile.

Silicification associated with weathering is a process which is similar to the formation of caliche. Silica-bearing waters from an actively-weathering zone reach an area where the rate of evaporation exceeds the rainfall. The general absence of such silicified crusts from the McArthur River area is accounted for by the well-coordinated drainage system and the relatively small effect of evaporation.

The regional variations in rainfall and temperature over Australia are shown in Figure 5-6. Note the high winter and summer temperatures and high median rainfall values in the McArthur River area. These characteristics, coupled with the strongly seasonal pattern of rainfall, combine to give a hot, sub-humid, dry winter (BSwh) climatic classification (Table 5-4). The pattern of climatic zones is illustrated on Figure 5-7. The climatic variations combine with regional topographic and lithologic variations to define the nature of weathering profiles (Figure 5-8) and degree of preservation of deep weathering profiles (Figure 5-9). The McArthur River area lies within the western plateau with little or no ferruginous or siliceous crusts developed. As indicated above, this apparently results from the high annual rainfall and well-coordinated external drainage which removes excess silica-bearing waters. This area is one of partial-to-complete preservation of the deep weathering profile, which is kaolinitic and probably lateritic. In the sediment being transported to the ocean basin to the North, most of the clay-sized material is kaolinitic, supporting this conclusion.

5.2.3. Conclusions

From the above discussion of weathering processes and climatic controls, we may draw the following conclusions:

1. The current style of weathering in the McArthur River area is one of deep kaolinite profiles and a general lack of both ferruginous duricrusts and siliceous crusts or silcretes. The preservation of illite is not favored.

2. A period of more arid climatic conditions in the geologic past could have favored surface silicification. Examples may be represented by chalcedony zones below local unconformities in the Yalco Formation.

3. The principal weathering processes in the Roper Group quartz arenites are:

   a. Conversion of illite to kaolinite under near-surface acidic conditions with accompanying release of free silica and potassium ions.

b. Conversion of chlorite to kaolinite under near-surface acidic conditions with accompanying release of iron, magnesium and free silica.

c. Degradation of detrital feldspar to kaolinite, with possible illite/smectite intermediate products.

d. Conversion of iron released in the breakdown of chlorite to stable iron oxides, largely hematite, within the upper weathering layer or within active aquifers. Oxidizing fresh waters of probable low Ph are implied in both environments.

e. Localized minor removal of authigenic quartz overgrowths.

f. Degradation of undifferentiated, rare labile rock fragments to clays and iron oxides.

4. The secondary quartz overgrowths observed in the quartz arenites formed in the deep subsurface, and the silica pore-fillings in dolomitic units formed in paleo-weathering zones. This conclusion is partly based on the relative solubilities of quartz and silica versus temperature (Figure 5-10).

5. Minor enhancement of porosity, and moderate to major enhancement of permeability are expected in the surface outcrops of the quartz arenites, primarily due to conversion of pore-choking illite and chlorite to less restrictive kaolinite and hematite.

6. Zones of enhanced porosity and silicification a few metres to tens of metres thick are associated with dissolution of carbonates in the vadose zone. They are associated with unconformities and are frequently underlain by zones of reprecipitation of carbonates.

7. Depths of weathered zones (saprolites) are highly variable and depend upon the accessibility of freely circulating ground water within the pore system. Values in excess of 100 metres are reasonable in porous zones open to the surface and may be recognized by the mineralogical changes discussed above.

8. Organic compounds are especially susceptible to chemical weathering. Active ground-water flow creates strongly oxidizing conditions which quickly destroy the kerogen within potential source beds. Estimates of source richness based on TOC values are sensitive to this, but thermal maturity and convertability estimates based on hydrocarbon ratios and elemental ratios are extremely sensitive and may frequently be in error due to the slightest weathering.

6. EXPLORATION HISTORY

Historically, exploration for various types of mineralization has been carried out within the McArthur River region. Initial discovery of lead-zinc-copper mineralization in the vicinity of McArthur River Homestead was made by Tom Lynott in 1887. Other periods of interest in the area occurred in 1889, in 1909 with the drilling of Cook's deposit, in 1918 with the discovery of copper mineralization at Coppermine Creek, and in 1953 with Consolidated Zinc Pty. Ltd. drilling the Bald Hills prospect. As a result of a large prospecting program commenced by Mount Isa Mines Ltd. in 1955, two major discoveries were made. These were the Reward prospect (since abandoned) and the H.Y.C. (Here's Your Chance) deposit (Plumb and Paine, 1964; Smith, 1972), the world's largest lead-zinc deposit. Since that time, abundant lead-zinc exploration has occurred throughout the region. Various other deposits exist in the area such as the Yah Yah copper deposit, the Darcy's copper deposit, workings in the Amelia Creek area, and Conzinc-Rio Tinto Almalgated Exploration's Eastern Creek lead-barite prospect.

Mention of bituminous rocks present within the sequence has been presented in various publications. In 1911, L.C. Ball referred to some bituminous mudstones located 5 miles upstream from Borroloola along the McArthur River (N. Wilkins, pers. comm.). These were assumed to be Carboniferous in age; in actuality, this unit is probably the Corcoran Formation.

Host rocks for the H.Y.C. deposit's sulphide mineralization consist of carbonaceous, pyritic, and dolomitic silts and shales of the Barney Creek

Formation (McArthur Group). Also, various unpublished, verbally transmitted accounts of bituminous sequences such as the Wollogorang Formation (Tawallah Group) and Lynott Formation (McArthur Group) exist.

Amoco Production Company (International)'s interest in the region was initiated by N. Wilkins, a geologist with Amoco Minerals Australia Company, through various written communications; he also submitted samples from the Barney Creek Formation for source rock analysis. Since that time, he has maintained participation in the project through aiding in geologic fieldwork, familiarizing past and present members of the project with the structure and stratigraphy of the region, helping select coresites, and sharing geologic concepts on the area.

In 1979, Amoco Minerals was actively exploring for Barney Creek sub-basins similar to that at the H.Y.C. deposit. In November of 1979, P. Benson, III (geologist-Amoco International Oil Company) and L. Ross (organic geochemist-Amoco Production Research Center), along with N. Wilkins, sampled a number of cores from the region. In December 1979, Kennecott Copper Company, while drilling a minerals exploration corehole on Amoco Minerals acreage in the Glyde River area, encountered a flow of gas from the Coxco Dolomite, which immediately underlies the Barney Creek Formation. The gas flow subsequently ignited, finally being extinguished by rain.

Application was made by Amoco Production Company (International) in January 1980 for an exploration permit in the region. Kennecott subsequently applied for adjoining acreage to the north. As a result, two five-year permits were issued: O.P. 191 to Amoco on September 11, 1980 and O.P. 198

to Kennecott on August 21, 1981. A cross-assignment agreement was reached during February 1982 between Amoco and Kennecott.

6.1 1981 Field Program

From May through to late July 1981, geological fieldwork was conducted within the McArthur River permits by Amoco Australia Petroleum Company. Five geologists were involved in the program: N. Wilkins, P. MacKay, F. Gallagher, G. Eden, and P. Dorrins. The purposes of this field program were to identify, describe, and sample potential source and reservoir rock horizons within the Tawallah, McArthur, and Roper Groups; to conduct an initial stratigraphic analysis; to conduct a regional study of deformation; and to identify and describe structural and/or stratigraphic hydrocarbon traps. The field program was two-fold in nature:

1. Six weeks of drilling utilizing a Jackrow 18 diamond drilling rig which had the capability to core to a depth of 60 metres in NQ diameter (47 mm) core. These coreholes were drilled as an attempt to obtain unweathered potential source and reservoir rocks.

2. Ten weeks of geological fieldwork involving study of various Proterozoic units in the region. This involved extensive sampling, tracing out units throughout the area in order to observe facies changes, measuring structural attitudes, describing structural features such as faults and folds, and describing the core.

Enclosure 1-2 shows the corehole locations and outcrop sample locations.

Mr. Larry Ross, a geochemist from the Tulsa Research Center, visited the area in order to sample the cores for potential source rocks. A number of surface samples also were submitted for source rock analysis; however, it was found that most of them were too highly weathered and leached to allow preservation of any organic carbon previously present. Some surface samples analyzed as good, oil-prone, source rocks (Gallagher and MacKay, 1981); these were sampled in areas of recent exposure in stream cuts. Similarly, the weathering profile, as observed in core, in some cases extended down below 60 metres in depth. Therefore, doubt remained as to whether any of the coreholes fully penetrated unweathered lithologic units.

A number of prospective source and reservoir rock horizons were identified throughout the McArthur and Roper Groups, and numerous potential hydrocarbon traps were identified throughout the region. In particular, abundant domes were observed in the western portion of O.P. 191 and O.P. 198. A number of recommendations were made considering results of the 1981 program. These are summarized below:

1. Drill deeper (±500 metres) coreholes to get below the weathered layer in order to sample unweathered source rocks. A blow-out preventer would be required for the rig.

2. Conduct a more detailed stratigraphic analysis of the region.

3. Evaluate the source-rock potential of fine-grained clastics in the Roper Group and carbonates in the McArthur Group.

4. Analyze prospective structures in detail.

5. Log coreholes (including those drilled prior to Amoco's interest in the area) with downhole logging tools.

6. Conduct a test seismic program utilizing dynamite and vibroseis.

6.2 1982 Field Program

From April through to September 1982, a second geological field program was carried out by Amoco Australia Petroleum Company in the McArthur River region (see Enclosure 1-1). An anthropological survey was carried out by P. Ray (Amoco Minerals) and A. Palmer (anthropologist) in order to ascertain that the proposed coresites and test seismic lines did not violate any sites of significance to aboriginals residing in the region (see Appendix VI). Following this, the fieldwork proceeded. Initially, the program was intended to be two-fold in nature: drilling of up to eight 600 metre coreholes from April through to mid-June, overlapping with field mapping, facies analysis and structural analysis operating from June 1, 1982 through to mid-August. The coring involved one to two geologists (P. Dorrins, N. Wilkins), and the field work involved two to occasionally three geologists (P. Dorrins, M. Womer, N. Wilkins) and two geological field assistants (W. Espegren, D. Puls). Various factors, including weather, availability of a blow-out preventer for the rig, and the breakdown of the road train transporting the rig, delayed commencement of the drilling program until the end of April. The corehole locations and outcrop sample locations are shown on Enclosure 1-2, and the stratigraphic intervals sampled by the cores are shown on Enclosure 8-2.

6.2.1 Coring Program ODH

This involved drilling eight NQ diameter (47 mm) coreholes totalling 3687 metres. A Longyear 44 drilling rig, designed to be slung between coresites by Bell 206-B Jet Ranger helicopter, was utilized. An average of between 37 and 44 helicopter loads were required in order to move the rig, pumps, drill rods, and associated equipment between drill sites. Helicopter rig moves ranged between 15 to 35 kilometres distance, involving 25 to 37 hours flying time per move.

Criteria for choosing coresites included the following elements:

1. Stratigraphic intervals to be cored (from potential source and reservoir rock standpoint).

2. Structural location. All sites were to be preferentially located near anticlinal axes if possible, in order to avoid effects of artesian water flushing as found in synclinal features. This was done in order to obtain representative samples of potential reservoir rock.

3. Availability of surface water for drilling operations. Both the pump and length of polyhose required coresite locations within 2

kilometres horizontally and 30 metres vertically of surface water.

4. Proximity to faults: to avoid drilling problems, sites were not chosen in areas of known extensive faulting.

5. Logistical considerations: distance between coresites no greater than approximately 35 kilometres.

6.2.1.1 Corehole 82-1

Located at grid coordinates 5965-321133, Corehole 82-1 was spudded to the north of a large, north-plunging anticline (Enclosure 6-1). This corehole was drilled to evaluate the source rock potential of mudstones and the reservoir rock potential of sandstones within the Cobanbirini Formation. It encountered 25 metres of Crooked Creek Limestone (laminated, micritic limestone), 197 metres of the Cat Creek Member (interbedded greenish-black silts and shales), 152 metres of Broadmere Sandstone (quartz sandstone) and 195 metres of Lansen Creek Member (interbedded black mudstones, and whitish-gray, silty very fine-grained sandstones). Bitumen was observed within the Broadmere Sandstone Member as irregular clots and porosity infills. A kerosene-like volatile hydrocarbon or light oil weeped out from the lower portion of the Broadmere Sandstone, quickly evaporating. Abundant volatiles with a sulphurous kerosene-like odor were noted within the Lansen Creek Member.

Apparent degradation of drill-rod grease by these light hydrocarbons may have been the cause of repeated sticking of the drill string and resultant breaking of drill rods.

Due to the pungent odor of light hydrocarbons present at the coresite, the proximity to the top of the porous Bessie Creek Sandstone (see Section 8 (Stratigraphy)) and the continual sticking of the rod string and breaking of drill rods, drilling was terminated at a depth of 569 metres.

6.2.1.2 Corehole 82-2

Located at grid coordinates 5966-353318, Corehole 82-2 was spudded near the culmination of a small, faulted dome within the Mainoru Formation (Enclosure 6-2). This location was chosen in order to evaluate the source rock potential of carbonaceous shales within the Mainoru, the reservoir rock potential of the Limmen Sandstone, and the source and reservoir rock potential of the upper McArthur Group. A reverse fault zone was encountered within the Limmen and a repeated section of Mainoru and Limmen Sandstone was intersected. The corehole attained a depth of 494 metres within dark-colored mudstones of the Dungaminnie Formation. Due to continual sticking of drill rods within the Mainoru, drilling beyond a depth of 494 metres was impossible.

6.2.1.3 Corehole 82-3

Situated at grid coordinates 5966-285605, Corehole 82-3 was spudded a few metres below the top of the Hodgson Sandstone

Member of the Abner Sandstone Formation, near the crest of an anticline (Enclosure 6-3). This corehole was designed to test the Abner Sandstone Formation as a potential reservoir, the Crawford Formation as a potential source and reservoir rock unit and the Mainoru as a potential source rock horizon. The Abner Sandstone, Crawford Formation, and upper part of the Mainoru Formation were intersected. Artesian water flow was encountered at approximately 260 to 266 metres depth within the Arnold Member. Total depth of the corehole was 592 meters, bottoming in the Mainoru.

6.2.1.4 Corehole 82-4

Located at grid coordinates 5967-130867, Corehole 82-4 was spudded within upper McArthur Group sediments at the culmination of a faulted dome (Enclosure 6-4). This corehole was drilled in order to evaluate the source and reservoir rock potential of McArthur Group sediments in this region, as well as to acquire stratigraphic information on them. Lithologies encountered include a previously unmapped sequence of carbonates, coarse clastics, and red beds. The corehole attained a depth of 541 metres.

6.2.1.5 Corehole 82-5

Situated at grid coordinates 6065-037062, Corehole 82-5 was spudded within the lower beds of the Donnegan Member of the Lynott Formation. Structurally, this corehole was located within an anticlinal feature, to the west of a small fault (Enclosure 6-5). This corehole was drilled in order to evaluate the source rock potential of the Lynott Formation and the reservoir rock potential of sandy interbeds within the sequence. As the coresite was established in the vicinity of the Lynott depocentre, a formational thickness on the order of 1 kilometre was anticipated. Lithologies intersected by the corehole include interbedded greyish shales, siltstones, and fine-grained sandstones with nodular anhydrite pseudomorphs in the Donnegan Member. Interbedded gray to black sands, silts and shale, forming thin turbiditic sequences, comprise the Middle Lynott Formation. The corehole attained a total depth of 455 metres; drilling could not continue beyond this depth as a fault was intersected and severe problems with wedging of core in the core barrel ensued.

6.2.1.6 Corehole 82-6

Located at grid coordinates 6164-319527, drilling commenced within the Cambrian Bukalara Sandstone, approximately 200 metres to the east of outcropping conglomeratic facies of the Stretton Sandstone (Enclosure 6-6). Evaluation of the reservoir rock potential of this unit and other possible coarse clastic units, and of the Yalco Formation, and the source rock potential of mudrocks within the sequence, was the basis of locating the coresite in the vicinity of the Emu Fault Zone. Clastic breccia wedges had been previously recognized along the Emu Fault Zone. The corehole attained its programmed depth of 300 metres, encountering Looking Glass mudstones, a condensed Stretton Sandstone consisting of interbedded pebble-sized conglomerate-breccia and coarse litharenite, (representative of the easterly lateral extent of the conglomeratic facies), Yalco shallow-water carbonates, and interbedded mudstones and dolarenites of the Donnegan Member. Bitumen was present within porous Stretton conglomeratic beds and within Yalco stromatolitic units.

6.2.1.7 Corehole 82-7

Spudded at grid coordinates 6064-064445 within the Beetle Springs Anticline (Enclosure 6-6), this corehole was a re-drill of a previous BMR corehole located nearby to the north, which had bitumen shows within the Looking Glass Formation. Both the source and reservoir rock potential of the upper McArthur Group were tested in this hole. Lithologies encountered include interbedded mudstones, carbonates, and fine clastics of the Balbirini Dolomite, stromatolitic and algal carbonates of the Looking Glass Formation, interbedded shales, siltstones, and very fine-grained sandstones of the Stretton Sandstone, stromatolitic and algal carbonates, dolarenites, intraclast breccias, and dololutites of the Yalco Formation, and dolomitic mudstones and intraclast breccias of the Donnegan Member. Bitumen was present within fractures and vugs within the Yalco and Looking Glass Formations. Drilling was halted at 494 metres as the core-to-bedding angle (approximately 75°) was too extreme to justify further drilling.

6.2.1.8 Corehole 82-8

Situated at grid coordinates 6064-880553, this hole was drilled to evaluate the source rock potential of the basal Cobanbirini Formation, the reservoir rock potential of the Bessie Creek Sandstone, and the source rock potential of the Corcoran Formation (Enclosure 6-6). A highly friable zone of virtually unconsolidated sand within an aquifer in the Bessie Creek Sandstone was encountered. As a result, coring could not proceed. Drilling was terminated at 221 metres and the corehole was plugged. Thus the Corcoran remains an untested potential source rock horizon.

6.2.2 Fieldwork

Surface geological fieldwork completed during the 1982 field season includes:

1. Core description and downhole geophysical logging of coreholes.

2. Geologic traverses along test seismic lines in order to tie in surface geology.

3. Mapping of a previously-recognized large anticline (the Broadmere Anticline) in the western portion of O.P. 191, and stratigraphic units within the Cobanbirini Formation.

4. Facies analysis of the Stretton Sandstone in the vicinity of the Emu and Mallapunyah Faults.

5. Study of the Mt. Birch Sandstone to the west of Corehole 82-5.
McMinn Subgrp

6. General study of the Roper Group.

7. Geologic mapping along a major northerly-trending fault in the vicinity of Corehole 82-4.

8. Reconnaissance geologic mapping in the St. Vidgeon area in order to identify structure, potential source rocks, potential reservoir rocks, facies variations in the McArthur Group, and nature of prospective hydrocarbon traps.

9. Examination of possible growth along northwest-trending faults throughout the region.

10. Study of the Donnegan Member of the Lynott Formation.

11. Study of paleo-vadose weathering profiles in the upper McArthur Group.

12. Regional reconnaissance.

A total of 365 surface samples were collected during this period and are spotted on Enclosure 1-2.

The results of these studies were compiled and are presented in the remainder of this report.

7. REGIONAL STRUCTURE AND TECTONIC HISTORY

7.1 Regional Structure

The McArthur River Area is situated within a northwest-trending, right-lateral wrench system extending from Mt. Isa, Queensland through to Arnhem Land, Northern Territory (Figure 7-1). Numerous northwest-trending faults, including the Calvert, Hot Springs, Mallapunyah, Flying Fox and Bulman Faults, partly comprise this system. Northwestern orientation of the present-day coastline along the southwestern edge of the Gulf of Carpentaria suggests similar fault control. Within this system there are also several northerly-trending, high-angle, normal faults, including the Emu Fault, Tawallah Fault, and numerous others. A number of folds exist throughout the region, oriented subparallel to many of these faults (Plate 7-1).

Several graben-like basins have developed throughout this wrench system. These are similar in many respects to aulacogens, particularly in morphology and lithologic types; however, it is thought that these features developed through pull-apart movement within the right-lateral wrench system (Figure 7-2).

Enclosure 7-1, a structural airphoto interpretation completed by Intrasearch in 1981, displays major fault traces and rose diagrams which have both fault and fold axes plotted for the areas outlined. Also plotted on this map is a strain ellipsoid highlighting forces and structures which may result from right-lateral wrench faulting (Harding, 1974). This strain ellipse is oriented parallel to the northwesterly-trending wrench faults, of which the Mallapunyah appears to be the major one in the permit acreage. Orientation of the Emu and Tawallah Faults (normal faults) conforms to orientation of normal faults plotted on the strain ellipse.

Enclosure 7-2 highlights various tectonic features in the McArthur River area. The major fault traces that are shown are in part mappable at surface. Interpretation of gravity and magnetic data has aided in locating these fault traces where they exist in the subsurface (Enclosures 7-3, 7-4, 7-5, 7-6, and 7-7). Previous interpretations of gravity data (Gallagher and MacKay, 1981) assumed that gravity highs were coincident with an increase in the thickness of the McArthur Group (predominantly a carbonate sequence). This interpretation appears to be valid in the case of outcropping McArthur Group sediments, but when these units are covered by a considerable thickness (±1500 metres) of Roper Group clastics, this relative effect becomes masked.

The present gravity interpretation considers thicker accumulations of sediment to be represented by low gravity values. Magnetic data support this interpretation. Similarly, McArthur Group lithologies encountered in Corehole 82-4 indicate proximity to an erosional high during McArthur Group time. A corresponding positive gravity anomaly exists to the east of this site.

Other features exhibited on Enclosure 7-2 include various basins and ridges. A number of these appear to be fault-bounded. Lithologic types preserved within basins in the region suggest that these fault-bounded ridges acted as major hingelines, influencing sedimentation greatly. For instance, McArthur Group sediments outcropping to the north of the ridge in the southwestern portion of O.P. 198, differ lithologically from McArthur Group sediments exposed within the Batten Trough and on the eastern flanks of the Broadmere Trough (informal name). Another example is numerous apparent fanglomerate deposits present in the Mt. Birch Sandstone preserved in the northwestern portion of O.P. 198. These appear to have been deposited in response to fault movement along the Urapunga Fault Zone.

The Batten Trough, a presently-uplifted, former pull-apart basin recognized from 1981 field work, formed in a double "half-graben" manner by alternating normal movement along the Emu and Tawallah Faults, which resulted from pull-apart along the northwesterly-trending wrench-fault system.

A second north-trending graben-like feature, informally referred to as the Broadmere Trough, has been recognized through recent interpretation of gravity and magnetic data. This fault-bounded feature appears similar in character to the Batten Trough, with the exception that it has not undergone later uplift. The two major north-trending, bounding faults appear to be basement-controlled, and are contiguous to the north. A fault-bounded ridge forms the northern boundary; the trough appears to be open to the south.

A large McArthur Group basin, oriented roughly east-west, is situated in the northwestern portion of the permit. The orientation of this basin appears to be controlled by the westerly-trending Urapunga Fault Zone. The relation of the fault zone and basin to the regional wrench system is at present poorly understood.

7.2 Tectonic History

Deposition of McArthur Group sediments seems to have been largely controlled by movement along the northwest-trending, right-lateral wrench system. The timing of the origin of this wrench system and the initial stresses involved are not known.

A minimum of three stages of movement along the wrench system have been identified within the McArthur River area. Discussion of these stages with regard to deposition of the McArthur and Roper Groups, including later deformations, follows (see Enclosures 7-8 and 7-9).

7.2.1 Faulting Stage 1 - Sedimentation Phase 1

Initial pull-apart of the Tawallah Group sediments through right-lateral wrenching resulted in downwarping to the east and west of the Tawallah Range and possibly to the south of the Urapunga Fault Zone. The resultant marine transgression deposited a sequence of shallow marine and supratidal deposits. Initial deposition of glauconitic shale and minor sandstone (Mallapunyah) was followed by shallow water stromatolitic and oolitic carbonates (Amelia), sabkha sequences (Tatoola and Tooganinie), and massive lamellar and hemispherical stromatolitic carbonates (Emmerugga and Teena). Emergence at the end of Teena deposition allowed development of a karst surface (Coxco).

7.2.2 Faulting Stage 1 - Sedimentation Phase 2

This stage of fault movement and sedimentation is evident in the Batten Trough. Activation of the Emu Fault system by normal movement (west side down) resulted in the formation of major half-grabens. Development of a sequence of deep-water, interbedded, organic mudstones (Barney Creek Formation) and coarse clastic conglomerate-breccia wedges (proximal to the Emu Fault zone) occurred. Breccia wedges also formed along northwesterly-trending faults at this time. A subsequent period of relative quiescence allowed deposition of lamellar stromatolitic carbonates (Reward Dolomite). To the west and south of the Abner Range, sediments predating the Lynott Formation have been folded into asymmetrical, north-trending domes and basins, with one limb vertical and the other near horizontal (Jackson, et al., 1979). The basins' vertical limbs are often oriented parallel to northerly-trending faults; these basins are thought to be half-grabens (Jackson, et al., 1979). Subsequently, initiation of normal movement (east side down) along the Tawallah Fault formed a second half-graben structure. A sequence of organic-rich black shales (Lower Lynott) and turbiditic mudrocks (Middle Lynott) were deposited into the resulting deep, euxinic basin, now known as the Batten Trough.

7.2.3 Sedimentation Phase 3

This is characterized by a general period of stability with sporadic fault activity. Deposition of tidal-flat mudrocks (Donnegan Member) was followed by deposition of intertidal to supratidal carbonates (Yalco Formation). Minor fault reactivation, with an associated marine transgression, deposited fine-grained clastics (Stretton

Formation). Growth along both the Emu Fault system and some north-westerly-trending faults occurred at this time, resulting in deposition of local conglomeratic units. Subsequent deposition of stromatolitic carbonates (Looking Glass Formation) occurred under stable tectonic conditions. Local uplift and erosion with localized deposition of poorly-sorted clastics (Mt. Birch Sandstone) occurred both east and west of the Tawallah Range as well as in the vicinity of the Urapunga Fault Zone. A later transgression allowed deposition of shallow water carbonates, sandstones, and mudstones (Balbirini, Dungaminnie and Kookaburra Creek Formations). Minor volcanicity during this period in the northwest is evidenced by the local presence of volcanic flows and tuffaceous beds (Yalwarra Member). A period of uplift and erosion of unknown duration followed.

A similar style of deposition is thought to have occurred within the Broadmere Trough. This interpretation is supported by the presence of McArthur Group sediments east of the Four Archer's Fault extension and west of Batten Range.

7.2.4 Sedimentation Phase 4

This involved regional downwarping to the west and progradation of clastics from the west in a series of three transgressive episodes. Primary deposition of a moderately to well-sorted quartz sandstone (Limmen Formation) over a peneplaned McArthur Group surface, was succeeded by deposition of a transgressive sequence of shallow-marine mudstones, minor sandstones and very minor carbonates (Mainoru Formation) (Enclosure 8-10). Some growth along northwesterly-trending faults occurred, allowing deposition of local sandstone lenses. Deposition of a regressive sequence of interbedded siltstones and sandstones (Crawford Formation), lower shoreface or offshore bar sandstones (Arnold Member), lagoonal or offshore interbedded sandstones and mudstones (Jalboi Member), and upper shoreface to foreshore beach sandstones (Hodgson and Munyi Members) followed. A second transgression, with resultant interbedded sandstone and mudstone deposition (Corcoran Formation), was superceded by deposition of a regressive beach sandstone (Bessie Creek Formation). The third transgression, followed by progradation of sediments, deposited a sequence of mudstones (Lansen Creek Member, Velkerri Formation) and fluvial and/or beach-bar sandstones (Broadmere and Moroak Members). Later marine transgression deposited a mudstone sequence (Cat Creek and Kyalla Members). Deposition of an algal, laminated, micritic limestone (Crooked Creek Limestone) followed.

Paleomagnetic reconstruction of the polar-wander curve for Australia during the Proterozoic is displayed in Figure 7-3. Data indicate that Australia was located in relatively high latitudes during the upper Proterozoic (Embleton, 1980). The paucity of carbonates within the upper Proterozoic Roper Group may be due in part to the area's paleo-latitudinal (paleo-climatic) position.

7.2.5 Faulting Stage 2

Reactivation of faults appears to have occurred during upper Proterozoic time, subsequent to Roper Group deposition. Apparently the right-lateral wrench system was active at this time. Uplift of the

Batten Trough and of the Tawallah High may have deflected the north-westerly right-lateral stresses, and reactivated former northerly-trending normal faults in the western portions of the Permits as dextral strike-slip faults. Orientation of en echelon folds is consistent with this interpretation of dextral strike-slip motion.

7.2.6 Faulting Stage 3

Later reactivation of the regional northwesterly wrench system by left-lateral motion is suggested by en echelon fold morphology. The large anticlinal structure in the Broadmere Trough area may have formed in response to this sinistral wrench movement. Folds present within the central Batten Trough probably formed as a result of compression associated with uplift of the Batten Trough.

Some of the faults within the lease acreage appear to have been sites of somewhat higher heat flow. For instance, mineralization (Pb-Zn) within the H.Y.C. deposit appears to have been controlled by the Emu Fault. Similarly, the faulted Limmen Sandstone in Corehole 82-2 contained small amounts of chalcopyrite and resinous honey-brown colored sphalerite within fractures. Also, the Wollogorang Formation from Corehole 81-9 was situated in the vicinity of a fault; chlorite was found lining a fracture within this sequence. These examples of higher heat-flow appear related to major basement controlled faults in the region.

Precise age dating of fault movement in the region is difficult. Dolerite sills intruding into Roper Group sediments in the northwestern portion of the lease acreage have been dated: K-Ar dates range from 1095 to 1280 X 10^6 years for these (Peat, et al, 1978). It is possible that the last fault movement (Stage 3) may be somehow related to emplacement of these sills due to the magnitude of fault movements involved (i.e. reversal of motion). Worldwide, abundant basic dike swarms abound in Proterozic rocks over two periods in particular; 2500-2000 m.y. and 1300-600 m.y. (Windley, 1977). Perhaps emplacement of the dolerite sills in the northwestern portion of the McArthur River area (with possible associated activation of left-lateral motion along the former right-lateral wrench system) is coincident with break-up of a large continental mass.

8. STRATIGRAPHY

General discussion of the lithologic nature of various units within the McArthur River Region was presented in the 1981 McArthur River Field Report (Gallagher and MacKay, 1981). As work undertaken during the 1982 field program focussed on study of upper McArthur Group and Roper Group sediments, detailed discussion and environmental interpretation will be limited to these units (see Gallagher and MacKay, 1981, for stratigraphy of underlying units) (see Enclosures 8-1, 8-2).

8.1 Lower Proterozoic (Nullaginian?)

8.1.1 Tawallah Group

Volcanics, fine to coarse clastics, and minor carbonates characterize this group of sediments. In the 1981 field report (op. cit.), it was interpreted that Tawallah Group sediments had undergone low grade (greenschist facies) metamorphism. This interpretation was made on the basis of the presence of chlorite infilling fractures within a sequence of Wollogorang Formation shale, which was cored during the 1981 field program. This interpretation did not take into account proximity of the coresite to a fault. Some of the faults in the area appear to have been areas of formerly somewhat higher heat-flow. An example of this is the H.Y.C. Lead-Zinc deposit, adjacent to the Emu Fault zone. The observed chlorite may have formed in this way, and regional low grade metamorphism of upper Tawallah Group sediments might not have occurred. The presence of bitumen within the Wollogorang Formation has been communicated by various workers, and it is possible that the Wollogorang remains a good potential source rock unit.

8.2 Middle Proterozioc (Carpentarian)

8.2.1 Lower to Middle McArthur Group

This sequence consists of a basal sequence of shallow water to supratidal deposits formed under sabkha-like conditions, including the Mallapunyah, Amelia, Tatoola, and Tooganinie Formations. Deposition of the Emmerugga and Teena Formations probably occurred over a large, stable shelf over which both intertidal and supratidal conditions prevailed. Emergence was followed by activation of the Emu Fault system which resulted in deposition of deep water mudstones of the Barney Creek Formation. Subsequently, a period of quiescence prevailed, resulting in deposition of the Reward Dolomite.

8.2.2 Upper McArthur Group

Deposition during this period was influenced by early motion along the Tawallah Fault followed by a period of general stability within the Batten Trough (see Section 7.2, Tectonic History). The following discussion considers units within the Batten Trough followed by a discussion of lithologic units within the St. Vidgeon area.

8.2.2.1 Lynott Formation

This formation disconformably overlies the algal Reward Dolomite, and is conformably overlain by the Yalco Formation. Three distinct units have been recognized in the region: Lower Lynott (informal), Middle Lynott (informal), and Donnegan Member (formal).

Lithologically, the Lower Lynott comprises an interbedded sequence of dolomitic siltstone, pyritic siltstone, pyritic shale, minor dolomite, and locally-developed slump-breccia. Abundant convolute laminae exist throughout this unit. Deposition occurred during early activation of the Tawallah Fault. This unit has been classified as a subtidal turbidite (Plumb, 1979).

The Middle Lynott unconformably overlies the Lower Lynott. The contact is discordant with bedding, often exhibiting extensive slumping (Plumb, 1979). Lithologies consist of interbedded black shales, grey dolomitic shales, greenish-grey dolomitic shales, grey dolomitic siltstones and poorly-sorted litharenite beds. In the vicinity of the Tawallah Fault, boulder to pebble conglomerate was deposited in response to extensive normal fault movement (Plate 8-2). Lithologies encountered within Corehole 82-5, which was drilled near the Lynott depocenter, exhibit many small turbiditic sequences on the order of three to twenty centimetres in thickness (Plate 8-3). Bouma Divisions A through E were recognized in core, although commonly Divisions D and E were absent, probably due to erosion by pulses of clastic influx. These units are interpreted to represent distal turbidites deposited within a deep euxinic basin and probably represent lateral equivalents of the aforementioned conglomerates.

Upsection, this unit appears to exhibit evidence of shallower water deposition, possibly indicative of cessation of movement along the Tawallah Fault. A minimum of 350 metres of this unit was encountered in Corehole 82-5 (Enclosure 6-5).

The Donnegan Member conformably overlies the Middle Lynott and is conformably overlain by the Yalco Formation. The basal contact was picked at the first appearance of cauliflower chert nodules (nodular anhydrite pseudomorphs) (Walker, et al, 1977) in Corehole 82-5. Lithologies present comprise an interbedded sequence of grey dolomitic shales, grey dolomitic siltstones, fine to medium-grained sandstone, black shale, and dolarenites. Cauliflower cherts, local solution breccia, and possible infilled mud cracks suggest restricted to supratidal conditions, possibly representative of a sabkha or tidal-flat environment.

Composite thickness of the Lynott Formation is about 1000 metres (Oehler, et al, 1977), although in the depocenter a greater thickness may have existed. These sediments appear to be restricted to the Batten Trough and to the Broadmere Trough (informal).

8.2.2.2 Yalco Formation

This unit conformably overlies and is in gradational contact with the Donnegan Member and is conformably (locally unconformably) overlain by the Stretton Sandstone. Lithologies consist of a sequence of interbedded dolarenites, dololutites, algal dolomites, stromatolitic dolomites, intraclast (mud-flake) breccias, minor medium-grained quartz sandstone, and minor black shale. Lower portions of the Yalco consist of a predominance of algal dolomite, mud-flake breccias, dolarenites, dololutites and quartzose dolarenites. Teepee structures are also locally present. This lithologic sequence is interpreted to be representative of a supratidal to intertidal environment similar to tidal flats present at Andros Island. Quartzose sandstones within the sequence are similar in nature to tidal-channel distributory deposits. Upsection, a general increase in algal dolomite and stromatolitic dolomites was observed. Local unconformities occur throughout the sequence with thin mudstone beds and black shales overlying stromatolitic dolomites. Common development of vuggy porosity and preferential silicification of algal laminae is associated with these unconformities, in some cases extending up to 20 metres below the unconformity surface. This is interpreted to be representative of emergence of "intertidal" stromatolitic forms with resultant vadose weathering. Bitumen and fluorescence have been observed within pore spaces in these "paleokarstic" zones.

At the surface, the Yalco outcrops as high ridges and is ubiquitously silicified. Previous thickness estimates are on the order of 140 metres (Smith, 1972). A minimum thickness of 224 metres was encountered in Corehole 82-6; the upper portion of the Yalco had been removed by erosion in this area. The Yalco occurs throughout the Batten Trough and outcrops along the eastern edge of the Broadmere Trough, where it is anticipated to occur at depth.

8.2.2.3 Stretton Sandstone Formation

This unit consists of a flaggy, sandy siltstone to medium-grained litharenite which has local development of cherty, algal, dolomite-clast, conglomerate-breccia in the vicinity of the Emu Fault zone. This laterally- restricted conglomeratic facies, informally referred to as the Catfish Conglomerate, was shed off the Wearyan Shelf and along active northerly and northwesterly-trending faults. Sedimentary structures commonly present include ripple laminae, cross-bedding, and dewatering structures. Local erosion or scour channels are also present (Plumb, 1979).

Deposition of the Stretton Sandstone is interpreted to have occurred during a regional transgression resulting from renewed normal movement along the Emu Fault. Stretton Sandstone conglomeratic facies intersected in Corehole 82-6 consist of approximately 21 metres of interbedded siltstones, coarse litharenites, and pebble-sized conglomerate-breccia. Bitumen was found infilling porosity in the breccia beds. At outcrop, approximately 300 metres west of the corehole, this unit consists of approximately 30 metres thickness of cobble to pebble conglomerate (Enclosure 6-6, Plate 8-4).

Corehole 82-7 encountered approximately 37 metres of interbedded siltstones and fine-grained litharenites. BMR estimates place the average thickness of this unit at 120 metres (Smith, 1972). Stretton Formation clastics occur in the McArthur River region to the south of the northern boundary of the Broadmere Trough, to the east of the Four Archer's Fault, and to the west of the Emu Fault zone.

8.2.2.4 Looking Glass Formation

This formation consists of interbedded, laminated, algal dolomite, intraclast breccia, stromatolitic dolomite, and minor silt and silty dolomite. Stromatolitic forms predominate within the upper portions of the unit, while predominance of silt near its base indicates a zone of gradational contact with the underlying Stretton Sandstone. The Looking Glass Formation is unconformably overlain by the Mount Birch Sandstone in the vicinity of the Tawallah Range, and by the Balbirini Dolomite in the vicinity of the Abner Range. Thickness of the Looking Glass in Corehole 82-7 was 29 metres, while the BMR ascribes an average thickness of 80 metres to it (Smith, 1972). The Looking Glass appears to have been deposited in a shallow water, intertidal to supratidal environment as evidenced by stromatolitic forms, paleokarst (i.e. vadose weathering), and fenestral or birdseye texture. Bitumen was found lining vugs within this unit in Corehole 82-7.

8.2.2.5 Balbirini Dolomite Formation

Lower portions of this unit comprise interbedded wavy, nodular, microcrystalline dolomite, thinly laminated reddish-colored mudstones, dolomitic siltstone, dololutite, dolarenite, intraclast or mudflake breccia, acicular gypsum pseudomorphs, and nodular anhydrite pseudomorphs. Overlying this basal portion are interbedded dolarenites, flake breccia, stromatolitic dolomite, and minor sandstone, siltstone, shale, and dololutite (Jackson, et al., 1978). Thickness of the Balbirini Dolomite varies considerably over the lease acreage. The interpreted environment of deposition is supratidal to intertidal, in a possible sabkha-like setting.

8.2.2.6 Dungaminnie Formation

This formation has been described by the BMR (Jackson, et al., 1978) as consisting of two members. The lower member, with a maximum thickness of 100 metres, is composed of purple and red siltstone and fine-grained sandstone, and minor oolitic sandstone and conglomerate. The upper member, ranging in thickness from 140 to 170 metres, is predominantly composed of laminated sandy dolarenites (Jackson, et al., 1978). In Corehole 82-2, the Dungaminnie consisted of interbedded greyish siltstones and shales, green shales, and green and red shales.

8.2.3 St. Vidgeon Area

This is the northwestern portion of O.P. 198, which was mapped extensively in 1982. A geologic map of this area is included as Enclosure 8-3. Sediments deposited within this area consist of clastics, carbonates, and minor volcanics. This sedimentary basin, unlike others within the remainder of the permit acreage, is oriented east-west. Movement along the Urapunga Fault Zone appears to have strongly influenced sedimentation within this region.

8.2.3.1 Vizard Formation

This unit consists of a sequence of interbedded and interlaminated siltstone, shale, laminated algal dolomite, feldspathic sandstone, and minor felsic tuffs (Plate 8-5). Soft-sediment deformation is evident within the mudstone sequence. Volcanics consist of laminated to massive, pink, felsic tuff and amphibole-crystal tuff or lapilli tuff. Correlations with McArthur Group sediments in the Batten Trough (see Enclosure 8-2) are uncertain as this unit appears restricted to a separate basin in the northwest portion of O.P. 198. The BMR correlates this unit with the Tooganinie, Tatoola, Amelia, and Mallapunyah Formations; thickness estimates are on the order of approximately 1200 metres (Plumb and Paine, 1964).

8.2.3.2 Mt. Birch Sandstone Formation

The Mt. Birch Sandstone unconformably overlies the Vizard Formation in the St. Vidgeon Area, and the Looking Glass Formation within the Batten Trough. This unit consists of interbedded, friable and porous, feldspathic quartz sandstone, quartz sandstone, oligomictic quartz sandstone-pebble to boulder paraconglomerates and orthoconglomerates, and chert-pebble conglomerate-breccia. Conglomeratic beds commonly lack stratification and are massive in nature. A variety of interpreted depositional environments are represented by this formation. In the northwest, the great abundance of unstratified conglomeratic beds suggests an alluvial fan environment with finer sandstones deposited as a result of possible fluvial and/or alluvial deposition (Plates 8-6, 8-7). Possible activity along the Urapunga Fault Zone could have controlled deposition of this unit. Fining of this formation to the southeast, coupled with the appearance of conglomeratic channel infills (Plate 8-8) and sedimentary structures such as cross-bedding, suggests a fluvial environment. This environment of deposition is indicated for the W-Fold area (informal name) (see Enclosure 8-5) where conglomeratic beds occur as channel infills within a predominantly rippled and cross-bedded sandstone (Plate 8-9). A possibly correlative conglomeratic unit was intersected in Corehole 82-4, and appears to have been deposited in response to local uplift to the east (as indicated by gravity). Thickness of the Mt. Birch Sandstone is approximately 80 to 120 metres in the northwest, thinning and fining southeastwards.

8.2.3.3 Yalwarra Member

Consists of interbedded shale, siltstone, cross-bedded and rippled, feldspathic, quartz sandstone, oligomictic quartz sandstone-pebble to cobble paraconglomerate, and scattered pebble to cobble paraconglomeratic lenses (Plate 8-8). A laterally restricted, massive to amygdoloidal or vesicular intermediate volcanic flow occurs within a portion of this unit. The Yalwarra Member appears to be in gradational contact with the underlying Mt. Birch Sandstone.

8.2.3.4 Kookaburra Creek Formation

Lithologically, this formation consists of a basal stromatolitic dolomite grading upsection to a silicified oolitic wackestone to packstone. A paleokarst surface was developed, with subsequent infill by a well-sorted, fine-grained quartz sandstone unit (Plate 8-10), and apparent gradation upsection into an interbedded shale and siltstone. All units are poorly exposed within this upper sequence (Enclosure 8-9). The BMR correlates this formation with the Balbirini Dolomite and approximates its thickness at greater than 150 metres (Plumb and Paine, 1964). A probable transgression allowed deposition of the carbonate sequence in a high energy, shallow water environment. Subsequent emergence and development of a karsted surface followed by a later transgression resulted in deposition of the "infill sandstone" and overlying shaley sequence. The upper siltstone-shale sequence is a possible equivalent of the Dungaminnie Formation located to the southeast. This sequence is unconformably overlain by the Limmen Sandstone (see below).

8.3 Middle to Upper Proterozoic (Carpentarian-Adelaidean)

8.3.1 Roper Group

This predominantly clastic group unconformably overlies the McArthur Group. Paleocurrents indicate a westerly to northwesterly source for these sediments, and the group also thickens to the west where estimated accumulations of up to 5,000 metres exist (Gallagher and MacKay, 1981). Easterly-thinning of individual formations can be demonstrated; for instance, the Abner Sandstone thins to approximately 40 metres in the vicinity of Caranbirini (Enclosure 8-10). Various transgressions and regressions are recognized and are also displayed in Enclosure 8-10.

8.3.1.1 Limmen Sandstone Formation

Generally, this unit outcrops as silicified ridges throughout the lease area (Plate 8-11). Local pods of porosity are developed sporadically throughout. In the eastern part of O.P. 191 in the vicinity of the Wearyan River, this unit outcrops as extremely friable slabs of cross-bedded quartz sandstone. Lithologically, it consists of a blocky-weathering, medium to thick-bedded, moderately to poorly sorted, medium to coarse-grained quartz sandstone to litharenite. Numerous grit-conglomerate laminae and beds are present in the upper to central portion of the unit, often alternating with fine-grained sandstone and shale laminae. Shale rip-ups as well as lithic clasts occur locally. Planar and trough cross-stratification and ripple marks were observed.

Within Corehole 82-2, the Limmen Sandstone was fault-repeated. A basal pebble-conglomerate layer approximately 2 centimeters thick overlies a thin greenish coloured mudstone of the Dungaminnie Formation (Appendix I). A high degree of silicification was observed and thoroughly masked clastic textures. As chalcopyrite, traces of galena, and brown sphalerite were seen to exist within fractures, this reverse fault probably was an area of somewhat higher heat flow at some time in the past. Possibly, fluids migrating along this conduit contributed to silicification of the Limmen. It is of note, however, that this unit is ubiquitously silicified at surface west of the Emu Fault, and therefore it is felt that porosity development at depth would be limited to localized porosity pods or widespread porosity as preserved in the eastern section of O.P. 191. Thickness of the Limmen Sandstone in Corehole 82-2 was approximately 77 metres.

8.3.1.2 Mainoru Formation

This unit conformably overlies the Limmen Sandstone and comprises a sequence of interbedded red and green variegated siltstones and shales, fine-grained glauconitic sandstones, whitish siltstones, black carbonaceous shales, and in the upper part of the unit, thin carbonates with cone-in-cone structures and anhydrite pseudomorphs. Complete penetration of this unit through coring has not yet been achieved, and therefore its thickness and the relative abundance of carbonaceous shales within the sequence remain unknown. The BMR estimates its thickness at approximately 550 metres (Plumb and Paine, 1964). This unit appears to have been deposited as a result of marine transgression, subsequently shallowing upwards as evidenced by shallow-water carbonates locally preserved in the upper portion of the formation.

8.3.1.3 Crawford Formation

This unit represents a gradation between underlying silts and shales of the Mainoru Formation and overlying quartz arenites of the Arnold Sandstone Member. Lithologically, it is composed of interbedded, rippled, glauconitic and micaceous, fine to locally medium-grained, quartz sandstones, micaceous siltstones, and shales. It generally coarsens upwards cyclically (5 cycles recognized in Corehole 82-3) from 2-20 centimetre thick silts and shales at the base, coarsening gradually upwards to fine to medium-grained glauconitic quartz sandstone. Each cycle is from 22 to 48 metres in thickness. Low angle cross-stratification also has been observed in outcrop, and this unit is interpreted to represent a sublittoral or offshore bar environment. Its thickness in Corehole 82-3 was approximately 172 metres, while the BMR estimates thicknesses of between 85 and 160 metres, thickening to the west (Plumb and Paine, 1964). Traces of bitumen were observed in fractures and in fine-grained sandstone interbeds in Corehole 82-3.

8.3.1.4 Abner Sandstone Formation

This is a widespread lithologic unit occurring throughout the area, generally thinning to the east. Four members have been identified by the BMR; Amoco's 1982 field mapping subdivided the formation into three members.

8.3.1.4.1 Arnold Sandstone Member

Consists of blocky weathering, moderately to well sorted, fine to medium-grained quartz arenite. Shale rip-up clasts and minor fine to medium-grained rock fragments are also constituent elements. Generally, this unit fines upsection. Sedimentary structures include low angle (7° to 10°)

cross-bedding with alternating fine to medium-grained and medium to coarse-grained laminae; large wavelength ripples and hummocky cross-stratification near the base of the unit; and smaller oscillatory ripples upsection (Plate 8-12). This unit is interpreted to represent a shallowing-upward sequence within a lower shoreface or offshore bar environment. Thickness of this unit in Corehole 82-3 is approximately 44 metres.

8.3.1.4.2 Jalboi Member

This unit is in gradational contact with both overlying and underlying units. Generally, it consists of an intricately interbedded and intercalated sequence of black, green, yellow, and red shale, siltstone, rippled fine-grained glauconitic quartz sandstone, quartz sandstone, and micaceous quartz sandstone. Shale rip-up clasts occur in minor numbers. Sedimentary structures include ripple cross-lamination and dewatering structures. The Jalboi Member is interpreted to represent a shallow offshore shelf or lagoonal environment developed as a result of a marine transgression. Corehole 82-3 intersected a thickness of approximately 99 metres of this unit.

8.2.1.4.3 Hodgson Sandstone Member

This stratigraphic unit is conformably overlain by the Corcoran Formation. Lithologically, it is a characteristically pillar weathering, thin to medium bedded, friable, porous and permeable, well rounded, well sorted, fine to coarse-grained, clean quartz arenite (Plate 8-13). The unit is moderately sorted with subangular grains present near its base, quickly becoming well sorted and well rounded upsection. Thin, gritty or grit-conglomerate interbeds occur within upper beds of this member. Sedimentary structures include shallow angle (8°-14°) planar, tabular, and wedge-shaped cross-stratification, and bidirectional ripples. The interpreted environment of deposition is upper shoreface to beach. Estimated thickness of this unit in the vicinity of Corehole 82-3 is on the order of 150 to 165 metres, with the lowermost 50 to 55 metres being somewhat more poorly sorted.

8.3.1.5 Corcoran Formation

This formation is conformably overlain by the Bessie Creek Sandstone and consists of an interbedded sequence of shale, micaceous siltstone, minor sandstone, and local mudstone concretions (Plate 8-14). This unit was not encountered by any of Amoco's 1982 coreholes and remains an untested potential source rock horizon. Average estimates of this formation's thickness are on the order of 130 metres (Plumb and Paine, 1964).

8.3.1.6 Bessie Creek Sandstone Formation

Generally, this formation consists of slabby weathering, thin to medium-bedded, friable, porous and permeable, well-rounded, well-sorted, medium-grained, clean quartz arenite with a few mudstone chips present in some beds (Plate 8-15). Thin pebble to grit conglomeratic layers were also present within the lower portions of the formation, and general coarsening-upward in particle size was observed throughout. Sedimentary structures include planar, tabular, and wedge-shaped cross-stratification with alternating medium and coarse-grained laminae near the unit's base; a predominance of shallow-angle (10°) planar cross-bedding and straight ripples, in an interbedded quartz arenite with very minor silty-shale interbeds, in the central portion of the unit; and shallow-angle planar cross-bedding in the upper portions of the unit. In Corehole 82-8, the middle to lower sections of this formation washed out. The thickness of the Bessie Creek Sandstone is estimated to average 120 metres (Plumb, et al, 1964). Its environment of deposition is interpreted to be upper shoreface to foreshore or beach.

8.3.1.7 Cobanbirini (Lansen Creek Member)/Velkerri Formations

This unit consists of a poorly-exposed sequence of interbedded olive-black to grey shales, micaceous siltstones, and very minor, whitish, silty to very fine-grained sandstones. These sandstones occur near conformable and gradational contacts with the underlying Bessie Creek Sandstone and the overlying Broadmere Sandstone Member. Small-scale trough or rippled cross-lamination exists within some silty interbeds. A few ooids or microfossils are scattered through shalier portions of the unit. Ooids, similar to those found higher in the sequence, indicate an open marine environment (see Appendix V). A few flecks of bitumen-like material are present within siltier beds. In Corehole 82-1, the Lansen Creek Member had a very strong kerosene-like odor (see Enclosure 9-3); volatiles released also stung one's eyes during logging of the core. Minimum thickness of the unit is approximately 160 metres. BMR estimates place its thickness at approximately 300 metres (Plumb and Paine, 1964).

8.3.1.8 Cobanbirini/McMinn Formations

8.3.1.8.1 Broadmere/Moroak Members

The Broadmere Sandstone Member comprises blocky, friable, fine to medium-grained, clayey, quartz sandstone with alternations of laminae with approximately 10% intergranular clay and laminae with approximately 20% intergranular clay. Three subdivisions were noted in Corehole 82-1: a lower porous zone (10% to 15% visually estimated porosity) of medium-grained quartz sandstone with minor shale partings; a middle fine-grained quartz sandstone unit with more abundant shale partings and interbeds; and an upper porous unit with cross-stratified coarse-grained and medium-grained quartz sandstone laminae. Generally, upwards-fining sequences can be found throughout the unit. Surface outcrops exhibit various sedimentary features including planar cross-bedding and ripple marks. The environment of deposition is interpreted to be an offshore bar. The thickness of this unit in Corehole 82-1 is approximately 150 metres. Bitumen was present as large clots and intergranular pore-fillings throughout the upper and lower porous sections; a kerosene-like hydrocarbon or light oil weeped out from lower portions of the unit (Plate 8-16).

The Moroak Sandstone Member consists of blocky weathering, thin to medium-bedded, moderately sorted, fine to medium-grained, feldspathic quartz sandstone. Grain size is locally bimodal with rounded medium to coarse grains and fine subrounded grains. Sedimentary structures consist of low-angle planar cross-stratification, high angle (15° to 20°) cross-stratification, long sinuous ripple marks, cuspate ripple marks and cut-and-fill structures. A few poorly-sorted granule to very coarse-grained sandstone beds commonly occur near the base of the unit. Depositional setting has been interpreted to be fluvial to tidal channel environment (Peat, et al., 1978).

8.3.1.8.2 Cat Creek/Kyalla Members

This poorly outcropping unit is composed of flaggy weathering, interbedded very fine-grained sandstone, micaceous siltstone, and shale. In Corehole 82-1, it consists of a sequence of interbedded mudstone, greyish-green to black shale, and silt to very fine-grained sandstone. Ooids or microfossils present within the sequence indicate an open marine environment (see Appendix V). This unit is in gradational contact with the underlying Broadmere Sandstone Member. Within

Corehole 82-1, the Cat Creek Member was approximately 160 metres in thickness.

8.2.1.8.3 <u>Sherwin Ironstone Member</u>

This member occurs as discontinuous lenses and continuous bands within the Moroak Sandstone, and also interfingers with the Kyalla Member. Lithologies include botryoidal goethite, hematitic oolites, and a ferruginous matrix to a medium-grained quartz sandstone. All four types of iron occurrences are contained and intermixed within this unit: oxides, silicates, sulphides, and carbonates (Peat, et al, 1978).

8.3.1.9 <u>Crooked Creek Limestone</u>

This unit comprises micritic limestone with algal laminations. Numerous intraclast breccias and silt infills are present. Porosity is moldic to vuggy in nature, attaining a maximum of 15%. This unit was penetrated by Corehole 82-1.

8.3.2 <u>Dolerite Sills</u>

Isotopically (K-Ar) dated at between 1095 to 1280 x 10^6 years (Peat, et al., 1978), these fine crystalline diabases to coarse crystalline gabbros to gabbro-diorites intrude at various levels within the Roper Group in the northwestern portion of O.P. 198, where they were observed to occur locally within the Jalboi Member. To the northeast of the block, they occur within the McMinn Formation. Where observed, these units were not exposed but were found as boulders within some streams.

9. RESERVOIR PROPERTIES

9.1 Introduction

Based on published reports and the 1981 Amoco field mapping and coring program, several formations within the middle to late Proterozoic McArthur and Roper Groups were described as having adequate to very good reservoir potential. However, because of the severity and duration of the weathering processes of this area, samples from neither surface outcrop nor the shallow 1981 coring program were considered representative of actual reservoir quality in the subsurface.

The 1982 corehole drilling program was designed to encounter, in the unweathered subsurface, the units which were considered to have the highest source and reservoir rock potential. This section summarizes the results of the 1982 drilling program with respect to reservoir quality.

9.2 Analytical Techniques

One hundred and thirty-one samples from the eight coreholes were selected for reservoir analysis. Laboratory measurements of porosity, horizontal air permeability and grain density were made by U.S. Testing Company, Inc. of Tulsa. From this group of samples a representative suite of eighty-three samples was chosen for further work, including thin-sectioning and semi-quantitative X-ray diffraction analysis by Mineralogy Inc. of Tulsa, and petrographic analysis and photography, performed in-house. In addition, these samples were examined by scanning electron microscopy at the Tulsa Research Center. The analysis of fluid inclusions and isotopic composition of diagenetic minerals is planned, and will also be performed at the Tulsa Research Center.

9.3 Objectives

The analyses described above were performed to determine the following:

1. Reservoir quality, as measured by porosity and permeability.

2. Qualitative estimates of reservoir conditions and quality, such as degree of interconnection of pore network, anisotropy of pore network, pore size, type, etc.

3. The diagenetic history of each of the formations sampled, and the primary controls of porosity/permeability reduction.

4. Lateral and/or vertical reservoir quality trends.

5. Timing of hydrocarbon emplacement where it is preserved as bitumen, and its effect, if any, on subsequent diagenesis of the units that contain it.

9.4 Results

Results and conclusions for this segment of the 1982 study are abstracted below. Specific data on core analysis are presented in Appendix III. Other data, including SEM photos, thin section photos and descriptions and XRD results are presented in Appendix II and IV.

The results from the 1982 porosity-permeability analyses indicate the following ranking of reservoir quality:

Abner Fm. (Hodgson Mbr.)	-	Good
Bessie Creek Fm.	-	Good
Cobanbirini Fm. (Broadmere Mbr.)	-	Fair to Good
Stretton Fm.	-	Fair to Good
Yalco Fm.	-	Fair to Poor
Looking Glass Fm.	-	Fair to Poor
Balbirini Fm.	-	Fair to Poor
Limmen Fm.	-	Poor

The following formations encountered in 1982 exhibited no reservoir potential, although unrecognized lateral facies changes or porosity enhancement below local unconformities could create local porous zones:

Cobanbirini Fm. (Lansen Creek Mbr.)

Cobanbirini Fm. (Cat Creek Mbr.)

Mainoru Fm.

Dungaminnie Fm.

Crawford Fm.

Towns Fm.

Childer Creek Fm.

Four Archers Fm.

Nathan Dolomite

Lynott Shale

Abner Fm.	(Jalboi Mbr)
Abner Fm.	(Arnold Mbr)

The following formations were not encountered in the 1982 corehole drilling program; ranking of reservoir quality is based on published reports and the 1981 field mapping and coring program.

Teena Dolomite	-	Fair to Good, locally Very Good
Reward Dolomite	-	Fair
Barney Creek Fm.	-	Fair, locally Good
Mallapunyah Fm.	-	Fair to Poor
Tatoola Fm.	-	Poor to Fair
Toogannie Fm.	-	Poor to Fair
Emmerugga Fm.	-	Poor
Amelia Fm.	-	Poor
Corcoran Fm.	-	Poor

9.4.1 Abner Sandstone Formation

Encountered in Corehole 82-3, the Upper (Hodgson) Member showed good reservoir quality, and the Jalboi and Arnold Members displayed poor reservoir quality.

9.4.1.1 Hodgson Sandstone Member

Described from outcrop as a thin to medium bedded, friable, clean, quartz arenite, this unit was apparently deposited in the upper shoreface to beach environment. High energy conditions are evidenced by very good sorting and abundant cross-beds and ripples (see Section 8). The Hodgson Member, encountered in Corehole 82-3 from the surface to a depth of 145 metres, exhibits very good reservoir properties in the upper 85 metres, with porosities ranging from 10.1% to 13.4%, averaging 12.2%, and permeabilities of 68.7 md to 1200 md, averaging 425 md (Enclosure 9-1, Appendix III). X-ray diffraction analysis shows 95% to 100% quartz in this upper section of the Hodgson Member. Below 85 metres, down to its base at 145 metres, this unit displays much poorer reservoir quality, with porosity ranging from 7.3% to 14.0%, averaging 10.5%, and permeability ranging from 0.035 md to 1.8 md, averaging 0.8 md. X-ray diffraction analysis over this interval shows that quartz content ranges from 90 to 94%, significantly lower than in the porous section above.

One possibility that we have assessed is that the zone of high porosity-permeability is the result of a weathering profile, and therefore unrepresentative of reservoir conditions in the unweathered subsurface. Based on detailed analysis of thin section and SEM photographs (Appendix II), it is apparent that the zone of weathering extends down to approximately 70 metres, and that there is pronounced enhancement of porosity and permeability to this depth. The weathering process has created a mottled color visible in core (Appendix I). It appears in thin section that the weathering has converted all clays to kaolinite. This conversion of permeability-reducing illite/chlorite clays to kaolinite enhanced reservoir quality (see Enclosure 9-1). In addition, the weathering has leached virtually all iron oxides from the fine matrix; at depth these iron oxides appear to have a major effect on permeability. Petrographic evidence suggests that the major "break" in permeability below 85 metres (Enclosure 9-5) lies below the base of weathering, and is actually the result of a fining-downward facies change. This facies change probably represents the progradation of well-sorted beach sands over sub-tidal silty sands. The smaller "break" in permeability between 57 metres and 71 metres reflects the gradational base of the weathering profile; the four samples between 70 metres and 90 metres are believed to be representative of reservoir quality at depth. These samples have average porosity of 12.3% and average permeability of 83 md.

In addition to the effects of weathering, this unit has undergone several diagenetic processes which have typically reduced original porosity and permeability. Authigenic quartz overgrowths are abundant and obviously have a large effect on porosity and perhaps permeability. Pressure solution of the primary quartz grains is rarely seen in these samples and has had little effect on reservoir quality. Most of the secondary quartz displays euhedral crystal faces which indicates that the pore spaces it was growing into had not been totally filled with secondary minerals. It also indicates that this material grew as quartz rather than as amorphous silica with later conversion to crystalline quartz. Typically the authigenic quartz preceded all other secondary phases, but crystals of authigenic illite have locally interfered with the growth of quartz. As stated above, kaolinite is a secondary mineral that appears to have formed in the near-surface weathering environment rather than in the deep sub-surface. The other secondary mineral present is hematite, which occurs below 71 metres. The hematite clearly followed quartz and illite, coating the walls of the relatively small pores remaining after these phases formed. The iron may have been derived from oxidation of some of the abundant sulphide minerals seen throughout the section, or may have been released by kaolinization of chlorite during weathering.

9.4.1.2 Jalboi Member

Encountered at a depth of 145 to 243 metres in Corehole 82-3, this unit was described in outcrop as a complexly interbedded sequence of shales, silts and micaceous, glauconitic, quartz sandstones. It probably represents a shallow offshore shelf or lagoon associated with a minor transgression. Both porosity and permeability are very low. In thin section the heterogeneous, less mature character of the sediment becomes apparent, even in the "cleanest" sand units; several percent lithics, plus mica and some mafics are present. These samples are also more poorly sorted, and have an abundance of clay matrix, much of which has been chloritized. Many of the quartz clasts have secondary quartz overgrowths, and iron oxides are locally abundant, occluding much of the remaining pore space.

9.4.1.3 Arnold Sandstone Member

Encountered at depths of 243 metres to 288 metres in Corehole 82-3, this member is described in outcrop as a blocky-weathering, fairly clean, quartz arenite with abundant high-energy sedimentary structures. It was apparently deposited in a shallowing-upward outer shoreface environment (see Section 8). Reservoir quality of this unit is poor, with porosity ranging from 2.2% to 7.1%, averaging 5.1%, and permeability ranging from 0.007 md to 0.98 md, with a possibly fractured sample showing 65.3 md. X-ray diffraction analysis indicates compositions of 97% to 100% quartz, with minor amounts of illite or local kaolinite. The poor reservoir quality results from abundant formation of authigenic quartz which has nearly completely destroyed all pore space. Some pressure solution has occurred, suturing original quartz grains, and minor illite/chlorite is present in interstices. The large amount of secondary quartz in this unit implies an active flow of pore fluid under deep sub-surface conditions.

9.4.2 Bessie Creek Sandstone Formation

Encountered in Corehole 82-8 from approximately 110 metres to the total depth of 221 metres, this formation typically displays good reservoir quality, with porosity ranging from 4.3% to 21.8%, averaging 9.6%, and permeability ranging from 0.25 md to 3594 md, averaging 111 md, discounting the single anomalously permeable sample. This formation is described in outcrop as a thin to medium-bedded, porous and permeable, well-sorted, medium-grained, quartz arenite. Some silty-shale interbeds occur near the center of the formation (see Section 8). Observations from both optical and scanning electron microscopy confirm these observations. The quartz grains tend to be very well-rounded and nearly spherical, and are typically not well-sorted. There is little silt or clay-sized matrix, however, so initial porosity was high. Most quartz grains are variably overgrown by secondary quartz, which appears to have been the most important porosity/permeability reducing process. Kaolinite is abundant and has probably formed as a result of the action of actively flowing groundwater. Further evidence for active water flow is the artesian flow from approximately 200 metres depth that was encountered during the drilling of this corehole. The kaolinite has little effect on permeability, and reservoir conditions may have been poorer before the probable conversion of illite to kaolinite. Hematite is present in most samples, and is seen under SEM views to be authigenic in character, consisting of small crystal rosettes growing with kaolinite on secondary quartz crystal faces. It tends to form a fairly light coating and probably has only locally had any significant effect on permeability. The zone of low permeability from 136 metres to 165 metres corresponds to the silty-shaly zone at the center of the formation. The poor reservoir quality results primarily from poor sorting during deposition; diagenetic deposition of quartz and clay minerals has also degraded reservoir quality, however.

9.4.3 Cobanbirini Formation

Encountered in Corehole 82-1 from a depth of 223 metres to 374 metres, this formation typically displays fair to good reservoir quality.

Porosity ranges from 4.5% to 20.5%, averaging 13.7%, and permeability ranges from 0.0033 md to 1006 md, averaging 53.2 md. Omitting the single sample with 1006 md permeability, the average permeability is 11.8 md. This formation is described in outcrop as a blocky, friable, fine to medium-grained, clay-rich, quartz sandstone with interbedded clay laminae. The environment of deposition is believed to be offshore, based on the presence of tabular cross-beds, ripple marks, upward-fining sequences and abundance of clay matrix. Numerous bitumen clots and occasional shows of bleeding light oil were reported in core descriptions (Enclosure 9-3). Examination by optical and scanning electron microscopy indicates that the presence of detrital and secondary clays is locally important in reducing both porosity and permeability, but the most pervasive and important cause of low permeability is the formation of authigenic quartz overgrowths. These overgrowths are frequently observed to have grown until void spaces were completely filled with quartz. Pore throats are even more completely blocked. A very important observation is that where authigenic quartz and hydrocarbon (bitumen) co-exist, the continued growth of quartz into void spaces was apparently inhibited by the hydrocarbon (see Appendix II). If this observation is correct, an early timing for the migration of hydrocarbon into the reservoir is implied, with probable preservation of reservoir quality in an oil-saturated reservoir, and the formation of diagenetic traps. The hydrocarbon appears to have migrated into a water-wet reservoir.

Most of the authigenic clays followed quartz; locally the two were contemporaneous, as clay crystals are seen disrupting quartz crystal faces.

9.4.4 Stretton Sandstone Formation

Stratigraphically located within the McArthur Group, the Stretton Formation was encountered in Corehole 82-6 from 23 metres to 42 metres, and in Corehole 82-7 from 81 metres to 116 metres. It displays highly variable reservoir quality, typically ranging from fair to good. The porosity ranges from 5.2% to 16.4%, averaging 9.5% and permeability ranges from 0.00047 md to 122.7 md, averaging 27.0 md. It is described in outcrop as a flaggy sandy-siltstone to medium-grained litharenite with local conglomerate-breccia wedges. The strong lateral facies changes reflect active growth faulting during Stretton time. The reservoir properties are also laterally variable with best potential in coarse conglomerate wedges shed from active fault scarps (Section 8). Some type of winnowing is inferred on the basis of the total lack of matrix in several samples of core. The clasts consist of a diverse suite of chert, quartz and dolomite fragments derived locally from erosion of McArthur Group sediments. Most are sub-angular to angular and show evidence for short transport distance. "Blobs" of bitumen are preserved in two of the samples examined. The hydrocarbon appears to be genetically related to pyrite, which it is frequently associated with. In addition, the hydrocarbon is observed in contact with euhedral quartz crystals which clearly preceded migration of hydrocarbon, and sparry dolomite cement which post-dated the hydrocarbon. Several examples are presented in Appendix II of dolomite forming in cracks in bitumen which were caused by the loss of volatiles from the hydrocarbon. There may have been two phases of dolomitization; and all of the porosity-destroying effects of the later phase may have been inhibited within an oil-saturated reservoir. Trapping mechanism within the Stretton Formation may therefore be a combination of stratigraphic and diagenetic types.

9.4.5 Yalco Formation

Also part of the McArthur Group, the Yalco Formation was encountered in Corehole 82-6 from 42 metres to 266 metres, and in Corehole 82-7 from 116 metres to 413 metres. It is unconformably overlain by clastics of the Stretton Formation, which consists in part of sediments derived from erosion of the Yalco. This unit consists of a series of dolarenites and dololutites, stromatolitic and algal dolomites, mud-flake breccias, and minor black shale and quartz sandstone. Local unconformities occur throughout this intertidal to supratidal sequence, and are preserved as thin mudstone and shale bands above zones of vuggy porosity and silicification.

Laboratory analyses of porosity and permeability reflect the vertically-variable nature of the Yalco Formation. Porosity ranges from 0.8% to 18.0%, with an average of 7.1%, and permeability ranges from less than 0.0001 md to 1792 md, with an average of 137.1 md (9.8 md deleting the single high value of 1792 md). High values of porosity and permeability invariably correlate with zones of vuggy porosity developed below the local unconformities described above. Primary porosity and permeability are nil.

Examination of core samples by optical and scanning electron microscopy serves to confirm the secondary nature of porosity in the Yalco Formation. Solution of the dolomitic framework occurred along fractures, forming highly porous and permeable zones up to 20 metres thick. The sample from 113.7 metres in Corehole 82-6, which has porosity of 17.3% and permeability of 1792 md represents an example that was probably fairly typical during the solution process. This sample displays very minor precipitation of subsequent pore-filling cements, whereas most other samples have been extensively re-cemented, greatly reducing porosity and permeability.

Two stages of extensive silicification have also occurred in the Yalco Formation. An early episode, possibly before the vuggy solution, formed pervasive chert zones throughout the formation. The second phase was subsequent to formation of secondary porosity and is typified by multiple layers of amorphous silica and fibrous quartz, lining pore walls. Frequently, the remaining pore space is filled by crystals of blocky quartz, indicating precipitation in the deeper subsurface.

Crystals of sparry dolomite are also commonly observed partly or totally occluding the remaining pore space. These dolomites are relatively late-stage products, and are observed to have always formed after all quartz and silica cements.

Some bitumen is preserved in the Yalco Formation. One sample, from 119.0 metres in Corehole 82-7 (Appendix II), displays bitumen in contact with authigenic quartz. It is clear from the SEM photographs that the hydrocarbon was emplaced subsequently to the euhedral quartz crystals that line the void walls. Little sparry dolomite occurs in this sample; however it appears that the hydrocarbon preceded, or was contemporaneous with, secondary dolomite cements.

9.4.6 Looking Glass Formation

Encountered in Corehole 82-6 from 4.0 metres to 23.0 metres and in Corehole 82-7 from 54.0 metres to 81.0 metres, the Looking Glass Formation is in gradational contact with the Stretton Formation below, and is unconformably overlain by the Balbirini Dolomite. It is described as an interbedded sequence of laminated algal dolomites, intraclast breccia, stromatolitic dolomite and minor silt and silty dolomite. Development of pore space is variable, and appears to result from dissolution of dolomite and chert in the shallow weathering zone, probably during the formation of the unconformity at the top of the formation. Only one sample was measured; it had a porosity of 8.2% and permeability of 0.013 md (Corehole 82-7, 55.4 metres).

Evidence from optical and scanning electron microscopy suggests that the secondary porosity was originally much greater, but was subsequently reduced by the formation of quartz and dolomite pore-filling cements. In most cases these cements have completely occluded all pore space. Sparry dolomite always post-dates secondary quartz. Bitumen is also preserved in this sample, and appears to have partially prevented the diagenetic re-cementation of the Looking Glass Formation. The hydrocarbon was emplaced into a water-wet reservoir consisting of vugs lined with minor secondary quartz and some sparry dolomite. Hydrocarbon locally prevented the further growth of dolomite, or has become completely encased by it. The growth of large amounts of sparry dolomite requires active water flow through the pore system, yet the hydrocarbons preserved as bitumen were not flushed out. This may mean that the hydrocarbon was degraded to immobile bitumen before much of the secondary dolomite was deposited. If hydrocarbon-saturated reservoirs exist, most of these sparry dolomites would be absent and reservoir properties would be greatly enhanced over those seen in core.

9.4.7 Balbirini Dolomite Formation

Encountered in Corehole 82-7 from the surface to a depth of 54.0 metres, this formation unconformably overlies the Looking Glass Formation and consists of a heterogeneous sequence of sabkha-type deposits, including microcrystalline dolomite, laminar mudstone, dololutite, dolarenite, mud-flake breccia and pseudomorphs of gypsum and anhydrite.

No samples of Balbirini Dolomite were taken for reservoir analysis. It is open to the surface at Corehole 82-7 and extensively weathered. The Balbirini Dolomite is considered a fair to poor reservoir prospect based on observations from core descriptions. There may be local unconformities preserved within this unit that have associated zones of secondary porosity, as were seen in the Yalco and Looking Glass Formations. Protection of such porous zones from diagenetic effects may allow preservation of sufficient reservoir quality to consider this unit as a secondary reservoir target.

9.4.8 Limmen Sandstone Formation

Stratigraphically located at the base of the Roper Group, the Limmen Sandstone is separated from the underlying McArthur Group sediments by a regional unconformity. Based on results of the 1981 field program, the Limmen Formation was considered a fair to good potential reservoir. It was encountered in Corehole 82-2 from 161 metres to 256 metres, and from 352 metres to 427 metres. A highly brecciated fault zone is interpreted to lie from 216 metres to 255 metres. This fault has an apparent vertical throw of 191 metres and has caused the Limmen Formation to be repeated in this corehole.

The formation is described in outcrop as a silicified, medium to thickly-bedded, medium to coarse-grained, quartz sandstone. It locally appears as a litharenite. It is a resistant ridge-former of regional extent, with some locally porous "pods" at some stream cuts. Although the unexpected proximity to a fault zone at depth in Corehole 82-2 has had an unknown effect on the silicification of this unit, the non-porous character of core samples is considered typical, based on the surface observation of regional silicification.

Examination of thin section and SEM samples verifies the extreme effects of silicification on the Limmen Sandstone. Virtually all porosity has been destroyed through the deposition of quartz, and although present in small amounts, iron oxides and clay minerals also contribute to low permeability. The authigenic character of hematite crystals is clearly evident under scanning electron microscopy.

Porosity ranges from 0.6% to 4.4% with an average of 2.1%, and permeability ranges from less than 0.0001 md to 0.0044 md, with an average of 0.001 md.

The source of authigenic quartz is unclear. Some suturing (pressure solution) of primary quartz grains is evident, but it alone cannot account for the quantity of quartz required. Perhaps at some time in the geologic past the Limmen Sandstone was an active aquifer; clearly many pore volumes of water were required to supply all the authigenic quartz in place.

9.5 Summary

Of the formations cored in 1982, several clastic units display reservoir potential. These are, in order of quality, the Hodgson Member of the Abner Formation, Bessie Creek Formation, Stretton Formation and Broadmere Member of the Cobanbirini Formation. In addition, several of the dolomitic formations also display limited reservoir potential. These are, in order of quality, the Yalco, Looking Glass and possibly Balbirini Formations. Several other formations from the McArthur Group were untested in 1982 but may have reservoir potential.

The quartz clastic units, primarily in the Roper Group, have had a complex diagenetic history. Pervasive silicification occurred in the deep subsurface, accompanied by some pressure solution of primary quartz grains and formation of minor authigenic clay. Hydrocarbon preserved as bitumen in the Cobanbirini Formation appears to have been emplaced before the precipitation of most quartz. Later phases precipitated in the deep subsurface include illite, chlorite and hematite. Minor dolomite and abundant kaolinite appear to be the latest phases, and may have formed under shallow conditions. Enhanced reservoir conditions may have been preserved from the effects of diagenesis in oil-saturated reservoirs that have remained unbreached.

The dolomitic units, primarily in the McArthur Group, have also had a complex diagenetic history. Very early changes include dolomitization and chertification of the carbonate muds, and formation of vuggy porosity associated with local unconformities and vadose zones. Subsequently a series of amorphous silica and crystalline quartz cements were precipitated, partly occluding the secondary pore space. Hydrocarbon was emplaced in Yalco and Looking Glass Formations after the quartz, and largely before deposition of the last phase of sparry dolomite cements. Moderate reservoir enhancement may be expected in unbreached oil-saturated reservoirs, where the formation of late-stage dolomite would have been inhibited.

Based on the results of the 1982 program, it is apparent that reservoir quality, while still adequate, is lower than predicted by results of the 1981 program. Specifically, we do not consider the Jalboi or Arnold Members of the Abner Formation, the Limmen Formation, or the Lynott Formation within the central Batten Trough, to have adequate reservoir potential. In addition, the 1982 program has revealed pervasive diagenetic reduction of reservoir quality in all units. We now consider early migration of hydrocarbons with consequent inhibition of diagenesis critical to the prospectivity of the area.

10. ORGANIC GEOCHEMISTRY

10.1 Introduction

Based on results of the 1981 field mapping and corehole program, several formations were defined as having potential for acting as source beds for hydrocarbon. These were primarily the Barney Creek and Lynott Formations of the McArthur Group, and the Mainoru Formation of the Roper Group. In addition, several other formations, discussed below, were considered to have some degree of source potential.

One of the primary objectives of the 1982 corehole program was to sample as many of the potential source units as possible in the deep subsurface, below the zone of weathering. A standard suite of laboratory analyses was applied by the Tulsa Research Center to selected samples from the eight coreholes, in order to fully evaluate the source rock quality of these units. All samples have been analyzed for total organic carbon content, and those samples with TOC values above the cutoff value of 0.6 weight percent were further analyzed. These additional analyses have consisted of determination of generated hydrocarbon, volatile hydrocarbons, temperature of maximum generation and the molecular distribution of hydrocarbons through chromatographic analysis. The results of all analyses are included in Appendix V.

10.2 Procedure

The first analytical step is to determine the content, in weight percent, of organic carbon present in the samples. This is done by leaching all carbonates from the sample with acid, burning the residue and measuring the amount of carbon dioxide formed. The Tulsa Research Center uses the following rating system for TOC values.

TOC Wt.%	Rating
<0.4	Non-source
0.4-0.6	Poor
0.6-1.0	Fair
1.0-1.5	Good
>1.5	Very Good

In this study, only those samples with values in excess of 0.6 weight percent were considered to have source potential; therefore only they received further source rock analyses.

The second analytical step, applied to these selected samples, is known as Thermal Evolution Analysis (TEA). The TEA pyrolysis method measures both the pre-existing volatile and oil-like hydrocarbons in the rock and the remaining ability of the sample to generate hydrocarbons. The volatile hydrocarbons are measured during low temperature heating of the rock; the quantity present is partly a function of thermal maturity of the sample (see Table 10-1). Typically, oil-prone sediments in the "oil window" will have ratios of volatile hydrocarbon/TOC that are greater than 0.05. Sediments that are either thermally immature or in the past-peak oil to peak gas stage will have ratio values of less than 0.05.

The generated hydrocarbons are measured during higher temperature heating of the sample. For thermally immature samples, the quantity of generated hydrocarbons is a primary measure of the source richness. The ratio of generated hydrocarbon/TOC (convertability) is a measure of the liquid and/or gas generating capability of the kerogen. For thermally immature sediments, low convertabilities indicate a gas-prone source and high convertabilities indicate an oil-prone source. As shown in Table 10-1, however, this ratio may also be low due to a high stage of thermal maturity. The ratio of generated to generated-plus-volatile hydrocarbons is the productivity index, which indicates oil zones at depth.

TEA pyrolysis also yields data on the quantity of bitumen present in the samples. The ratio of bitumen to total organic carbon may be used to define convertabilities, with values greater than 0.05 indicating oil prone source. This ratio may also help indicate degree of maturity, with values greater than 0.05 falling in the early peak oil and peak oil ranges.

Other analyses performed on some samples include chromatography, to measure the molecular distribution of hydrocarbons present, and elemental analysis, which measures the abundance of carbon, hydrogen, oxygen and nitrogen. The percent carbon and O/C ratio are indices of thermal maturity. The hydrogen content and H/C ratio are indices of both thermal maturity and the liquid generating capability of immature hydrocarbons. These facts are all summarized on Table 10-1.

10.3 Results

The laboratory analyses of 1982 corehole samples indicate the following ranking of source rock quality:

Yalco Fm.	-	Locally Good
Lansen Creek Mbr. (Cobanbirini Fm.)	-	Good to Fair
Lynott Fm.	-	Fair to Poor
Mainoru Fm.	-	Non-source
Crawford Fm.	-	Non-source
Dungaminnie Fm.	-	Non-source

In addition, the Corcoran Formation, Reward Dolomite and Barney Creek Formations were untested in 1982, but are considered to have source potential based on published data and results from the 1981 program. The Barney Creek Formation is considered to have the best source potential of all units.

10.3.1 Yalco Formation

Of the several formations encountered in the 1982 corehole program, the Yalco Formation, tested in Coreholes 82-6 and 82-7, yielded the best source rock characteristics. As discussed in Sections 8 and 9, the unit consists largely of silicified algal dolomite with interbedded shale bands. Several of the source rock analyses performed on the Yalco Formation were from samples of such shale bands.

Source quality of the Yalco ranges from non-source to very good, based on total organic carbon content, as shown in Figure 10-1. This formation is organically variable, with TOC values ranging from less than 0.1 weight percent to 7.0 weight percent. The average for the eight samples tested is 1.6 weight percent. A second scale for measuring source richness is the quantity of generated hydrocarbons, also shown in Figure 10-1. The samples show a range of fair to very good quality but are shifted downward slightly, interpreted to be the result of conversion of some source material to hydrocarbon within the formation.

Three methods of estimating thermal maturity are displayed in Figure 10-2. The most discriminating of these is the ratio of generated hydrocarbon to TOC, which indicates an early peak oil to peak oil stage of thermal maturity. The other two methods are less discriminating but seem to indicate a pre-generation to very early peak oil stage. This is also indicated by the Thermal Evolution Analysis temperature curves, shown plotted in Figure 10-3.

The productivity index, also shown in Figure 10-3, is the ratio of volatile hydrocarbon to volatile plus generated hydrocarbon. It is often used to show trends in generation of hydrocarbons, with the ratio normally increasing with depth; zones of anomalously high or low hydrocarbon content indicate migration into and out of the formation, respectively. The few data points plotted on the PI graph of Figure 10-3 appear to show an anomalous trend, and may indicate some concentration of volatile hydrocarbon toward the top of the formation.

All the data, when taken together, indicate that the Yalco Formation is a good to locally very good oil source, in an early peak to peak oil stage of maturity, in which some generation and possible slight migration of hydrocarbons has taken place. These conclusions are based upon a small number of samples, however, and must be used cautiously.

10.3.2 Cobanbirini Formation (Lansen Creek Member)

Encountered in Corehole 82-1 from 374 metres to 569 metres, and in Corehole 82-8 from 7 metres to 12 metres, the Lansen Creek shale displays variable source quality, typically ranging from good to fair. Total organic carbon values range from 4.2 weight percent to 0.0 weight percent, and average 0.7 weight percent (Enclosure 10-1, 10-2). In both coreholes, it appears that the upper portion of the Lansen Creek shale is organically richer than the lower section. Higher TOC values correlate closely with the occurrence of pyrite in Corehole 82-1 (Enclosure 9-3). In addition, the upper section of this unit is distinctly finer-grained in both coreholes (Enclosures 9-3, 9-10). These observations all seem to indicate that the upper Lansen Creek Shale was deposited under low energy anoxic conditions that favored preservation of organic material, and the lower Lansen Creek shale was deposited under slightly higher energy, oxidizing conditions.

Figure 10-4 graphically displays source richness of the Lansen Creek Shale from both Coreholes 82-1 and 82-8. Note that source richness, as measured by generated hydrocarbons, is shifted downward somewhat relative to TOC values. This apparently indicates thermal maturation and generation of hydrocarbon in the subsurface.

Three methods of estimating degree of thermal maturity from TEA data are displayed in Figure 10-5. The ratio of generated hydrocarbon to TOC is the most discriminating, and indicates a peak oil to past peak oil stage. The other two methods, volatile hydrocarbon to TOC ratio and bitumen to TOC ratio, are less precise, but appear to verify a peak oil to past peak oil stage of thermal maturity.

Figure 10-6 displays the degree of thermal maturity based on the temperature at which peak generation occurs during Thermal Evolution Analysis. It indicates that the shales from Corehole 82-1 are in the oil zone (peak oil to past peak oil), whereas the shales from Corehole 82-8 are in the pregeneration to early peak oil stage. This may simply result from a difference in heat flow between the two areas, or it may reflect a shallower depth of burial in the area of Corehole 82-8. This corehole, it will be recalled, was drilled on the Abner Range, a high standing area in the southern Batten Trough. In addition, Roper Group sediments are believed to thin from northwest to southeast, so the depth of burial of the Lansen Creek Shale in the Abner Range area may have been relatively shallow throughout the geologic history of the area.

The Productivity Index, also displayed in Figure 10-6, serves to show the different maturation level for the two corehole locations. The data for Corehole 82-1 reflect the peak oil stage of maturation and also show a well-developed trend toward increasing generation of hydrocarbon with depth. The data for 82-8 display no such trend, and indicate uniformly slight generation of hydrocarbon.

In summary, the Lansen Creek Formation consists of an upper sequence of organic shale, ranging from good to fair quality, and a lower sequence of fair to poor quality silty shales. In the Corehole 82-1 area the unit is at peak oil to past-peak oil stage whereas in the 82-8 area it is in the pre-generation stage. It is expected to be uniformly oil-prone, based on the abundance of algal material in the organics.

10.3.3 Lynott Formation

Encountered in Corehole 82-5 from the surface to the total depth of 455 m, the Lynott Formation displays variable source quality, typically ranging from fair to non-source; a small number of samples fall in the "Good" range (Enclosure 10-2). Total organic carbon values range from less than 0.1 weight percent up to 1.4 weight percent, and average approximately 0.4 weight percent. The distribution of TOC values is also shown in Figure 10-7. Note the high proportion of samples which fall in the non-source area.

Additional analyses were performed on only ten of the richest samples of the original thirty-six. The generated hydrocarbon data derived from these additional analyses are shown in Figure 10-7, and all are qualified as non-source based on this criterion. The strong downward shift in source quality between the two halves of Figure 10-7 indicate that most of the organic material in these samples has been converted to hydrocarbon in the subsurface.

Thermal maturity of the Lynott Formation is graphically summarized in Figure 10-8. All three indices show that the samples have undergone extensive heating and have essentially no generating capability remaining. These results are considered valid as all Proterozoic source material is algal in character, and therefore oil-prone.

Figure 10-9 displays thermal maturity based on the temperature of maximum generation during TEA. The three circled data points in the pre-generation zone at far left are of poor quality; these samples had very low carbon contents. The remaining seven data points fall in the extreme end of the gas zone, indicating an advanced degree of catagenesis. They form a poorly-defined trend of increasing catagenesis with depth. This trend, and resulting thermal cracking of hydrocarbon, are also indicated by the distribution of points on the Productivity Index graph, Figure 10-9. Discounting the three circled data points, the PI forms a poorly-defined trend of decreasing value with increasing depth. The data apparently indicate the breakdown of volatile hydrocarbon caused by high temperature at depth.

In summary, in the vicinity of Corehole 82-5, the middle Lynott Formation is today organically lean and in an advanced stage of thermal diagenesis. One cannot discount, however, the possibility that hydrocarbons were generated and migrated out of this formation during Proterozoic time, resulting in the low source values observed today. Also, there may be other areas within the Batten Trough where conditions were more favorable for the preservation of organic material. In addition, outcrop and core evidence suggests that the middle Lynott Formation consists of many small density-flow deposits, while the lower Lynott was deposited under lower energy, possibly anoxic conditions which may have been more favorable to the preservation of organic material.

10.3.4 Mainoru Formation

Encountered is Corehole 82-2 from surface to 161 metres and from 255 metres to 352 metres, and in Corehole 82-3 from 459 metres to total depth of 592 metres, the Mainoru was expected to be a good potential source unit. Results from source analyses indicate, however, that it is organically lean. TOC ranges from 0.09 weight percent to 0.28 weight percent, and averages 0.18 weight percent (Enclosure 10-1).

Source richness is also graphically displayed in Figure 10-10, and visually demonstrates the very low organic content as measured by both TOC and quantity of hydrocarbon generated during TEA. Note that few samples received TEA analysis.

Thermal maturity estimates are graphically displayed in Figure 10-11. Please note that only three analyses are represented, and no data are available on bitumen content. These very limited data appear to show a past-peak oil to advanced stage of catagenesis, although these ratios become very unreliable for samples with low content of organic carbon, such as these.

In summary, the Mainoru shale appears to be organically lean in the vicinity of Coreholes 82-2 and 82-3. There may be other areas in the

McArthur River area and other stratigraphic portions of the Mainoru shale which were deposited under conditions more favorable to organic preservation. Very limited data indicate that the Mainoru Shale is in a past peak oil to advanced stage of diagenesis; however, these may not be accurate due to poor sample quality. Alternatively, they may not be representative of the formation over the entire permit area.

10.3.5 Crawford Formation

Encountered in Corehole 82-3 from a depth of 288 metres to 459 metres, this unit was considered a possible source bed of secondary importance. A total of six samples were analyzed for TOC content. Values range from 0.15 weight percent to 0.21 weight percent, and average 0.18 weight percent (Enclosure 10-1). One TEA was performed, and showed low values for volatile and generated hydrocarbon. Based on the low values discussed above and the outcrop descriptions of this unit, it is not considered a potential source unit. It was apparently deposited under relatively high energy, oxidizing conditions not favorable to the preservation of organic material.

10.3.6 Dungaminnie Formation

Encountered in Corehole 82-2 from 427 metres to total depth at 493 metres, this unit is the uppermost McArthur Group sediment preserved below the regional unconformity at base of Roper Group. It is described as purple to red siltstone and fine sandstone grading upward to laminated sandy dolarenites (Jackson, et al., 1978). In Corehole 82-2 the Dungaminnie Formation consists of grey siltstone and shales, and red to green shales.

A total of seven samples were analyzed for TOC content. They ranged in value from 0.06 weight percent to 0.15 weight percent, with an average of 0.11 weight percent. One sample was chosen for TEA; the quantity of generated hydrocarbons indicates non-source organic content. Quantity of TOC and hydrocarbons are too low to allow any meaningful estimate of thermal maturity from the single analysis.

In summary, the uppermost part of the Dungaminnie Formation is very lean in organic material in the area of Corehole 82-2, and is rated as non-source. It is probably in a past peak to advanced stage of thermal maturity, based on analyses of the Mainoru Shale, discussed above.

10.3.7 Other Units

The Barney Creek Formation, although untested by the 1982 Corehole program, is considered to have very good source potential, based on the results of the 1981 field and corehole program and previous published reports. One weathered surface sample taken from the Glyde River area during the 1981 field program, tested at 16.3 weight percent TOC in the early-peak to peak oil stage of maturity. In Corehole 81-5, 13 samples ranged from 0.1 to 4.4 weight percent TOC, averaging 0.8 weight percent. In Corehole 81-11, 8 samples ranged from 0.5 to 1.6 weight percent and averaged 1.1 weight percent. Two samples from Amoco Minerals corehole GR-NT-79-1 averaged 1.9 weight percent TOC and have fair to very good oil generating capability, with oil-prone kerogen, in the peak oil stage of thermal maturity. Two samples from Amoco Minerals corehole GR-NT-79-2 average 2.2 weight percent TOC and have good to very good oil generating capability, with oil-prone kerogen in the peak oil stage of thermal maturity. In several other Amoco Minerals and BMR coreholes, a total of twelve core samples contained an average of 2.25 weight percent TOC and were typically at the peak oil stage of thermal maturity.

The Reward Dolomite is considered to be a potential source unit, despite the lack of any geochemical analyses. This formation may have organic material preserved due to the quiet, low energy conditions and abundant algal growth reported from outcrop. The Reward Dolomite was anticipated at depth in Corehole 82-5, but was not encountered due to high dips within the overlying Lynott Shale.

The Corcoran Formation was expected at depth in Corehole 82-8, but was not reached due to hole problems while drilling the overlying Bessie Creek Formation. Three samples from Amoco Corehole 81-15 had an average of 0.5 weight percent TOC and displayed oil prone kerogen that was in the past peak oil stage of thermal maturation. One other subsurface sample, from a non-Amoco corehole, had 0.5 weight percent TOC and oil-prone organics in an advanced stage of catagenesis. This formation is considered a potential source unit of secondary quality, although it is in an ideal position to source both Abner and Bessie Creek Formations, and to seal the former.

10.4 Summary and Conclusions

Over 130 samples from the 1982 corehole drilling program were analyzed for source rock potential. Of the formations tested, the Yalco Formation appears to have the best source rock potential, averaging 1.6 weight percent TOC and having oil-prone algal organic material in an early peak to peak oil stage of thermal maturity.

The Lansen Creek Shale, which was encountered in Coreholes 82-1 and 82-8, displays good to fair source-rock potential, averaging 0.7 weight percent. The best source quality is found in the uppermost part of the shale, which displays evidence of reducing conditions. The thermal maturity of this unit shows great variation between Coreholes 82-1 and 82-8, with 82-1 showing peak oil to past-peak oil stage and 82-8 showing pre-generation to early-peak oil stage. This may be the result of different heat flow values in the two areas or a different burial history, and indicates the danger of classifying the source rock properties of a formation on the data from a single corehole.

The Lynott Formation, encountered in Corehole 82-5, is classified as fair to non-source quality, with TOC averaging approximately 0.4 weight percent. The organic material is oil prone but is in an advanced stage of catagenesis.

The Mainoru Formation, encountered in Coreholes 82-2 and 82-3, is classified as non-source with an average of 0.18 weight percent organic carbon. Thermal maturation estimates are unreliable but indicate past peak oil to advanced stage catagenesis. In addition, both the Crawford and Dungamminnie showed low TOC values and are considered non-source.

It is apparent that the thermal maturity of these units varies rather unpredictably, with highly mature units overlying early-peak units such as the Yalco Formation. We consider this apparent inconsistency to result from the following:

1. The degree of thermal maturity varies from area to area due to differences in depth of burial and/or heat flow values.

2. A degree of unreliability in the geochemical data, caused by both organic leanness and the great age and oxidized character of some samples.

Technical service reports summarizing all test data and conclusions of the Tulsa Research Center personnel concerning source rock quality and thermal history are attached as Appendix V.

11. SEISMIC TEST DATA

11.1 Introduction

In permits O.P. 191 and O.P. 198 our work obligations require the acquisition of seismic and gravity data during the period from August 1982 to September 1983, and continued seismic work between September 1983 and September 1984. Before commencing the acquisition of a major quantity of seismic data in this difficult terrain, test lines were shot during 1982 to investigate the seismic response of the subsurface, and to determine optimum acquisition and processing parameters.

11.2 1982 Field Program

Seismic test data were shot in license O.P. 191 during the 1982 field season, to determine optimum field parameters prior to shooting the obligatory seismic in 1983. A total of 28 km. of vibroseis data were obtained on five separate lines, the longest of which, line 101, is 19 km. The other short lines were recorded primarily to see whether we could record reflections in those areas. In addition, comprehensive testing was performed to establish field parameters, and several wave/noise tests were obtained. The locations of the test lines are shown on Enclosure 11-1.

For most of the work the vibroseis pilot was 14-56 Hz with a 7 second sweep, although various sweeps were tried. A dynamite source was also tried. Line 101 attains a maximum coverage of 24 fold.

Processing of the test data was done in-house and to date, we have been able to reach the following conclusions:

1. The vibroseis source is far more successful than dynamite.

2. 48-fold coverage will be necessary in order to obtain satisfactory data.

3. No serious coherent noise problems were encountered in areas where wave tests were run.

4. Static problems exist but can be resolved through the use of certain acquisition parameters and processing programs.

5. Velocity analyses indicate that seismic velocities are shifted to the very high ranges, in the order of 18,000 to 20,000 fps.

6. We now know those areas in which a vibroseis crew could operate optimally. For example, there are only a few places in the Batten Trough where such a crew could operate economically.

7. A brief seismic testing program is being designed for the initiation of the 1983 survey. Parameters for such a program were obtained from results of the 1983 testing as well as necessary input related to the sign-bit recording system which will be used in 1983.

11.3 Proposed 1983 Seismic Program

The proposed 1983 seismic program, comprising a total of 600 line kilometres of vibroseis, is displayed on Enclosure 11-1.

Three prospective areas have been chosen based upon the following criteria;

1. Closed structures identifiable at surface

2. As thick a stratigraphic sequence as possible, with the better source and reservoir rocks buried at prospective depths.

3. Logistic feasibility and accessibility.

The proposed program is subject to change if the field party finds that some of the areas are inaccessible.

11.3.1 Area 1 - Broadmere Anticline

This area is located in the western portion of O.P. 191 to the north of the Mallapunyah Fault (Enclosures 11-1 and 11-2). Surficial deposits include thin Mesozoic clastics, recent laterite, sand, and alluvium which overly a sequence of Proterozoic rocks. This structure consists of a large anticline which appears to have developed as a result of transcurrent motion along the Mallapunyah Fault coupled with normal movement along northerly-trending faults bounding the Broadmere Trough (see Section 7). To the south, structural closure is provided by a northwest-trending fault observed as a lineament on Landsat images. Estimated area of closure is on the order of 110 square kilometres. As this structure occurs within the Broadmere Trough, McArthur Group units are expected to be similar to those found within the Batten Trough. A summary stratigraphic column, down to a depth of 2500 metres, is shown on Enclosure 11-1.

Prospective reservoir units include the Bessie Creek Sandstone, the Abner Sandstone, the Mt. Birch Sandstone, the Looking Glass Formation, the Yalco Formation, and other carbonate units lower within the McArthur Group. The seismic grid shown, totalling 263 line-kilometres, has been placed to adequately demonstrate closure, particularly on the northwest-trending fault that is thought to close the structure to the south.

11.3.2 Area 2 - St. Vidgeon Area

This 206 line-kilometre vibroseis survey is situated in the northwestern portion of O.P. 198. (Enclosures 11-1 and 8-3). Physiographically, the area is generally plateau-like with low rounded hillocks and local thin mesa-like cappings of Mesozoic clastics. Surficial deposits of laterite, sand, soil and alluvium are present. Structures within the area consist of a series of en echelon folds developed along northerly-trending, right-lateral, strike-slip faults. Precise locating of fold axes in the survey area was not possible due to the outcropping nature of the Kyalla Member, which consists of an interbedded sequence of silts and shales. Topography and drainage deflections were used to locate the fold-axes shown. The sedimentary sequence present in the vicinity includes Roper Group clastics and a McArthur Group sequence of carbonates and clastics. Potential reservoirs include the Bessie Creek Sandstone, the Abner Sandstone, the Kookaburra Creek Formation carbonates, Yalwarra Member clastics, and Mt. Birch Sandstone conglomerates and sandstones. Potential McArthur Group source rocks remain untested in this region. The seismic grid exhibited is designed to best delineate domes present within this area.

11.3.3 Area 3 - Cox River Area

This survey area, comprising 131 line kilometres of seismic, is located in the southwestern corner of O.P. 198 (Enclosure 11-1). Surficial units consist of local thin Mesozoic mesa-croppings overlying thin, flat-lying Cambrian sandstones. Deeply incised gorges exist in portions of this area, therefore careful field scouting of seismic line locations is required. En echelon anticlines, similar in morpohology and areal extent to those in the vicinity of Corehole 82-4, are developed along a major, north-trending, right-lateral, strike-slip fault. The top of the Proterozoic sequence could be as high in the section as the Cobanbirini Formation, or as low as the upper units of the Abner Sandstone. McArthur Group sediments, here deposited on a tectonic ridge (inferred from gravity data) (Enclosures 7-2 and 7-3), should consist predominantly of shallow-water carbonate units with numerous hiatuses and unconformities preserved (including porous zones enhanced by paleo-vadose weathering/ dissolution). Prospective reservoirs, dependant upon the stratigraphic level of breaching, include the Bessie Creek Sandstone, the Abner Sandstone, possible sand units within the Mainoru Formation, and McArthur Group sediments consisting of the Kookaburra-Balbirini Formations, possible Mt. Birch Sandstone, Looking Glass Formation equivalents, Yalco Formation equivalents and a probable condensed lower McArthur Group carbonate sequence.

The grid shown is located to identify structures mapped through airphoto interpretation of Cambrian "pseudo-structures." It should be noted that reverse-topographic effects are commonly associated with Cambrian clastics in the McArthur River Area; Cambrian infilling of breached Proterozoic anticlines often results in the formation of apparent Cambrian synclines, and vice versa.

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