GEOLOGY, MINERALISATION
AND EXPLORATION STRATEGY
PINE CREEK INLIER

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TABLE OF CONTENTS

1. INTRODUCTION
2. SUMMARY
3. CONCLUSIONS
4. RECOMMENDATIONS
5. PREVIOUS WORK
6. AZTEC DATA BASE
7. STRATIGRAPHY
   7.1 Introduction
   7.2 Basement
   7.3 Batchelor Group
      7.3.1 Beestons Formation
      7.3.2 Celia Dolomite
      7.3.3 Crater Formation
      7.3.4 Coomalie Dolomite
   7.4 Frances Creek Group
      7.4.1 Whites Formation
      7.4.2 Acacia Gap Quartzite/Mundogie Sandstone
      7.4.3 Koolpin Formation
      7.4.4 Gerowie Tuff
      7.4.5 Mt Bonnie Formation
   7.5 Finniss River Group (Burrell Creek Formation)
   7.6 Middle Proterozoic
      7.6.1 El Sherana Group
      7.6.2 Katherine River Group
      7.6.3 Edith River Group
      7.6.4 Tolmer Group
   7.7 Cambrian - Ordovician (Daly River Group)
   7.8 Jurassic - Cretaceous
8. INTRUSIVES
   8.1 Dolerites
   8.2 Lamprophyre and other Dykes
   8.3 Concordant Granites
   8.4 Discordant Granites
9. METAMORPHISM
   9.1 Early Thermal Metamorphism
   9.2 Regional Metamorphism
   9.3 Granite Contact Metamorphism
10. STRUCTURAL GEOLOGY

10.1 Bedding Concordant Structures
10.2 Cosmic Faults
10.3 Doming
10.4 Upright Folds and Cleavage
10.5 Transpressional Faults
10.6 Compressional Zones
10.7 Pine Creek Shear and Associated Structures
10.8 South Alligator Faults
10.9 Giants Reef Faults
10.10 North Trending Structures

11. MINERALISATION

11.1 Introduction
11.2 Stratiform Mineralisation
11.3 Polymetallic Veins
11.4 Stockwork/Concordant Gold - Quartz Veins
11.6 Tin Deposits
11.7 Unconformity Related Uranium - Gold - Platinoid Mineralisation

12. HYDROCARBONS

12.1 Hydrocarbons in the Pine Creek Inlier

12.1.1 Source Rocks
12.1.2 Maturation and Timing
12.1.3 Migration
12.1.4 Reservoirs
12.1.5 Traps
12.1.6 Conclusions of Hydrocarbons

12.2 Role in Sulphide Precipitation

12.2.1 Relationship Between Mississippi Valley Type Deposits and Hydrocarbons
12.2.2 Examples of Mississippi Valley Type of Deposits
12.2.3 Discussion

13. GEOLOGICAL HISTORY

13.1 Basin Wide Sedimentation
13.2 Basement Highs
13.3 Compressional Deformation
13.4 Granite Emplacement
13.5 Later Faulting
13.6 Stratiform Mineralisation
13.7 Polymetallic Vein Mineralisation

13.7.1 Timing of Polymetallic Veins
13.7.2 Relationship Between Hydrocarbons and Polymetallic Veins
13.7.3 Regional Scale Distribution
13.7.4 Prospect Scale Distribution

13.8 Stockwork Concordant Gold - Quartz Mineralisation
13.9 Unconformity - Related Mineralisation
14. COMPARISON WITH OTHER PROVINCES

14.1 Introduction
14.2 McArthur River
14.3 Mt Isa
14.4 Glengarry Basin
14.5 Broken Hill
14.6 Mississippi Valley
14.7 Zambian Copperbelt
14.8 Reefton
14.9 Bendigo/Ballarat
14.10 Forrestania

15. EXPLORATION STRATEGY

15.1 Commodities and Mineralisation Style
15.2 Districts

15.2.1 Lloyds Creek
15.2.2 De Monchaux Creek
15.2.3 Woodcutters
15.2.4 Waterhouse
15.2.5 Kylie - Mt Mabel
15.2.6 Tumbling Waters
15.2.7 Rum Jungle Embayment
15.2.8 Darwin River - Acacia
15.2.9 Maureen - Mt Woods
15.2.10 Adelaide River
15.2.11 Mt Bundey
15.2.12 Plateau Point - Green Ant Creek
15.2.13 Howley
15.2.14 Ringwood
15.2.15 Brocks Creek - Golden Dyke - Burundie
15.2.16 McKinlay River
15.2.17 Frances Creek - Jessops
15.2.18 Allamber
15.2.19 Mary River
15.2.20 Union Reefs - Pine Creek
15.2.21 McCarthy's - Moline - Little Mary
15.2.22 Driffield - Mt Todd
15.2.23 Daly River
15.2.24 Fletchers Gully
15.2.25 Eva Valley

16. REFERENCES
LIST OF TABLES

1. Stratigraphy of the Pine Creek Inlier
2. Temporal Relationship of Structural Elements in the Pine Creek Inlier
3. Pine Creek Inlier - Examples of Stratiform Mineralisation
4. Pine Creek Inlier - Examples of Polymetallic Vein Mineralisation
5. Hydrocarbon Generation Criteria - Pine Creek Inlier
6. Pine Creek Inlier - Examples of Stockwork/Concordant Gold Quartz Mineralisation
7. Pine Creek Inlier - Examples of Unconformity - Related Uranium - Gold - Platinoid Deposits.

LIST OF ENCLOSURES

1. 1:100,000 Scale Geology - Rum Jungle
2. 1:100,000 Scale Geology - Mary River
3. 1:100,000 Scale Geology - Ranford Hill
4. 1:100,000 Scale Geology - Pine Creek
5. 1:100,000 Scale Geology - Daly River
LIST OF FIGURES

1. Location of Major Tectonic-stratigraphic Units in the Katherine - Darwin Region.
2. Status of Aztec Regional Compilation
3. Geology of the Rum Jungle/Waterhouse Area
4. Distribution of the Zamu Dolerite, Cosmic Faults and Thrust Faults - Pine Creek Inlier
5. Concordant Granites, Basement, Cosmic Faults and D_2 Fold Trends - Pine Creek Inlier
6. Concordant Granites, Discordant Granites and Bouguer Gravity Anomalies - Pine Creek Inlier
7. Bouguer Gravity and Cosmic Faults - Rum Jungle/Waterhouse Area
8. Different Interpretations of Cosmic Fault Location - Waterhouse Area
9. Seismic and Interpreted Cross Section through the Woodcutters Mine
10. Distribution of D_1 Faulting and D_2 Folding - McCarthy's and Frances Creek Areas
11. Interpreted Relationship between Concordant Shears/Breccias and Folding, McCarthy's Area
12. Howley Anticline Cross Section
13. Woodcutters Mine - Cross Section 4910N
14. Woodcutters Mine - Interpreted Geology 890RL
15. Little Mary Prospect - Interpreted Surface Geology
16. Distribution of Diapiric Basement Compressional Zones and Bouguer Gravity - Pine Creek Inlier
17. Simplified Geology of the Pine Creek Inlier
18. Deformations around constrained and unconstrained diapirs
19. Fold - Thrust Structures
20. Granite Magma Generation with Pressure Release
21. Stratigraphic Distribution of Stratiform and Polymetallic Vein Mineralisation - Pine Creek Inlier
22. Distribution of Diapiric Basement, Polymetallic Vein and Stratiform Deposits - Pine Creek Inlier
23. Pine Creek Inlier - Basin Subsidence and Diapiric Basement Uplift Rates Over Time
24. Woodcutters Mine - Longitudinal Projection - 1 and 3 Systems
25. Woodcutters Mine - Longitudinal Projection - 5 system
26. Woodcutters Mine - Mineralisation in Dilational and Tensional Structures
27. McCarthy's Prospect - Thickening of Mineralisation in Possible Dilational Zone
28. Woodcutters Mine - Longitudinal Projections showing Ag/As Ratio for 1 and 3 orebodies
29. Woodcutters Mine - Geochemical Zonation 3N Orebody 950RL
30. Woodcutters Mine - Time - depth burial curves
31. Southeast Missouri, U.S.A. - Regional Gas Cap
32. Central Shield of North America - Palaeozoic Stratigraphic Table showing oil and ore distribution
33. Distribution of oil and ore occurrences around the Ozark Uplift, North America
34. Sorby Hills - Location and Geology of Onshore Bonaparte Basin
35. Sorby Hills - Geological Map and Cross Sections
36. Coxco Location and McArthur River District Geology
37. Coxco Deposit - Geology
38. Distribution of Diapiric Basement, Compressional Zones, Pine Creek Shear, and Stockwork/Concordant Gold - Quartz Deposits
39. Stereographic Projection of Poles to Stockwork/Concordant Gold - Quartz Vein Sets - Pine Creek Inlier
40. Distribution of Tin Deposits and Discordant Granite - Pine Creek Inlier
41. Distribution of Basement Diapirs, Archaean Granitoids and Unconformity - Related Deposits - Pine Creek Inlier
42. Distribution of Basement Highs, Wollogorang Formation, McArthur Group and Base Metal Deposits - Batten Trough, McArthur Basin
43. Basement Highs, Mt Isa Group, Mary Kathleen Group and Base Metal Occurrences - Mt Isa Inlier
44. Spatial Distribution of Gold and Copper Mineralisation and Basement Highs, Glengarry Basin, W.A.
45. Bouger Gravity - Broken Hill Area
46. Distribution of Base Metal Mineralisation and Basement Depth - Southeast Missouri, U.S.A.
47. Surface Geology of Karila Bomwe - Nachanga Area
48. Zambian Copperbelt - Stratigraphic Section and Facies Diagram
49. Reefton Goldfield, N.Z.
50. Bendigo/Ballarat - Distribution of Gravity Lows, Fold Axial Planes and Gold Mineralisation
51. Forrestania Greenstone Belt - Distribution of "Syntectonic Granites" and Gold Mineralisation
52. Pine Creek Inlier - Exploration Districts and Localities
1. INTRODUCTION

The Pine Creek Inlier covers about 45,000 square kilometres in the Katherine to Darwin area (Figure 1). The Inlier consists of a deformed Early Proterozoic sedimentary/igneous sequence overlying Archaean and older Early Proterozoic basement. It hosts numerous showings and significant resources of uranium, gold, base metals and tin and has been subjected to a considerable amount of exploration and geological study.

Aztec have a significant interest in the Inlier due to their ownership of the Woodcutters Mine; large exploration tenement holdings; their corporate objective of exploring for and mining gold and base metals; and their considerable data base and experience in the region.

This report summarises the geological data on the Inlier, describes the distribution of mineral occurrences and elaborates on exploration models. Further exploration opportunities for gold and base metals are identified and courses of action recommended.
2. SUMMARY

Sedimentation in the Pine Creek Inlier occurred during two main periods - from about 2450 to 2300 ma, and from 2200 to 1800 Ma. Metamorphism and deformation occurred between the two. Although the second period of sedimentation may have started in a tensional regime, it is likely that compression and associated deformation began midway through the second sedimentary period, and continued during subsequent regional metamorphism. The effects of this compressional deformation were locally modified above and around rising diapirs of granitic Archaean basement. This diapiric movement probably began during the first period of sedimentation, and continued throughout the second period and during compressional deformation.

The relaxation of compression allowed some rising sialic basement to melt, forming younger granite plugs. Some magma continued to rise and spread, resulting in extensive granite sills. Uplift and erosion was followed by the deposition of Middle Proterozoic sediments.

Gold and base metal mineralisation occurred during sedimentation and compressional deformation. Possible interaction with hydrocarbons determined the style of deposits formed. Gold mineralisation also continued after the relaxation of compression and during the sedimentation of the overlying Middle Proterozoic.

Although mineralisation during these periods takes different forms and has different local structural, stratigraphic and lithological controls, most mineralisation occurs closely around, and often between, bodies of diapiric basement.

The techniques used to recognise the position of diapiric basement and the close association between this and a number of different metal deposit types are tested in different mineral provinces.

The relative potential of different districts within the Pine Creek Inlier are assessed in terms of the patterns described.
3. CONCLUSIONS

- The main (later) Early Proterozoic sedimentary sequence is underlain by a basement of Archaean and older Early Proterozoic rocks.

- Some published regional stratigraphic studies incorrectly correlate a number of units within the later sequence, and some units between this sequence and the basement. This study shows that the Acacia Gap Quartzite is correlative with the Mundogie Sandstone; and the Masson Formation is correlative with the Whites Formation. The Wildman Siltstone is an obsolete unit with its equivalents now assigned to either the Koolpin Formation or Whites Formation.

- Regional compression began during sedimentation and was marked by the basin wide deposition of fyschoid turbidites (Acacia Gap Quartzite/Mundogie Sandstone, lower member of Mt Bonnie Formation and Burrell Creek Formation) and early deformation of the sedimentary sequence.

- Centres of granitic material within the Archaean and older Early Proterozoic basement acted as rising diapirs during and after sedimentation and compression of the Early Proterozoic sequence. These modified the structure of the surrounding and overlying sediments and possibly acted as a heat source for hydrothermal fluids. The distinctive faults which bound the diapirs are called cosmic faults. After the relaxation of regional compression, some rising diapirs melted, forming younger granite intrusives.

- Stratiform mineralisation occurs within the Frances Creek Group around and between closely spaced basement highs. It is most common adjacent to transpressional and cosmic faults. Reasonably systematic changes in the composition of this mineralisation occurs through the stratigraphic sequence.

- Polymetallic vein deposits are hosted by concordant and transpressional faults within the Frances Creek and Finniss River Groups. These deposits are clustered around and between closely spaced basement highs in districts with restricted occurrences of stratiform mineralisation. Interaction of mineralising fluids with hydrocarbons possibly explains the district-scale and local distribution of polymetallic veins. The composition of polymetallic veins and the trends of changing composition through the sequence show similarities with stratiform mineralisation.

- Stockwork/concordant gold-quartz mineralisation is hosted by interbanded brittle and ductile lithologies in the Upper Frances Creek and Finniss River Groups. Although these deposits occur mainly within compressional zones and the Pine Creek Shear corridor, they do not appear to occur along fault zones on a prospect scale.

- Unconformity related mineralisation occurs in Early Proterozoic rocks which were accessed by fluids produced during the sedimentation and diagenesis of overlying Middle Proterozoic rocks. This access was gained via faults and karst cavities. Proximity to Archaean basement (and subsequent associated younger granites) was also important.

- A similar relationship between basement highs, sedimentation, doming, compressional folding and gravity highs can be demonstrated in a number of other provinces.

- Consideration should be given to the possibility that many "syntectonic" granites in other provinces represent pre-tectonic basement blocks that have been recrystallised and remobilised during compressional deformation.

- The spatial relationship between basement highs and a number of different deposit types in different provinces confirms the importance of this pattern in the Pine Creek Inlier and suggests it could be used successfully elsewhere as an exploration tool.
4. RECOMMENDATIONS

- Exploration for stratiform mineralisation should concentrate on zinc deposits between the Fenton, Prices Springs and Burnside highs; copper deposits in the Allamber area, particularly where basement embayments are indicated; and perhaps copper mineralisation in embayments in the Rum Jungle/Waterhouse area.

- Although the most significant occurrences of polymetallic vein mineralisation occur in compressional faults, concordant hosts should not be dismissed. These deposits should be drilled down plunge, rather than down dip (cf previous drilling at Acacia North, Waterhouse and McCarthy's). Possible relationships between these deposits and palaeo-hydrocarbon accumulations should be considered on a prospect scale; for example double plunging anticlines would be particularly favourable.

The location of the Acacia South anomalies between basement highs, together with the coincidence of a number of other favourable features, suggests particular emphasis should be placed on this area, if target depths are not excessive.

- The Daly River district has many favourable features indicative of a major polymetallic zinc occurrence. Its acquisition should be a major priority.

- A number of probable compressional zones with favourable stratigraphy appear poorly tested for stockwork/concordant gold quartz mineralisation. These include the Tumbling Waters, Green Ant Creek and McKinlay River areas. Further investigation of these, as well as the extension of other recognised compressional zones, is warranted.

- The Allamber and Rum Jungle/Waterhouse (in particular Kylie) areas should be explored for unconformity gold deposits.

- Some of the principles outlined in this report should be applied to Aztec's exploration elsewhere, for example, in the Halls Creek region, Bangemall Basin, McArthur Basin, Mt Isa Inlier and perhaps Archaean greenstone belts, if that is not already being done.
5. PREVIOUS WORK

Mining, exploration and geological studies have passed through a number of stages since the first discovery of gold in the Inlier in 1864.

5.1 1864 - 1915 Mining and Prospecting

Gold was first discovered at the Finnis River in 1864. More significant finds in the early 1870's were followed by a rush involving small scale prospecting and mining which continued until the early 1900's. In addition to the numerous gold deposits found during this period (Enterprise, Cosmo Howley, Union Reefs, Brocks Creek, Moline), tin (Mt Finniss, Mt Wells, Hayes Creek), copper (Daly River, Iron Blow) and silver - lead (Evelyn) were also discovered. Jones (1987) describes the history of this period and cites other relevant references.

5.2 Depression Gold Mining

During the 1930's, a period of relatively high gold prices encouraged another flurry of activity. Further exploration and mining concentrated on the better, previously discovered prospects. Only minor production resulted. Descriptions of individual prospects are contained in a number of reports by Hossfeld, Rayner, Sullivan and Blanchard referenced by Crohn in Walpole et al (1968).

5.3 1950's and 1960's Uranium and Base Metal Mining

In 1949 uranium was discovered at Rum Jungle. Extensive follow-up over the next 20 years by the BMR and Territory Enterprises led to the discovery of a number of base metal and uranium mines and prospects including Whites, Browns, Dysons, Intermediate, Area 55, Mt Fitch and Woodcutters. A compilation of available literature on this period is contained in Nicholson et al (1991).

During the same period uranium and base metal mineralisation was also discovered and exploited in the South Alligator Valley/Moline area, mainly by United Uranium N.L. Descriptions on the geology from this period are referenced in Crohn in Walpole et al (1968).

The BMR completed the first regional mapping of the region at this stage. Their description of the geology is contained in Walpole et al (1968).

5.4 1970's Uranium Base-Metal Period

The major uranium discoveries in the Alligator Rivers area (Ranger, Jabiluka, Koongara, Nabarlek) in the late 1960's and early 1970's caused a resurgence of interest in the region. At the same time, relatively high base metal prices saw regional exploration for these commodities, mainly by CRA and Peko.

Descriptions of regional and deposit studies completed during this stage are contained and cited in proceedings of the conference on 'Uranium in the Pine Creek Geosyncline' held in Sydney in 1979 (Published by IAEA, 1980) and the AusIMM Conference Darwin, 1984. The BMR and N.T. Geological Survey remapped much of the region and published new 1:100,000 scale maps.
5.5 1980’s To Present Gold Exploration

Increased gold prices after 1980 led to increased exploration. A number of virgin discoveries were made including Goodall, Batman (Mt Todd), Tom’s Gully and Webers Gap. In addition, major extensions of previously discovered deposits were defined, (Cosmo Howley, Enterprise, Union Reef, Moline, Mt Bonnie, Golden Dyke, Chinese Howley, Woolwonga and Brocks Creek).

Descriptions of some deposits are contained in the 1984 AusIMM Darwin Conference volume, the Bicentennial Gold 1988 Excursion Guidebook for NT Gold Deposits (Geology Department and University Extension of University of W.A. Publication No. 16) and the Geology of the Mineral Deposits of Australia and Papua New Guinea (AusIMM Monograph No. 14).

Regional structural studies completed during this time include Johnston (1984).
6. **AZTEC DATA BASE**

There are four principle sources of data on the Pine Creek Inlier available to Aztec:-

1. Open file company reports;
2. Government agency reports and surveys (BMR, NTGS);
3. Projects offered to Aztec/Nicron;
4. Previous exploration by Aztec/Nicron.

In order to systematically compile and interpret this data, the following work has been completed:-

- Preparation of standard 1:25,000 topographic base plans over the Pine Creek Inlier by photo enlarging 1:50,000 government topographic plans;
- Systematic detailed literature search of company and government open file reports at the N.T. Department of Mines and Energy - a summary card was prepared for each report and hard copies obtained of the most relevant reports and maps;
- Computer digitisation of all geochemical sample sites and assay data;
- Presentation of data on standard 1:25,000 sheets, -

1. Geochemistry - includes soil and RAB traverses, drill holes, stream and rock chip sample points identified by company;
2. Geophysics (a) Airborne magnetics;
   (b) Airborne radiometrics;
   (c) Gravity;
3. Geology (a) Company mapping;
   (b) BMR/NTGS mapping;
   (c) In-house interpretation.

The data base and geological interpretation plans are continually updated with new data from Aztec’s investigations and from file reports of other exploration.

Detailed compilation has been completed over all of the Aztec project areas and is presently underway in surrounding areas (Figure 2).

In addition, geological interpretation of the Pine Creek Inlier was compiled at a 1:100,000 scale using:-
- In-house landsat images;
- Aztec 1:25,000 geology interpretations;
- NTGS/BMR geology;
- NTGS/BMR/company geophysics.

Each facet of the data base is used as an integral component of target generation, exploration programme planning and data recording.
7. STRATIGRAPHY

7.1 Introduction

The stratigraphy of the Pine Creek Inlier and overlying sediments is set out in Table 1. In this review it is assumed that the medium grade metamorphics of the Alligator Rivers, Litchfield, Woolner, Rum Jungle and Waterhouse areas are all correlatable and represent older, Early Proterozoic basement to the main Early Proterozoic sediments of the Pine Creek Inlier. Strong evidence for this relationship, which is consistent with our experience, is presented by Perring (1980) and Ferguson (1980). This conflicts with the interpretations of Needham et al (1980) and Needham and De Ross (1990).

In addition, we believe that the Mundogie Sandstone correlates with the Acacia Gap Quartzite, rather than the Crater Formation (cf Needham et al, 1980; Needham and De Ross, 1990). This is indicated by their similar lithology; the close correlation of the sequences immediately above both units in the Rum Jungle/Waterhouse and McCarthy’s/Mt Masson areas; and the similarity of the lithologies now recognised under the Mundogie Sandstone in the Allammer area (Earthrowl, 1988; Harrop, 1989) to the Whites Formation, Coomalie Dolomite and Crater Formation which underlie the Acacia Gap Quartzite in the Rum Jungle/Waterhouse area. This questions the need for the Masson Formation, which is here interpreted to correlate with the Whites Formation and the Wildman Siltstone, which is here correlated with the Koolpin or Whites Formation. It is considered here that the Whites Formation, Acacia Gap Quartzite/Mundogie Sandstone, Koolpin Formation, Gerowie Tuff and Mt Bonnie Formation represent one distinctive period of sedimentation, and are here referred to as the Frances Creek Group.

7.2 Basement

The younger Early Proterozoic sediments are bounded on the western and eastern margins by high-medium grade metamorphic complexes and granites. Similar lithologies are surrounded by younger Early Proterozoic sediments in the Rum Jungle/Waterhouse and Woolner areas.

The oldest exposed rocks are Archaean granite (Rhodes, 1965; Johnson, 1974; Needham and Stuart-Smith, 1980) which include parts of the outcropping Rum Jungle, Waterhouse and Nanambu Complexes. The Archaean Woolner Granite is covered by thin Cretaceous cover (Perring, 1980; Pietsch, 1986) and it is possible Archaean granites also occur in the Litchfield complex.

The granitic lithologies have been dated at 2550-2450 Ma in the Rum Jungle/Waterhouse area (Richards et al, 1966; Compston and Arriens, 1968); 2675 Ma in the Woolner Area (Williams and Compston, 1983) and 2470 Ma in the Nanambu Complex of the Alligator Rivers area (Page et al. 1980).

The basement provinces also include outcrops of medium to high grade metamorphosed sediments and volcanics. These include units within the Rum Jungle/Waterhouse Complexes (Rhodes, 1965; Johnson, 1974; Pietsch, 1989); the Dirty Water/Metamorphics in the Woolner area (Perring, 1980; Pietsch, 1985); metamorphics of the Litchfield Complex (Pietsch, 1985); and Kakadu Group, Cahill Formation, Nourlangie Schist and Myra Falls metamorphics of the Alligator Rivers area (Needham and Stuart-Smith, 1980; Needham and DeRoss, 1990). Most of the areas contain schists, gneisses, iron formation, amphibolite, quartzite, metaarkose and dolomitic and magnesitic marble. The Myra Falls Metamorphics also contain migmatite and lit-par-lit gneiss (Needham and Stuart-Smith, 1980).

These sediments were originally deposited from 2400-2100 Ma. They were at least partially deformed and metamorphosed prior to the start of deposition of the main (younger) Early Proterozoic sequence at about 2000 Ma, as indicated by the presence of metamorphosed fragments in the basal Early Proterozoic sequence (French, 1969).
7.3 Batchelor Group

This unit crops out in the Rum Jungle/Waterhouse area. Correlatives almost certainly occur in the Allamber area (Earthrowl, 1988; Harrop, 1989) and the Woolner area (Piestch, 1985), where they are covered by recent sediments.

7.3.1 Beestons Formation

This formation unconformably overlies the eastern side of the Rum Jungle and Waterhouse Complexes were it has a chloritic sheared contact with the basement (French, 1969). The succession comprises basal conglomerate, quartz sandstone and pebbly arkose (French, op cit). Clasts of schist, quartzite and quartz occur in the conglomerates and arkose. This unit was probably deposited in a fluvial environment. Rapid thickness changes and absences occur along strike.

7.3.2 Celia Dolomite

This unit is consists dominantly of massive crystalline dolomite and magnesite which display stromatolitic textures in places (Walpole et al, 1968, French, 1969; Bone, 1985). Stephansson and Johnson (1976) report the unit has been extensively altered to a tremolite, biotite phlogopite rich schist in places. Recent drilling indicates dolomitic and magnesite-rich intervals have conformable contacts although they interfinger along strike.

Exposures of the Celia Dolomite closely follow and conformably overlie Beestons Formation. They only occur on the eastern side of the Rum Jungle and Waterhouse Complexes. The Celia and overlying Coomalie dolomite are often overlain by younger sediments which fill an irregular karstic topography.

Bone (1985) concluded that the Celia and Coomalie dolomites were deposited in shallow, marine evaporitic environments.

7.3.3 Crater Formation

The Crater Formation almost completely surrounds the outcropping complexes. It comprises a basal hematite boulder conglomerate with iron formation and quartz clasts, which grades upwards into quartz greywackes, sandstones, shale and hematitic siltstone (French, 1969). The Crater Formation is characterised by an intermittent magnetic response (possibly magnetite rich banding) and a strong radiometric response caused by detrital thorium bearing minerals. Earthrowl (1988) reported conglomerates underlying dolomite in the basal sequence of sediments in the Allamber area. It is likely that these conglomerates are equivalents of the Crater Formation.

As with the Beestons Formation, the Crater Formation is likely to have had a fluvial origin, although it has a more continuous distribution.

7.3.4 Coomalie Dolomite

The Coomalie Dolomite is lithologically very similar to the Celia Dolomite except that it is comparatively less altered. (Walpole et al, 1968; French, 1969; Bone, 1985). It outcrops almost continuously around the Rum Jungle/Waterhouse Complexes and it is most likely equivalent to the dolomite reported by Earthrowl (1988) in the Allamber area and the Koolpinyah Dolomite in the Woolner area (Piestch, 1985). Massive limestone overlain by thinly bedded calcareous sediments around Evelyn Mine is possibly also Coomalie Dolomite.

7.4 Frances Creek Group

7.4.1 Whites Formation

Lithologies mapped by other workers as the Masson Formation and parts of the Wildman Siltstone, are considered here to be included in the Whites Formation.

The Whites Formation is known in most detail around the Rum Jungle/Waterhouse and Acacia Domes where it is described in detail by Meizits (1969), Ormsby, (1990, 1992) and Nicholson et al (1991). It is also exposed and described in the Allamber and Mundogie/Evelyn areas (Walpole et al., 1969; Earthrowl, 1988).

The predominant lithology is carbonaceous dolomitic mudstone. Carbonate, quartzite, tuffaceous and graphite-rich interbeds occur in a lesser proportions and allow detailed stratigraphic subdivision (Nicholson et al., 1991).

The carbonate content of the Whites Formation decreases upwards, and thin, turbiditic quartzite beds start to appear towards its top. This is consistent with increasing water depths during deposition of the Whites Formation.

7.4.2 Acacia Gap Quartzite/Mundogie Sandstone

The lithostratigraphic sequence established at Allamber (Earthrowl, 1988), McCarthy's (Butler, 1992) and Rum Jungle/Waterhouse (Nicholson et al., 1991) clearly indicates that Acacia Gap Quartzite and Mundogie sandstone are stratigraphically in the same position and are equivalent to each other. They both comprise quartzite, quartz grit, conglomerate, greywacke and carbonaceous mudstone. The greywacke, quartzite and conglomerate beds exhibit grading, scoured base, intraformational shale clasts and sometimes cross-bedded tops, where they have been drilled is in the Mundogie (Darby, 1985), McCarthy's (Butler, 1992), Woodcutters (Ormsby, 1990) and Acacia (Grove, 1993 a) areas. These textures indicate a turbidity/mass flow origin for the coarse clastics (cf Stuart-Smith et al., 1980). The occurrence of mass flow conglomerate in the McCarthy's area is indicative of a very proximal sediment source (Walker, 1979). Walpole, et al., (1969) describe ripple marks and cross bedding in places, indicating possible tidal current in a platform environment. Stratiform pyrothite occurs near the base and top of this group (Butler, 1992; Ormsby, 1992) and results in a characteristic high magnetic response.

The coarse clastics of these formations are continuous around the whole Inlier, except where disrupted by faulting. Only in the Waterhouse area can these units be shown to lens out completely. Significant thickness variation is known in many areas. This basin wide sedimentation of coarse clastics is consistent with uplift of adjacent areas and resultant increase in sediment availability.

7.4.3 Koolpin Formation

The Koolpin Formation comprises carbonaceous mudstone, mudstone, siltstone, pyrrhotitic carbonaceous mudstone, limestone/dolomite, argillaceous silicate iron formation, chert and minor greywacke. Carbonaceous mudstone and iron formation beds are continuous throughout the Inlier. Limestone-rich sections are only locally known in the Darwin River, South Alligator Valley and Burrundie areas. These probably indicate shallower water environments, particularly where stromatolitic (Walpole et al., 1969, South Alligator Valley). Greywacke-rich facies (for example at Glenluckie-Waterhouse) probably indicate a sediment source nearby.

The Koolpin Formation also includes the sediments assigned by other workers to Wildman Siltstone, above the Acacia Gap Quartzite/Mundogie Sandstone. Its lithological composition and local stratigraphic subdivisions have been described in the Glenluckie-Waterhouse (Nicholson, 1987), Darwin River (Grove, 1993b), Mt Bundey (Simpson, 1990), Craig Creek (Walpole et al., 1969), South Alligator Valley (Walpole et al., 1969; Valenta, 1991), McCarthy's (Butler, 1992a), Burrundie (Butler, 1992b), Golden Dyke (Nicholson, 1978; Nicholson, 1980), Cosmopolitan Howley (Nicholson, 1982; Alexander et al., 1990) and Mt Paqualin (Nicholson, 1983) areas.
7.4.4 Gerowie Tuff

The Gerowie Tuff consists of tuff, tuffaceous chert, chert, mudstone and siltstone (Nicholson and Eupene 1984). It has been described in detail in specific districts by Nicholson (1978), Wilkinson, (1982) and Goulevitch (1980). This formation represents a basin-wide, mudstone-rich sequence with interbeds of diagenetically altered distal tuff. The volcanics in the Daly River area probably represent a more volcanically proximal equivalent of this unit.

7.4.5 Mt Bonnie Formation

The Mt Bonnie Formation has been described locally in the Glenluckie-Waterhouse (Nicholson, 1987), Rustler's Roost (Higham, 1989), Little Mary (Butler, 1992c), Mt Bonnie (Goulevitch, 1980), Cosmopolitan Howley (Wilkinson, 1982) and Woolwonga areas (Kavenagh and Vooy, 1990). It contains interbedded mudstone, tuffaceous chert, siltstone, chert, carbonaceous mudstone, greywacke and magnetite-hematite iron formation. A greywacke-rich sub-unit near the base of the formation and iron formation beds near the top of the formation appear extensively and possibly continuously through out the Inlier. Mass flow conglomerate deposits have a very restricted distribution (Goulevitch, 1980).

Nicholson and Eupene (1989) suggest a relatively deep water environment of Koolpin-Gerowie-Mt Bonnie deposition punctuated by periods of basin instability. Circulation was often restricted and clastic supply limited, allowing the deposition of carbonaceous mudstone and iron formation beds. The widespread greywacke unit in the Mt. Bonnie Formation represents another period of plentiful sediment supply and flyschoid deposition. The conglomerate beds indicate local erosion and intra-basin sediment availability.

7.5 Finniss River Group (Burrell Creek Formation)

This is a thick flysch sequence of interbedded greywacke, mudstone and minor conglomerate which forms the upper part of the Early Proterozoic succession and conformably overlies the South Alligator Group. Local descriptions are contained in Pietsch (1989), Higham (1989), Warren et al (1983), Dann and Delaney (1984), Smith (1988) and Nihill (1989).

A two fold stratigraphic subdivision of the Burrell Creek Formation is tentatively proposed here. A lower member has an irregular, uneven TM and aerial photo texture. Conformable subtle aeromagnetic anomalies indicate some beds contain magnetite or pyrrhotite. The upper member contains prominent beds that can be traced for many kilometres on TM images. These have commonly been mapped as feldspathic grits. The upper member has a relatively flat aeromagnetic response. Both subunits appear to attain thicknesses of over 2 km.

As the Burrell Creek Formation predominantly consists of turbidite sequences with little evidence of reworking, accumulation rates must have been rapid. The large thickness of the unit indicates this was mainly due to rapid subsidence rather than infilling of topographic lows during a marine regression. The rare local presence of conglomerate beds, for example in the Waterhouse (Pietsch, 1989) and Little Mary (Nicholson, 1981) areas indicate close proximity to a sediment source, that is, an eroding area within the basin.

7.6 Middle Proterozoic

7.6.1 El Sherana Group

This group was deposited in the transitional period between the cessation of Early Proterozoic basin sedimentation and the beginning of Middle Proterozoic McArthur Basin sedimentation. It rests unconformably on the Early Proterozoic and comprises a suite of subaerial felsic volcanics and valley fill sediments (Needham and De Ross, 1990) consisting of rhyolite, greywacke, siltstone, sandstone and basalt (Walpole et al, 1968).
7.6.2 Edith River Group

The Edith River Group is also transitional and interpreted to be comagmatic with the Middle Proterozoic granites. It comprises rhyolitic and dacitic tuff, ignimbrite, basalt, sandstone and conglomerate, and unconformably overlies El Sherana Group, Early Proterozoic sediments and granites (Needham et al., 1980). The Tollis Formation, which has been mapped as part of this Group by the BMR, is here considered to correlate with the Burrell Creek Formation. This is due to the conformity, identical lithological composition and structural style of these two formations in the Mt Todd area.

7.6.3 Katherine River Group

Quartz sandstone is the predominant rock type with lesser pebbly beds and conglomerate. These lithologies make up the Kombolgie Formation. Flood volcanics of andesite and basalt composition interfinger with the sediments. The group was deposited in a fluviatile environment and rests unconformably on the Early Proterozoic sediments and basement throughout the Inlier (Stuart-Smith et al., 1980).

7.6.4 Tolmer Group

This group is an arenite-carbonate-lutite assemblage and has been subdivided into four formations: the Stray Creek Sandstone, Depot Creek Sandstone, Hinde Dolomite and Waterbag Creek Formation. Lithologically it dominantly comprises pink quartz sandstone, siltstone, quartz pebble conglomerate and dolomite (Walpole et al., 1968).

The Depot Creek Sandstone is commonly developed in karstic depressions on the Coomalie Dolomite in the Rum Jungle and Waterhouse areas.

7.7 Cambrian - Ordovician (Daly River Group)

These rocks have been subdivided into four formation:- Basal Conglomerate, Antrim Plateau Volcanics, Tindall Limestone and Jinducken Formation. The sequence is best exposed in the Daly River basin and consists of conglomerate, massive basalt and coarse sandstone passing up into limestone, dolomite, dolomitic arenites, siltstone and mudstone (Walpole et al 1968).

Explorers have located beds with Zn and Pb mineralisation in the Tindall Limestone around Dorisvale. The basin is considered to be prospective for Mississippi Valley type lead-zinc deposits (Ashton Mining Ltd Report EL 1768).

7.8 Jurassic - Cretaceous

The Petrel and Bathurst Island Formations were deposited in this period. The Bathurst Island Formation is best developed in the north and thins southward (Needham et al 1980).

These formations comprise marine and terrestrial sediments which unconformably overlie Proterozoic rocks. They form mesa outliers of are fine-coarse sandstone, siltstone and minor conglomerate.
8. INTRUSIVES

8.1 Zamu Dolerite

The Zamu Dolerite was first defined by Ferguson and Needham (1978). They described it as a preorogenic continental tholeiite.

The dolerite occurs as numerous folded sills within the Frances Creek Group and to a lesser extent, Finmiss River Group. The sills range in thickness from several metres to over 200 metres. They are laterally persistent at certain stratigraphic levels for over 40km in places, although local discordance can be demonstrated. The sills are composite bodies of a number of different compositional types which range from metadolerite to metagranophyre. Metadolerite, composed of actinolite, feldspar, epidote and calcite is the most common variety. Variable chloritisation and biotitisation are common. As the chlorite and biotite are commonly cleaved by S₂, this alteration appears to have preceded or coincided with the main period of regional deformation.

In the Rum Jungle/Waterhouse area some dolerite has been mapped by the BMR as belonging to the Mount Deane volcanics. However, field inspection indicates it is probably intrusive. This dolerite appears to occur preferentially along the outer cosmic fault (Figure 3).

On a regional scale, dolerite is preferentially distributed adjacent to postulated basement highs (see Section 10.10) and thrust faults (Figure 4).

8.2 Lamprophyre and Other Dykes

These rocks rarely cropout. They occur within transpressional faults, associated tensional structures or S₂ cleavage. Examples occur at the Woodcutters Mine (Taube, 1989; Smolongov, 1988), Mt Paqualin prospect, Temperance Pit (Yam Creek) and Goodall Mine.

Their cleaved fabric and location within the transpressional faults indicate emplacement during the S₂ deformation.

The "calcite" dyke at Woodcutters crosscuts fold axial planes and transpressional faults and is uncleaved. At McCarthy's a lamprophyre dyke fills a later, crosscutting fault. These occurrences therefore appear to postdate the S₂ deformation.
8.3 Concordant Granites

Although two types of granites are recognised in this study, Riley (1980) found that all granites within the Pine Creek Inlier crystallised at 1780 to 1790 Ma.

The concordant granites are recognised by:-

(i) Overall boundaries roughly concordant with stratigraphy. Although local boundaries can be markedly discordant, stratigraphic units are often domed and regional trends of $S_2$ fold axial planes and cleavage bend around these plutons (Figure 5).

(ii) Their coincidence with Bouguer gravity lows indicating vertical continuity to 3 to 5km depth (Figure 6).

(iii) Internal foliation in places.

8.4 Discordant Granites

These intrusive bodies have regionally discordant boundaries and no coincidence with Bouguer gravity lows. They often extend away from concordant granites (Figure 6). These bodies must represent extensive flat lying sills of granite compared with the thicker plugs of the concordant granite plutons.
9. METAMORPHISM

9.1 Early Thermal Metamorphism

Fander and Cowan (pers comm) recognised early cordierite development pre-slatey cleavage at a number of prospects including Mt Paqualin, Cosmo Howley and Golden Dyke. This could represent a pre-compressive deformation, low pressure, moderate temperature thermal event. However, recent work in the Pine Creek area apparently indicates all cordierite is later than the regional metamorphic assemblages (Bampton, pers comm).

9.2 Regional Metamorphism

Ferguson (1980) recognises two metamorphic provinces. These consist of: a medium to high grade Archaean and older Early Proterozoic basement, and a low grade, less deformed Early Proterozoic sediment and dolerite province.

Pressure-temperature estimates for the medium grade metamorphism are in the range 5-8kb and 550°-630°C. These rocks grade into antatetic granitoids. Also present in the basement province are granulites falling within an estimated P-T field of 7-10kb and 700°-800°C.

Mineral assemblages in the Early Proterozoic sequence include low albite, well ordered microcline, chlorite, biotite, muscovite and epidote group minerals in sandstone, greywacke and shale; dolomite, magnesite, calcite and tremolite in the carbonates; ferroactinolite, biotite, garnet, quartz and siderite in iron formation; and magnesium-hornblende, albite/oligoclase, quartz and minor prehnite, chlorite, biotite and epidote group minerals in metabasaltic (Ferguson, 1980, Nicholson, 1978). There is no obvious change in these assemblages across the Inlier, within the younger Early Proterozoic sequence. These mineral assemblages indicate pressures of less than 4kb and possibly less than 2kb and a temperature range of 400°-500°C (Ferguson, 1980). Minerals from this paragenesis commonly define the slatey cleavage sub-parallel to the axial planes of S2 folds.

9.3 Contact Metamorphism

Hornfels facies rocks are superimposed onto the regional metamorphic event within a 1 to 5km radius of the granite intrusives (Ferguson 1980). The pelitic/greywacke assemblages are characterised by the development of andalusite and cordierite porphyroblasts and quartz-muscovite recrystallisation section. In calcareous and calc-silicate rocks, the minerals found are diopside, wollastonite, dolomite, calcite, magnesite, talc, tremolite, and some scapolite. The Zamu Dolerite is recrystallised and plagioclase has the composition andesine to labradorite.
10. STRUCTURAL GEOLOGY

10.1 Cosmic Faults

Cosmic faults are defined as circular or elliptical faults with predominantly centre block up movement. They were originally recognised in the Rum Jungle area. Here numerous faults were previously mapped in the sediments surrounding the basement with convex-out shape and the juxtaposition of more deformed younger stratigraphic units outside the faults with much older stratigraphic units inside. The Woodcutters seismic section and detailed gravity surveys indicate that these relationships are due to large outer block down movements. Recent detailed aeromagnetic and radiometric surveys have helped trace these structures between areas of outcrop and elucidate their shape and distribution.

Cosmic faults with similar attributes to those of the Rum Jungle area were then recognised in the Moline/Allamber area. In the Burnside, Prices Springs, Fenton, Mt Bundey and Driffield areas the faults were recognised by more subtle vertical movements, sudden changes in structural style, and from gravity data. In the Burnside and Prices Springs area faults can be traced through almost 360 degrees. The location of the faults in the other areas is less precise.

In summary, these structures have the following characteristics:-

(i) Circular to elliptical shape with radii of 2 to 30km (Figures 4 and 7). It is possible that these structures are folded by D2 folds (Figure 8).

(ii) Invariably outer block down movements of up to 3km (Figure 3). Faults in upper parts of the stratigraphy commonly have smaller movements.

(iii) Steep inward dips (Figure 9).

(iv) A thickening of the stratigraphy in the outer block domain. This is indicated by the seismic section in the Woodcutters area (Figure 9), gravity data with Bouguer highs on the outer domains (Figure 7) and surface geological mapping. The Bouguer highs usually occur adjacent to central gravity lows, with gravity values decreasing again further away from the cosmic faults.

(v) An increase in intensity of D2 deformation in the outer domains. This is best illustrated in the Rum Jungle/Waterhouse area where folding changes from doming around basement to open folding and finally to isoclinal folding, over successive cosmic faults (Figure 3). This change in fold style can be seen in the same stratigraphic units either side of the faults.

(vi) High uranium radiometrics along their surface traces, eg. in the Acacia-Woodcutters-Waterhouse area.

(vii) An association with dolerite intrusives, for example, outcrops of Zamu Dolerite are common along the trace of the outer cosmic fault in the Rum Jungle-Waterhouse area (Figure 3).
10.2 Bedding Concordant Structures

These are the earliest post depositional deformation structures currently recognised. This is apart from a rare fabric interpreted to be associated with monoclinal warping (Johnston, 1984) and any fabrics associated with cosmic faulting. The bedding concordant deformation is called the D1 deformation in this report.

A bedding parallel cleavage (S1) has been recognised by Johnson (1984) at various preferred stratigraphic intervals in the Rum Jungle Area. These include the basement/Early Proterozoic interface, top of the Coomalie Dolomite, certain intervals within the Wildman Siltstone (here included in the Koolpin Formation) and base of the Burrell Creek Formation.

Johnston (1984) also recognised this bedding parallel cleavage in sparsely distributed pelitic outcrops in the Mundogie area; at the base of the Kapalga Formation (here correlated with the South Alligator Group) in the Black Jungle Springs area; and within the Koolpin Formation in the South Alligator Valley and Barramundi Creek South areas. Valenta (1991) confirmed the presence of this cleavage in the Mundogie and South Alligator Valley areas.

Stephansson and Johnson (1976) and Johnston (1984) measured a stretching lineation (L1) defined by pebbles and cobbles and mineral aggregates in the Batchelor Group. Stephansson and Johnson consider this lineation to be mainly orientated down dip, away from the basement domes. Johnston also measured this lineation, although he concluded that the orientations were inconsistent with Stephansson and Johnson’s generalisation. Valenta (1991) also considered that this lineation was also mainly in down dip orientations.

Folded concordant breccia zones, often localised in the same stratigraphic intervals as preferred by the bedding parallel cleavage, probably also belong to the D1 deformation. At the Frances Creek iron ore mine, conformable breccias are composed of angular clasts of pyritic carbonaceous siltstone within an anastomosing foliated matrix. Concordant breccias have also been mapped in the middle member of the Koolpin Formation in the Burrendie area (Nicholson, 1984) and mapped by the BMR as the Ella Creek Member (at the same stratigraphic interval) in the Rum Jungle area. Concordant breccia and shear zones have also been mapped in the upper Mundogie Sandstone and Koolpin Formation in the McCarthy’s area. No repetition of stratigraphy occurs across these structures in these areas. The distribution of these concordant structures in the Frances Creek and McCarthy’s areas indicates they favour fold limb positions within ductile lithologies between more brittle units (Figure 10).

Johnston (1984) and Valenta (1991) mapped similar structures over large distances in the Mundogie area (Figure 4). Thrusting of older stratigraphic units over younger units in a south westerly movement is indicated. It is not certain whether these more extensive regional structures are equivalent to the more local concordant breccias, shears and cleavage.

Some tight and pytymatic folding is also reported to parallel S1 in the Mundogie/South Alligator area. However, a large recumbent fold south-east of the Waterhouse Complex reported by Johnston (1984) to be intraformational is probably juxtaposed against a major fault and related to the later D2 folding.

10.3 Doming

The Lower Proterozoic sediments and dolerites are domed in a number of areas in the region. Generally the doming occurs over areas with radii 5 to 10km. Lithological units are either concentrically arranged around the domes without folding, for example, the sediments around the Rum Jungle Complex, Waterhouse Complex and Burnside Granite; or folded into composite structures with kilometre scale folds which plunge away from the dome in both directions (for example, the Burrundie Dome).
The domed sediments are often more openly folded with smaller amplitudes and wavelengths than surrounding sediments (Figure 5). Fold axes orientation sometimes also changes over domed areas. These changes in folding, away from domes are often abrupt, and identify the location of cosmic faults.

The doming generally coincides with gravity lows, and is often centred by either basement rocks or concordant granites.

10.4 Upright Folds and Cleavage

Upright folding with a well developed axial plane slatey cleavage ($S_2$) occurs over most of the Inlier. Johnston (1984) assigns this to his $D_1$ deformation although it will be referred to here as $D_2$, due to the rarity of deformation Johnston refers to as $D_1$.

Metadolomite, chert, carbonate, quartzite and greywacke are generally folded with rounded hinges and wavelengths of 0.5 to 4 km. Smaller folds are restricted to the hinge zones of some anticlines adjacent to transpressional structures. The fold profiles are close to concentric. Iron formation is folded with wavelength of 0.5 to 50 metres, as well as larger scale regional folds of 0.5 to 4.0 kilometres. The folds are rounded and fairly concentric (Figure 12). On a centimetre wavelength, sulphide-rich iron formation is sometimes chaotically folded adjacent to massive textured, gold enriched zones, for example at the Cosmo Howley mine (Nicholson, 1982). These features appear restricted to anticline closures.

Folds in mudstone and carbonaceous mudstone are markedly similar in profile. Hinge thickening of 2 to 4 times commonly occurs relative to the limbs (Figures 12 and 13). Fold wavelengths occur from a few centimetres to about 4 kilometres. Figure 5 shows the distribution of zones across the Inlier with different fold tightness and wavelength. These were compiled from aerial geophysics, geological traverses and TM Images (Enclosures 1 to 5).

Folding varies from open to isoclinal. The higher South Alligator and Finnis River Groups are generally folded with greater amplitude and tightness than the lower Batchelor and Namoota Groups. Similar lithologies and stratigraphic units inside cosmic faults tend to be less tightly folded than those outside. Tighter folding with smaller wavelengths often occur in linear or arcuate zones located adjacent to gravity lows in both directions perpendicular to the prevailing $S_2$ strike directions.

Fold axial planes are commonly bent around and dip away from outcrops of concordant granite and basement (Figure 5). Abrupt changes in fold shape and orientation define cosmic faults (Enclosures 1 to 5). On a regional scale axial planes subparallel the basin margin as defined by the outcrops of Archaean and older Early Proterozoic basement.

10.5 Transpressional Faults

Subparallel transpressional faults occur within zones several hundred metres to 5 km in width. The best known example occurs at Woodcutters and is described by Nicholson et al., (1991). The Howley Anticline and Coronet Hill fault/anticline are other well mapped occurrences. Probably similar, less well defined faults are known along the Golden Dyke/Yam Creek Anticline, Brock Creek/Zapopan anticline and the Ringwood line of gold workings. Long anticlines with associated en echelon smaller folds suggest similar faults also occur in the De Monchaux and Lloyd’s Creek areas.

The major faults consist of 0.5 to 5 metre wide zones of the following:

- intense cleavage development
- anastomosing slickensided graphite coated shears
- quartz carbonate veining which sometimes forms a matrix to incipient brecciation
- lamprophyre dykes
- banded sulphide veins
The faults are generally steeply dipping, and they steepen even further with depth in places (Figure 13).

Apparent vertical movements on individual faults are up to 300 metres. Subparallel faults often have different apparent vertical movements and individual faults can have different directions of apparent vertical movement over time (Figures 12 and 13). Apparent vertical movements at Woodcutters decrease with increasing depth (Figure 13).

Increased deformation occurs between and adjacent to these faults, as evidenced by intense cleavage development, micro-faulting along cleavage traces, small scale folding and thickening of stratigraphic units. This thickening defines long anticlines with apparent overall flat plunge on a regional scale. Small scale folds in these zones often plunge steeply in different directions. The intensity of deformation between transpressional faults varies from area to area, as indicated by the tightness of folding and frequency of faulting.

Cleavage and larger scale fold axial planes ($S_2$) diverge from the major faults by up to 20 to 30 degrees, as distance is increased perpendicularly away from the faults (Figures 14 and 15). Folding is often not parallel either side of the transpressional faults, and cannot be matched easily by removing fault movement. Cross faults defined by graphitic shears, quartz carbonate veins, lamprophyre dykes and sulphide veins occur perpendicular to the orientation of fold axes away from the faults. These generally have only minor apparent movement and are usually truncated by the major $S_2$ subparallel structures.

The horizontal offset of units across the transpressional faults is up to several hundred metres. It is hard to relate this to total displacements, as vertical movement has also usually occurred. However, regionals relationships suggest horizontal displacements are less than about 1 km.

The apparent lateral movement from the offsets across these faults and relationship between associated structural elements (small scale fold axes, cleavage, faults, cross faults, broad anticlines) are consistent with transpressional strike-slip faulting (Harding, 1973, 1990; Wilcox et al 1973). Both left and right hand structures are known (Figures 14 and 15). Within the compressional zones (Section 10.6) the major faults are arranged en echelon with a left hand stepping arrangement in the left hand zones and right hand arrangement in the right hand zones. Although data is sparse, left hand structures appear to favour the west side of the gravity lows and right hand structures the east.

10.6 Compressional Zones

As mentioned previously, tighter, smaller wavelength folding is known to occur in linear or arcuate zones adjacent to gravity lows in both directions perpendicular to the prevailing $S_2$ strike direction. These are termed compressional zones. They commonly coincide with the arcuate zones of higher gravity that commonly occur adjacent to gravity lows, in the Inlier (Figure 16). Large, open synclines, for example, the Howley syncline, Ringwood Range syncline, and synclines either side of the outer cosmic fault in the Rum Jungle/Waterhouse area often separate the compressional zones from the areas of gravity low. The compressional zones usually form broad anticlinoria relative to adjacent areas.

Many compressional zones contain transpressional faults, and all known transpressional faults are located within compressional zones. In the McCarthy’s/Frances Creek area a compressional zone contains many $D_1$ faults.
10.7 Pine Creek Structure

The Pine Creek structure is a 300km long zone which can be mapped from Darwin to Katherine. It strikes at 330 degrees and consists of a number of subparallel faults over a 5km corridor (Figure 17). These include the Phillips Creek fault and Pine Creek shear in the Edith River and Pine Creek areas; the Saunders Creek fault in the Burrundie Dome area, the MacCallum Creek fault in the Burrundie area; and the Noonamah fault in the Acacia area.

These faults have a consistent apparent sinistral movement of up to 2km. They crosscut and obviously postdate D2 folds and granites. In areas of poor outcrop, the Pine Creek Structure is well marked by linear magnetic anomalies, probably due to basic dykes.

A well developed fault/lineament trend at 080/090 degrees (Simpson et al, 1980) could be a conjugate shear to the Pine Creek structure.

10.8 South Alligator Fault Type

North westerly trending faults are one of 3 major fault sets transecting Middle Proterozoic rocks of the McArthur River region (Valenta, 1991). These show relatively minor displacements compared to their length.

In the South Alligator Valley, the South Alligator, Palette and Rockhole faults belong to this set. These and related faults deform both Lower and Middle Proterozoic rocks in a divergent dextral wrench system. (Valenta op cit). This corridor of faults can be traced along strike to the northwest for over a 200km by linear magnetic anomalies (Figure 17).

10.9 Giants Reef Fault Type

A number of north easterly trending faults occur through the region. These include the Giants Reef and Hayes Creek Faults. The faults have dextral displacements and some if not all movement postdates Middle Proterozoic sedimentation, the Pine Creek structure and South Alligator Fault types (Figure 17). Related faulting and kinking occurs within Early Proterozoic rocks in the Rum Jungle Embayment (Johnston, 1989; Peterson, Von Pechman and Borschoff, 1984).

Reactivation of cross faults associated with transpressional structures in the Woodcutters mine area is consistent with the conjugate shear direction related to these structures (Nicholson et al, 1991).

10.10 North Tending Structures

A prominent set of lineaments/joints/faults striking at 340/360 degrees was recognised by Simpson et al (1980). The Mt Shoobridge Fault belongs to this set. The exact timing relationship between these and the other structural elements is not obvious.
11. MINERALISATION

11.1 Introduction

In this section different styles of mineralisation found in the Inlier are distinguished and described. Although genetic models are proposed in a later chapter the emphasis here is on observations about the distribution of different styles of mineralisation relative to:

i) each other

ii) certain lithologies

iii) stratigraphic units

iv) intrusive types

v) structural elements.

11.2 Stratiform Mineralisation

The deposits assigned to this style are listed in Table 3 with their main references. Their locations are shown in Figure 22.

The main characteristics of this mineralisation are:

i) Individual lenses are closely conformable to bedding. The only possible exceptions to this are Earthwells, Area 44 and Maureen where structural complexity and/or lack of data prevent this being confirmed. However, the similar stratigraphic position, lithological host and composition of mineralisation at these prospects to other stratiform occurrences suggests a common origin.

ii) Stratification is common and varies from finely laminated to almost massive textured. Discordant mineral distribution can occur adjacent to crosscutting quartz veins and in high strain zones within anticline axes (Nicholson and Eupene, 1984).

iii) Ore minerals, or those that show a close spatial relationship to them (for example arsenopyrite, pyrite and pyrrhotite in the stratiform gold deposits), often show affects of the D2 deformation (Table 3).

iv) Cleaved, often stratified, tourmaline commonly occurs in carbonaceous mudstone immediately along strike, above or below stratiform mineralisation. This tourmaline comprises up to 40 percent by volume of beds up to 15m thick and 3 km long. Conversely, bedded tourmaline occurrences are almost completely restricted to areas of known stratiform mineralisation, suggesting a close genetic association between the two.

v) Extensive pyrrhotite-rich beds are known at certain stratigraphic intervals within the Inlier (Figure 21). These coincide with the stratigraphic positions of some stratiform deposits. The pyrrhotite takes the form of bedding and cleavage conformable masses and veins, and fine, stratified and cleaved disseminations. Minor fine grained sphalerite, galena and arsenopyrite are sometimes associated with the disseminated pyrrhotite. The stratigraphic interval along strike from the Area 44 mineralisation is enriched in manganese (Taube, 1984) and stratabound, baryte occurs close to the Plateau Point deposit (Nicholson, 1982).
vi) Iron-magnesium silicates and carbonates often envelope and extend along-strike from stratiform mineralisation. These range from massive, to finely laminated in texture, sometimes at the same deposit, for example, Yellow Track.

vii) Stacked lenses closely spaced across the stratigraphy are common (Table 3). In addition, a number of occurrences and zones of geochemical anomalies are often found clustered along the same stratigraphic interval (Table 3).

viii) Host lithologies are carbonaceous mudstone, mudstone and iron formation. Mineralisation often occurs within a relatively thin lens of one of these lithologies, or close to a contact with a different lithology (for example, Area 44 and Yellow Track occur at the base of a thick sequence of carbonaceous mudstone overlying a thick sequence of carbonate). Host lithologies often lens out away from the mineralisation alongstrike. For example, carbonaceous mudstone lenses thin away from the Afghan's Lode, Iron Blow and Mt Bonnie mineralisation. Mineralisation is sometimes underlain by coarse, debris flow deposits, (for example, Iron Blow, Mt Bonnie and Rustlers Roost/Beef Bucket Reef).

ix) Clusters of mineralisation can be sometimes shown to coincide with changing lithological facies across the sequence (Nicholson, 1980; Wilkinson, 1982).

x) Stratiform occurrences are restricted to the Frances Creek Group, in the later Early Proterozoic sequence. The mineralisation changes in composition through the stratigraphy (Figure 21). With decreasing age of the host rocks, the following compositions occur:

Cu-rich, Fe poor; Fe-rich; Fe - As - rich ± Au ± Zn; Fe-Zn-Pb - rich; Zn-Pb - rich, minor Cu, Sn.

xi) Deposits hosted by the Whites Formation are located adjacent to cosmic faults, particularly where they intersect to form ‘embayments’ (Figure 3). Stratiform mineralisation higher in the stratigraphy often occurs adjacent to transpressional faults. Districts between closely spaced basement highs appear to be particularly favourable (Figure 22).

11.3 Polymetallic Vein Mineralisation

The deposits belonging to this style are listed in Table 4. The location of these, as well as other possibly similar deposits, are shown in Figure 22.

The characteristics of this style of mineralisation are:-

i) Obvious epigenetic textures. Some mineralisation occurs in veins filling discordant faults. Where concordant, the mineralisation fills the matrix of post-sedimentary breccias and shears.

ii) Deformed sulphide textures. Mineral textures are often banded and brecciated. Preferentially aligned, roughly ovoid boudins of comparatively competent constituents are surrounded by often banded, more mobile sulphide minerals. In some places tension veins of later sulphides occur within and perpendicular to the elongation of these boudins. Sulphide minerals sometimes also fill the matrix between breccia fragments of country rock and vein gangue constituents. Massive, equigranular textures are also known.
Polymetallic vein mineralisation is preferentially contained within transpressional faults, and to a lesser extent concordant D₃ breccias.

Vein boundaries are generally sharp and alteration haloes, if any, are narrow. The exception to this are the Daly River occurrences, where mineralisation within acid and intermediate volcanics occurs within wide zones of chlorite-talc-carbonate alteration (Govey, 1992).

On a kilometre/100 metre scale mineralisation in discordant structures favours interbedded brittle and less competent lithologies; for example, dololutite and carbonaceous dolomitic mudstone at Woodcutters; tuffaceous chert and mudstone at Moline and Little Mary; and conglomerate/greywacke and mudstone at Gubberah, and Mt Diamond. On a 10 metre scale the mineralisation favours the intersection of brittle lithologies and the host structure (Figures 24 and 25).

Concordant structures, and associated mineralisation are generally in ductile lithologies, particularly carbonaceous mudstone. Sulphidic beds are favoured in places.

At Woodcutters and Little Mary, the mineralisation is located within doubly plunging antiforms (Figures 13, 15, 24 and 25).

Mineralisation favours dilational locations within host structures and may occur in related, cross cutting tensional structures (Figures 26 and 27).

The mineralisation changes composition gradually, although systematically, up the sequence (Figure 21). In ascending order, compositional assemblage are Fe-As; Zn; Zn+Pb+Ag; Pb+Ag+Sn; Sn+Cu+As; W +Bi. At Woodcutters the lower part of this zonation can be seen over 800m vertical extent (Figure 28). The zoning sequence reasonably agrees with the paragenetic sequence determined from mineragraphic study at Woodcutters (Just, 1990). Later minerals are frequently zoned closer to cross cutting tensional structures (Figure 29).

These deposits usually occur adjacent to or particularly between basement highs (Figure 22). They often occur within compressional zones. They may occur in the same area as stratiform Cu (Whites Formation hosted) mineralisation but rarely occur with stratiform Au and Pb-Zn deposits.

**11.4 Stockwork - Concordant Gold-Quartz Mineralisation**

The larger deposits of this style are listed on Table 6. The location of these deposits and numerous similar showings are shown on Figure 38.

The characteristics of these deposits are:-

Association with quartz-sulphide veins. The mineable reserves occur in thick (0.2 to 3m), continuous, semi-concordant quartz-sulphide veins and/or stockworks comprised of thinner (3mm to 0.3m) veins with a number of orientations. These thinner veins subparallel bedding, S₃ cleavage, planes perpendicular to bedding but striking parallel to S₃ and other orientations with no obvious relation to S₃ or S₄. The veins with no obvious relation to S₃ and S₄ show a clustering of orientation regardless of location, across the Inlier (Figure 39). Veins comprise 2 to 15 percent of stockwork ore zones by volume.

The stockwork ore bodies are flattened subparallel to S₀, S₁ or transpressional faults. They are often elongate in the direction of D₃ fold plunges.
iii) Stockwork veins generally favour interbedded brittle and ductile lithologies. The stockwork orebodies are often truncated by thicker units of ductile material, usually mudstone, for example, at Goodall and Woolwonga. The exception to this are stockworks dominated by bedding parallel veins, which may occur within predominately mudstone units, for example at Enterprise.

iv) Bedding concordant veins are often weakly banded subparallel to vein walls. They generally occur within mudstone units, particularly at their bases.

v) Sulphide mineralogy consists of pyrite and usually arsenopyrite. Variable amounts of base-metal sulphides occur in different deposits. Total sulphide content averages 3 to 10 percent in stockwork vein zones and 5 to 50 percent in concordant veins. Most sulphide occurs within the veins. Only a minor amount is disseminated in adjacent country rock.

vi) Vein gangue mineralogy consists of quartz, carbonate, feldspar and tourmaline. Moderate alteration (bedding and cleavage are usually still discernible) consists of assemblages of quartz, potassium feldspar, chlorite, sericite, tourmaline and biotite. This occurs up to 1m from thicker veins and is pervasive between dense stockworks (Cannard and Pearse, 1990).

vii) Folding within the host rocks of these deposits is on wavelengths of 0.2 to 0.5 km. Smaller wavelength folds are uncommon. Limbs are planar and hinges rounded. Pre-vein faulting within stockwork ore zones is not common. Structures with significant movement may occur 50 or 100m from ore zones.

viii) Most deposits are hosted by the Burrell Creek Formation, Mt Bonnie Formation and Gerowie Tuff. Only rare occurrences are found below these stratigraphic units, although lithologies and structure appear similar.

ix) Most showings and all significant deposits occur within compressional zones or adjacent to the Mt Shoobridge fault or along the Pine Creek shear corridor (Figure 38). Locations around, above and particularly between basement highs appear most favourable.

11.5 Tin Deposits

Tin occurs as a minor constituent in some polymetallic vein and stratiform deposits. It also occurs in the following forms:-

i) In quartz-cassiterite-tourmaline-iron oxide veins which fill shears, bedding and cleavage.

ii) Within greisens.

iii) As disseminated cassiterite with varying amounts of tantalite, beryllium and spodumene in poorly zoned pegmatites (Nicholson, 1988; Pietsch and Clayton; 1990).

Figure 40 shows the position of these deposits. The greisens and veins are generally situated adjacent to the discordant granites, and to a lesser extent the concordant granites.
11.6 Unconformity Related Uranium-Gold-Platinoild Mineralisation

These deposits are listed in Table 7 and their positions indicated in Figure 41. Characteristics of this style of mineralisation are:-

i) A close spatial relationship with sediment/volcanic covered Early/Middle Proterozoic unconformity surface.

ii) Location within structures or conduits formed after the deposition of Middle Proterozoic rocks. These include structures associated with the South Alligator fault zone (Valenta, 1991), Giants Reef Fault (Paterson, Von Pechman and Borshoff, 1984; Johnston, 1984) and other post Middle Proterozoic faults (Wilde and Noakes, 1990; Pagel, Borshoff and Coles, 1984; Snelling 1990); karstic caves and depressions (Ferguson et al., 1980; Hancock, Maas and Wilde, 1990); and breccias around altered carbonates which formed in Lower Proterozoic lithologies during Middle Proterozoic times (Eupene, 1980).

iii) An association with a widespread ferromagnesian metasomatic event (chloritisation, magnetitisation, hematitisation).

iv) The common proximity of carbonaceous and carbonate lithologies.

v) A stratigraphic control on a district scale.

vi) The presence of varying proportions of uranium, gold, platinum group elements and copper in different deposits. Gold mineralisation is more widespread than associated uranium mineralisation in some deposits (for example in the South Alligator Valley, Valenta; 1991) although in others the gold is restricted to the higher grade cores of uranium mineralisation, for example, at Jabiluka (Hancock, Maas and Wilde, 1990).

vii) The mineralisation has a preferred location adjacent to Archaean basement, or its remobilised equivalents (concordant granites). Proximity to cosmic faults and their intersections are common (Figure 41).
12. HYDROCARBONS

The likely geological history of palaeo-hydrocarbons in the Pine Creek Inlier is considered to elucidate its possible role in the distribution and localisation of some mineralisation types. It is considered most unlikely that any hydrocarbons survived the subsequent structural deformation and metamorphism.

12.1 Hydrocarbons in the Pine Creek Inlier

12.1.1 Source Rocks

Microscopic organisms comprising unicellular colonial or filamentous species are known to have existed in the Proterozoic (Schopf, 1983). Studies of the Middle Proterozoic McArthur Basin have identified various remnants of organic matter within fine grained clastic sediments (Crick, 1992). The occurrence of stromatolites in many Proterozoic sequences including the Pine Creek Inlier is further evidence of syn-depositional organic activity.

Precambrian rocks are however not commonly considered as source rocks for petroleum due to the comparatively high probability that petroleum would be destroyed by thermal alteration or lost due to tectonic movement. Doubt has also existed as to the suitability of Precambrian organic matter to generate hydrocarbons. Despite these factors, commercial quantities of Proterozoic sourced petroleum occur in Siberia and Oman and many observations of bitumen, and dead oil have been made in the unmetamorphosed McArthur Basin region (Powell et al, 1987).

The high carbon content of both the Whites Formation and Koolpin Formation implies that prior to metamorphism, both units were rich in organic matter and were potential hydrocarbon source rocks. Taube (1984) describes slate of the Whites Formation at Woodcutters Mine as consisting of about 50% fine dolomite, with the remainder comprising about equal parts of sericite, quartz and carbon (sub-graphite). The Koolpin Formation is similarly carbon rich (in excess of 10% carbonaceous matter in the Margaret Syncline area (Goulevitch, 1980). Total organic carbon (TOC) contents of greater than 4% are generally considered to be indicative of excellent source rock potential. This compares with TOC contents of up to 9% in the McArthur Basin and 5% in the Siberian Platform (Powell et al, 1987).

Other units such as the Coomalie Domomite may have originally also contained significant but lower amounts of organic matter. Whilst still being possible source rocks, their potential is correspondingly downgraded.
12.1.2 Maturation and Timing

Apart from bacterially generated gas, hydrocarbons are formed by the thermal breakdown of organic matter in sediments. The reaction rates involved in organic metamorphism depend exponentially upon temperature. In general, oil generation occurs from about 60°C, reaching a peak in the 80° to 90°C range and is complete by approximately 130°C. Temperatures can therefore define an oil window which varies depending upon organic matter type. Also depending upon organic matter type, gas may be generated either directly from organic matter or from the breakdown of oil. The thermal destruction of oil (to gas) begins at approximately 150°C. Time is also considered to be a secondary factor in hydrocarbon generation.

N.V. Lopatin of the Soviet Union developed a time temperature index (TTI) to estimate the maturity of source rocks. The Lopatin method involves the construction of time-depth of burial curves for various potential source rock units which are correlated with temperature to determine the TTI value (Waples, 1976).

The construction of time-depth of burial curves for sediments of the Pine Creek Inlier is difficult due to inadequacy in time control, and in many places insufficient information on stratigraphic thicknesses. Figure 30 illustrates a series of possible time-depth of burial curves for the Woodcutters Mine area, based upon known stratigraphic thicknesses, age and sedimentation rate constraints.

As the palaeogeothermal gradient is unknown, a range of possible gradients are shown (20°C/km to 80°C/km). In all cases, both the Whites Formation and Koolpin Formation experienced temperatures sufficiently high for hydrocarbon generation. A temperature of 130°C representing the end of the oil window is shown in Figure 30 for different geothermal gradients. The end of oil generation for the base of the Whites Formation and Koolpin Formation has also been calculated using the Lopatin method for a geothermal gradient of 30°C/km. In comparing the end of the oil window for both the Whites Formation and Koolpin Formation, the strong dependence of timing of hydrocarbon generation on depth of burial (and hence formation thickness) is shown.

A general thickening of all stratigraphic units can be expected towards the centre of the Pine Creek Inlier. Whilst information on the thicknesses of the lower stratigraphic units is unavailable for the central basin, thickness variations within the Frances Creek Group support this concept. For example total thickness of the Koolpin Formation, Gerowie Tuff and Mt Bonnie Formation on the eastern margin of the Waterhouse Complex is 1000m compared to over 1500m in the Burundie Dome area. Consequently hydrocarbon generation can be expected to have occurred considerably earlier in the centre of the Pine Creek Inlier where formation thicknesses are anticipated to be thicker than in the Woodcutters case.

12.1.3 Migration

After generation, hydrocarbons migrate into zones of higher permeability located either immediately under the source rocks and/or into any location above the source rocks. The upper Coomalie Dolomite therefore defines the lower level at which hydrocarbons generated in the Whites Formation could have occurred prior to structural deformation. Zones of higher permeability can include faults, de-collements, unconformities, and fractured/porous lithologies such as carbonates and sandstones.

The buoyancy of hydrocarbons will drive them towards the surface, and hence basin margins and/or local highs, until they are either trapped or escape to the surface. Opposing the buoyancy force are capillary pressures caused by the interfacial tension between hydrocarbons and water (Berg, 1975). The direction and rate of hydrocarbon migration can be modified by hydro-dynamics (Trindade et al, 1992).
12.1.4 Reservoirs

In the Pine Creek Inlier, the Acacia Gap Quartzite/Mundogie Sandstone is the only prospective unit likely to have had significant primary porosity, however this has been reduced considerably by subsequent quartz cementation. The timing of cementation with respect to hydrocarbon generation was an important factor in determining whether this unit was a significant reservoir and/or conduit for hydrocarbon migration.

Structural deformation probably played a significant role in the formation of hydrocarbon reservoirs by creating secondary porosity and permeability.

After lithification, folding and faulting of any of the more competent lithologies including carbonates, dololuties, quartzites, tuffs and cherts could have caused fracturing. Interbedded competent and ductile lithologies such as dololutite and slate may have been more conducive to fracturing than massive competent units. Decollements and thrust faults adjacent to thicker competent units could also have provided reservoirs and/or conduits for hydrocarbons, as could fault zones themselves.

Timing of the hydrocarbon generation with respect to structural deformation would have been important in determining whether significant reservoirs were developed by fracturing.

If no permeable zones were present adjacent to the source rocks, abnormal pressures may have developed as fluid pressures increased due to generation of hydrocarbons and expulsion of water. Overpressuring could have facilitated de-collision and fault formation.

12.1.5 Traps

Numerous mass balance assessments of present day oil producing basins show that amounts of entrapped oil are commonly 2-3 orders of magnitude smaller than the amounts of oil generated (Klemme and Vlmihe, 1991). Hydrocarbon accumulations can form wherever the upward movement of petroleum is retarded by impermeable or less permeable strata, and where rate of supply exceeds any losses due to leakage (Trindade et al, 1992). Thus during the main hydrocarbon generating phase, hydrocarbons may be temporally trapped, for example along imperfectly sealed fault planes. Once hydrocarbon generation is complete however, a combination of good trap and seal is required for any lasting accumulations.

The main trap type for hydrocarbons is the domal anticline. Other structural traps usually combine part anticlinal closures with fault closures against impermeable beds. Stratigraphic traps due to lateral facies changes and diagenetic traps due to partial cementation do also occur, but again usually require a structural component such as regional dip or a coincident anticline.

Structural timing is important in determining whether hydrocarbons are trapped at all. Consequently, favourable conditions for the retention of hydrocarbons were the formation of early structural traps and/or the relatively late generation of hydrocarbons. These conditions are best met in areas overlying early formed basement highs near the basin margins, such as around the Rum Jungle Complex.

Metamorphism at the end of the Early Proterozoic would have ensured that all hydrocarbon forming processes within the Pine Creek Inlier were completed by this time. The associated and subsequent structural deformation would also have aided the breaching of seals. It is therefore most unlikely that any hydrocarbons are currently preserved.
12.1.6 Conclusions of Hydrocarbons

- The carbonaceous Whites Formation and Koolpin Formations were the best potential hydrocarbon source rocks in the Pine Creek Geosyncline.

- Hydrocarbon generation would have occurred considerably earlier in the central basin areas than on the margins and basement highs due to increased depth of burial.

- The upper Coomalie Dolomite may define the lower limit at which hydrocarbons could have been encountered prior to structural deformation.

- Prior to cementation the Acacia Gap Quartzite/Mundogie Sandstone may have been a significant hydrocarbon reservoir and/or conduit particularly for earlier formed hydrocarbons.

- Competent lithologies such as dololulite, quartzite, tuff, greywacke and chert of the Frances Creek and Finnis River Groups could have formed temporary hydrocarbon reservoirs if they were sufficiently lithified and fractured from deformation.

- De-collements and fault zones could also have formed temporary hydrocarbon reservoirs and/or conduits. Overpressuring due to excessive hydrocarbon fluid pressures may have facilitated the formation of these structures.

- Anticlinal structures either domal, or in combination with faulting or stratigraphic/diagenetic barriers would have provided traps for migrating hydrocarbons.

- From a structural timing viewpoint, areas overlying long term basement highs particularly near the basin margins were most favourable for hydrocarbon accumulations.

- Due to subsequent structural deformation and metamorphism, it is unlikely that any hydrocarbons survived beyond the Middle Proterozoic in the Pine Creek Inlier.

12.2 Role of Hydrocarbons in Sulphide Precipitation

Hydrocarbons may be important in sulphide precipitation by causing thermochemical sulphate reduction, thereby producing hydrogen sulphide which in turn precipitates metallic sulphides from solution. Barton (1967) first suggested thermochemical sulphate reduction in relation to ore deposits (Leventhal, 1990). Leventhal (1990) provides a summary of much of the work in this field, and offered the following reaction as a possible example:

$$4 \text{R}_4 \text{CH}_3 + 3\text{SO}_4^{--} + 6\text{H}^+ \rightarrow 4\text{R}_4 \text{COOH} + 4\text{H}_2\text{O} + 3\text{H}_2\text{S}$$

(where R is a hydrocarbon molecule)

Leventhal (1990) notes that this reaction proceeds faster with increased temperatures, amounts of reactants, the presence of H$_2$S as an initiator, acid conditions, and catalysts such as clays. Anderson (1991) cites many references in the petroleum literature which, based mainly upon geologic and isotopic evidence, establish thermochemical sulphate reduction above 80°C as an accepted principle.

Thermochemical sulphate reduction brought about by hydrocarbons has mainly been invoked as a precipitation mechanism for Mississippi Valley type Pb-Zn deposits.
In examining the precipitation mechanisms for Mississippi Valley type areas, Anderson (1975) raised the following possibilities:

A) Metal and reduced sulphur transported to the site of deposition in the same solution. Precipitation caused by (1) cooling, (2) dilution and (3) neutralisation.

or

B) Metal transported to the site of deposition, reduced sulphur supplied at the site, causing deposition of the sulphides.

Anderson (1975) also listed the following processes which have been proposed by other workers to supply the reduced sulphur:

1) Mixing of metal-bearing brine with \( \text{H}_2\text{S} \) rich waters in carbonate rocks. \( \text{H}_2\text{S} \) supplied by bacterial reduction of sulphate.

2) Inorganic reduction of sulphate (ie thermochemical).

3) Thermal degradation of hydrocarbons.

4) Replacement of pre-existing sulphides.

Taking thermodynamic considerations into account, Anderson (1975) concluded that alternative (A) would require an acidic solution, which is not possible due to the demonstrated stability of calcite and dolomite at the time of sulphide precipitation. Anderson (1975) further reasoned that the most important single factor in the formation of ore of this type is not so much the availability of metal and sulphur, but the long-continued availability of both metal and sulphur at the same site. A continuing (separate) supply of hydrogen sulphide is required at the site of deposition for a larger massive sulphide body to form.

Anderson (1991) now suggests that Mississippi Valley type deposits were formed where hot hydrothermal fluids containing metals and sulphate in solution, entered permeable rocks containing methane and other reducing gases. Sulphate was reduced on contact with the gases, producing hydrogen sulphide and thus causing sulphide precipitation. By invoking hydrocarbon gases, Anderson solves the mass balance problems associated with using organic matter or remnant bitumen as a direct reductant for sulphate. Furthermore, mixing is likely because the permeability trends which control the distribution of the reductant (eg methane) and reduced gases (\( \text{H}_2\text{S} \)) also control the flow of metal bearing solutions (Anderson, 1991). Provided the escape of gases is impeded by trapping, supply of reductant can be accomplished by pressure or fugacity gradients which result from reduction (Anderson, 1991).

Anderson (1991) presented data suggesting that a regional gas cap may have controlled the distribution of Mississippi Valley type mineralisation in southeast Missouri. A regional gas/water interface could mark the lower limit of mineralisation if the proposed mechanism of sulphide mineralisation took place. Figure 31 shows the evidence for such a control in the southeastern Missouri area. Anderson suggests alternatively that a large number of smaller local gas traps may have controlled mineralisation. Evidence for local trapping includes the common concentration of mineralisation immediately below siltstones or impermeable horizons, and a preference for domes and arches. Anderson found that theoretically, sufficient hydrocarbons (methane, but also examined ethane, propane etc.) could have been generated in the immediate vicinity of the Viburnum mineralised trend to account for the known sulphide deposits. In this case, the hot, metal bearing solutions may have generated methane and other reducing gases locally where sufficient organic matter was encountered.
Anderson (1991) believes that other work carried out in the Missouri area is not inconsistent with his ideas. Fluid inclusion studies indicate that CO₂ effervescence was a widespread phenomenon during sulphide and dolomite precipitation and amounts of H₂S, SO₂, N₂, Ar and CH₄ and other hydrocarbon gases are much smaller (Anderson, 1991). Fluid inclusion and sulphur isotope work also indicate that more than one mineralising fluid was involved. The sulphate reduction precipitation mechanism is however independent of sulphur and lead source.

12.2.1 Relationship Between Mississippi Valley Type Deposits And Hydrocarbons

In regions where hydrocarbons are preserved, a correlation is evident between the stratigraphic horizons at which oil deposits and Mississippi Valley type ore deposits occur (Figure 32). Furthermore, remnant hydrocarbons are often found associated with the sulphide mineralisation. For example, in the Illinois/Kentucky district, pockets of crude oil are encountered in the mineral deposits (Dozy, 1970). On a larger scale commercial oil accumulations have an antithetic relationship with Mississippi Valley type ore deposits (Figure 33). Figure 33 also shows that the ore districts around the Ozack uplift in North America are located in the vicinity of basement highs, whilst the oil pools occur in the tectonically less disturbed basin lows. This pattern can be explained if hydrothermal metal bearing fluids only occur in the thermally or tectonically more active basement high regions. Original hydrocarbons in these regions therefore have either been largely consumed in the reduction process and/or had more opportunity to escape due to breached or imperfectly sealed caprocks.

12.2.2 Examples of Mississippi Valley Type Deposits


The Sorby deposit is located on the southern part of the onshore Bonaparte Gulf Basin, Western Australia. The sulphide bodies are stratabound within Early Carboniferous carbonates, and are situated to the north east of a Precambrian inlier (Figure 34). A resource of 16.24 mt grading 5.25% Pb, 0.6% Zn and 56g/t Ag has been delineated. The mineralisation is mainly hosted within a sedimentary and tectonic breccia zone (decollement?) at the base of the Knox Siltstone Member which disconformably overlies the Sorby Dolomite Member of the Burt Range Formation. The Knox Siltstone Member may have provided a source of hydrocarbons, whilst the basal breccia zone would have been a permeable reservoir. Hydrocarbon occurrences are common elsewhere within the basin. Anticlinal structural trapping is evident for pods H, I, and J in Figure 35 whilst pods A to G occur in palaeochannels, probably in areas of diagenetically enhanced permeability.


The Admiral Bay deposit occurs along a elongate, fault bounded, structural high which separates the Broome Arch from the Willara Sub-basin in the Canning Basin, Western Australia.
Sporadic low grade lead, zinc and lesser copper mineralisation occurs between 1280 m and 1420 m below the surface within Ordovician and Silurian sediments, over a strike length of 19 km. Narrower, high grade zones occur within the deposit, and are concentrated within the Nita Formation and Lower Carribuddy Group. The Nita Formation comprises carbonate sediment with minor shale, whilst the Carribuddy Group consists of calcareous and dolomitic shale with interbeds of limestone and minor sandstone and coal. The lower unit of the Nita Formation is mainly mineralised by a complex network of veins of barite, dolomite, calite, siderite and quartz, with associated galena, chalcopyrite, fluorite, pyrite, hematite, magnetite, sphalerite and hydrocarbons. The upper mineralised zone is characterised more commonly by sulphide and gangue cementation of porous sediments such as calcareous grainstone, packstone, and wackstone of the upper Nita Formation and quartz sandstone of the Carribuddy Group. Bituminous and liquid hydrocarbons occasionally occur in vugs, stylolites and in the sandstone matrix.

Coxco Deposit (after Walker et al., 1983)

The Coxco stratabound lead - zinc deposit is located in the McArthur River District in the Northern Territory. Mineralisation occurs in Middle Proterozoic McArthur Group sediments along a north plunging anticline adjacent to a dome exposing the lower Tawallah Group in the Emu fault zone (Figure 36). Host rocks are mainly stromatolitic dololutites, of the Mara Dolomite Member (of the Emmeruuga Dolomite) and the Reward Dolomite. The mineralised sequence is unconformably overlain by dolomitic carbonaceous siltstones of the Lynott Formation (Figure 37).

Two stages of mineralisation are recognised. Stage I comprises sphalerite, pyrite, marcasite and galena in a matrix of lutite sized and coarser grained dolomitic karstic fill which was deposited below the Reward-Lynott unconformity. The sphalerite in this stage of mineralisation is intimately associated with organic matter, and Walker et al suggest bacterial reduction of sulphate at temperatures below 100°C was probably responsible for the precipitation of this phase of mineralisation. Stage II mineralisation is volumetrically more important than Stage I and occurs mainly in the Reward Dolomite within 40 to 60m of an impermeable silicified zone which occurs below the upper unconformable surface. Zones of up to 10 to 20% Pb plus Zn several metres across are found immediately below the silicified cap and randomly distributed elsewhere in the interval. Stage II mineralisation occurs in veins and as matrix to dolomite breccias and crosscuts the Stage I mineralisation and in places the basal Lynott Formation. Bitumen accumulations up to a few millimetres in size are a common feature of the veins.

The mineralised breccias are considered to have formed by brittle deformation followed by solution along cracks. Sulphide depositional temperatures from fluid inclusions were between 100°C and 170°C. Importantly, the ore forming solutions did not cause dissolution of the underlying carbonates.

After considering all of the evidence, including mineralogy, fluid inclusions, sulphur, lead and oxygen isotopes, Walker et al., (1983) concluded that Stage II mineralisation was probably precipitated by reduced sulphur, produced at the site of sulphide deposition by abiological reduction of sulphate by hydrocarbons.
12.2.3 Discussion

The hydrocarbon related sulphide precipitation mechanism does not necessarily require a carbonate host rock to take place. Anderson (1991) suggests Mississippi Valley type deposits may usually be found in carbonates because they are often associated with evaporites which are commonly the source of sulphate. Present day hydrogen sulphide rich natural gas invariably occurs in carbonate reservoirs, nearly always associated with evaporites (Anderson, 1991). Nevertheless, Anderson also points out that aqueous sulphate could be introduced from other sources, including possibly with the metals. Spirakis (1983) invoked sulphur carried in the mineralising solution in significant concentrations in a partially oxidised thiosulfate ($S_{2}O_{3}^{2-}$) form, derived from fluids passing through a fractured basement.

Some sulphide mineralisation in the Old Lead Belt in Missouri does occur in the Lamotte sandstone (Anderson, 1991) which immediately underlies the main mineralised carbonate Bonneterre Formation. It is also interesting to note lead-zinc mineralisation in the quartz sandstone of the Carribuddy Group at the Admiral Bay Deposit (Connor, 1990). Even in the Coxco deposit, minor Stage II mineralisation is reported as occurring in the upper silicified zone of the Reward Dolomite and the basal few meters of the overlying Lynott Formation (Walker et al., 1983).

Theories on the origin of most sandstone hosted sulphide deposits require sulphate reduction as a precipitation mechanism. In discussing sandstone hosted stratiform copper deposits, Gustafson and Williams (1981) suggest that impregnations of such sandstones by humates or hydrocarbons introduced by groundwaters can greatly increase the potential for larger deposits such as Nacimiento (U.S.A.). Hydrocarbons may have also played a role in the formation of some sandstone lead deposits. For example, the Laisvall deposit in Sweden where trace hydrocarbons have been recorded in sphalerite (Gustafson and Williams, 1981).
13. GEOLOGICAL HISTORY

13.1 Basinwide Sedimentation

Sedimentation in the Pine Creek Inlier began with the older Early Proterozoic sequence. This was deposited after the 2500Ma crystallisation of the Archaean granites. These sediments were at least partially deformed, metamorphosed and uplifted prior to the start of deposition of the younger Early Proterozoic sequence.

Initial sedimentation in the younger sequence was in shallow water. The lowermost units (Beestons Formation and Celia Dolomite) had a restricted distribution, probably due to palaeo-topography. Rapid subsidence rates are subsequently indicated by thick continuous sequences of high energy, shallow water sediments (Crater Formation) which blanketed the earlier topography. Subsidence rate may have exceeded sedimentation rate during the deposition of the Whites Formation when water depths appear to have increased. This rapid start to subsidence is characteristic of an initial period of crustal stretching, which is experienced by many sedimentary basins (Klein, 1991). Subsidence rates then often exponentially decrease during a period of 'thermal subsidence' (Klein, op cit). This is consistent with the generally quiescent, sometimes shallow water sedimentation of the Koolpin Formation, Gerowie Tuff and Mt Bonnie Formation.

The Finnis River Group is a thick sequence of turbidite and mass flow deposits. The accumulation of such a thick sequence of rapidly deposited sediments without much apparent reworking indicates subsidence rates must have again been high. This was probably accompanied by adjacent uplift to provide the sediment source. Exhumation of higher grade older Early Proterozoic sediments may have accelerated at this time. The increasing subsidence rate and adjacent uplift are characteristic of periods of basin compression (Klein, 1991). The occurrence of sporadic periods of basinwide turbidite sedimentation in the Frances Creek Group indicates this compression may have overlapped with the period of thermal subsidence.

Figure 23 shows a generalised plot of basin subsidence over time. This combines the above interpretations from the Pine Creek Inlier's stratigraphy with the shapes of plots from more recent basins where detailed time/subsidence measurement has been made (Klein, 1991).

13.2 Basement Highs

The following features indicate significant lateral variations in subsidence across the Inlier:- large differences in the thickness of stratigraphic units across cosmic faults; variable distribution of sedimentary thicknesses as indicated by regional gravity data; and sedimentological changes in certain stratigraphic units along strike. The timing and driving mechanisms of the cosmic faults, as elucidated in the Rum Jungle/Waterhouse area, help better define the likely nature and distribution of these subsidence changes elsewhere in the Inlier.

As mentioned previously, thicker sedimentary sequences occur around and outside the cosmic faults. The thickenings, which are up to 400 percent, are too large for layer parallel shortening and cannot be explained by large lateral fault displacements as:-

   i) Gravity data suggests these thickenings (of varying extents) occur all the way around the faults.
   ii) Almost invariable outward block down movements are not consistent with lateral movements, when both up and downward movements would be observed.
   iii) There are no kinematic indicators of strike slip movement.
We conclude that a large component of movement on these faults must therefore have been synsedimentary. This is consistent with the following sedimentological changes and occurrences close to interpreted cosmic faults, which all imply a nearby palaeo-high:

i) Thick limestone in the Koolpin Formation in the Yellow Track and Emerald Springs areas which lenses out towards the Golden Dyke.

ii) Thick limestone in the Koolpin Formation at the Darwin River prospect.


A pre-D₃ folding start for cosmic fault movement is also supported by the distribution of pre deformational Zamu Dolerite around some structures (Figure 4) and the possible folding of some cosmic faults by D₃ (Figure 8). However, the cosmic faults could also have largely escaped folding during D₂ as large lengths are subparallel to S₂ and sections crosscutting S₂ could have acted as tear faults, particularly with the underlying basement acting as an incompressible mass.

The attitude, shape and position of the cosmic faults, together with the distribution of thicker sedimentation around them (as indicated by regional gravity data), are very similar to patterns of faulting and sedimentation described around synsedimentary salt diapirs (Trusheim, 1960; Seni and Jackson, 1983b; Brognon and Verrier, 1966). In these studies faults with inward (towards the salt diapir) dips help accommodate the relative upward movement immediately adjacent to and above the diapir. The centres of greatest subsidence occur as arcs or linear zones adjacent to circular or elongate diapiric bodies, respectively.

We propose that diapirism (or gravitational instability) also formed the apparently very similar cosmic faults and associated stratigraphic thickenings and thinnings. Alternative structural models to explain these concentric structures with inward, upward movements of over 3km, are not known. In the Pine Creek Inlier we propose that this diapirism was driven by lighter zones of granitic material within the Archaean basement. The presence of this lighter material is evidenced by the common outcrops of light granite and granitic basement within the faults and the Bouguer gravity lows underlying the zones within all cosmic faults. It will be argued later that the younger concordant granites which now often occupy these locations, represent remobilised and recrystallised granitic Archaean basement.

Ramberg (1972) calculated the possible uplift rate of granitic basement originally buried to 10km at 0.08 cm per year, or 80km per 100m.y. Berner et al (1972), who studied the factors affecting the rate of diapir growth and deformation in the surrounding medium, found that diapirs rapidly reach a constant state of uplift after initiation. Using these studies and stratigraphic thickness measurements, a relative rate of uplift within the cosmic faults (overlying the diapiric basement) in the Pine Creek Inlier is postulated and shown in Figure 23. It is suggested that uplift over the rising granitic basement may have commenced after deposition of the older Early Proterozoic sequence, that is, it had reached a constant rate by the time stretching subsidence began. The constant rate of basement high uplift (relative to the basin bottom) superimposed on the changing rate of overall basin subsidence would have produced a period when uplift (relative to the earth's surface) may have exceeded subsidence over the basement highs (Figure 23). Palaeo-highs may have been produced during this period. This is in agreement with the previously mentioned evidence for palaeo-highs during deposition of the Frances Creek Group and lower Finnis River Group.
13.3 Compressional Deformation

Compressional deformation is evidenced by thrusting, D2 folding and transpressional faults. Johnston (1984) suggested the Pine Creek Inlier resembled a foreland basin with a major uplifted block to the east now represented by high grade metamorphics and migmatites (Nimbuwah/Nanambu/Alligator Rivers areas); a central zone of thrust faulting (Mundogie/South Alligator Valley area); and a western fold belt (Rum Jungle/Pine Creek area).

The following are evidence for this compressional event commencing during sedimentation:-

i) The basin wide distribution of flysch-like greywacke units in the Frances Creek and Finniss River Groups. This is consistent with a period of adjacent uplift initiated by compression.

ii) Synsedimentary stratiform mineralisation hosted by the Frances Creek Group commonly shows a close spatial relationship to transpressional faults (Section 11.3). It could therefore be assumed that these structures, which were formed by compression, were present during sedimentation. In addition, compositional similarity between synsedimentary stratiform mineralisation and underlying vein mineralisation suggests a possible coeval origin for these styles (Section 11.4). As these veins formed in transpressional faults and concordant structures, it is concluded that these structures (and compression) had begun in Frances Creek times.

Dixon and Tirrul (1991) modelled folding and faulting in compressed sequences of different competencies. Their findings relevant to the deformation history of the Pine Creek Inlier include:-

i) Folding in thin, less competent cover over broad anticlines of more competent material is more open than in those areas away from the domes (Figure 19). This is analogous to the less tightly folded sediments seen adjacent to and overlying the basement diapirs. Movement on the cosmic faults during compressional deformation could therefore have accommodated the upward diapiric movement and differences in folding intensity on either side of the structures.

ii) Less competent sedimentary layers are more likely to be folded with larger amplitudes at shallow depths than at deeper levels (Figure 19).

iii) Disharmonic folding occurs in ductile layers within broad synclines defined by underlying competent beds. This is similar to the occurrence of local disharmonic folding (and crenulation cleavage) within the Koolpin Formation in the Darwin River area (Grove, 1993a).

iv) Folding in this environment is often initiated by detachment (or decollment) folding, as defined by Jamison (1987). The setting of many concordant faults in the Inlier are similar to Jamison's description of detachment faulting, for example, the faults generally do not cause stratigraphic repetition, associated folds tighten in stratigraphic units above the faults and have upright disposition, and the faults are located within ductile lithologies between more competent units. The apparent concentration of these faults on fold limbs (Figure 10) is consistent with this mechanism initiating folding prior to the concordant structures themselves being folded during further compression (Figure 11).

The presence of 'compressional zones', as postulated in section 10.6, indicates that the strain produced by this compressional deformation was not evenly distributed over the Inlier. The apparent spatial association of these zones with bodies of diapiric basement suggests that these bodies exerted some influence on deformation during regional compression.
Modelling by Berner et al (1972) of diapirism in laterally constrained and laterally unconstrained situations demonstrates:

i) faster diapir growth in constrained cases.

ii) an increase in compression adjacent to and about 0.5 to 3 diapir radii away from constrained diapirs (Figure 18).

iii) upward flow of material in a zone about (Figure 19) 0.5 to 3 diapir radii away from constrained diapirs.

iv) decreased compression in the same situations adjacent to unconstrained diapirs.

These phenomena are consistent with the location of compressional zones some distance away from basement diapirs in the direction perpendicular to prevailing \( S_2 \) (that is parallel to compression). It is possible this additional strain could have manifest itself as zones of increased concordant thrusting and folding, rather than transpressional faulting and folding, for example, the McCarthy’s-Frances Creek areas. The location of these high strain zones relative to the basement highs suggests diapir movement continued during compressional deformation.

The bending of \( S_2 \) surfaces around the cosmic faults/gravity lows is consistent with their emplacement before (or during) deformation (Mandal and Chakraborty, 1990). A superimposed, regional \( D_3 \) cross folding cannot explain the changing orientations of \( D_3 \) fold axial planes and plunges (cf. Nicholson, 1978; Johnston, 1984). Localised refolding and a crenulation cleavage do occur in places, however, these may be due to the affects produced in synclinal positions above competent units, as mentioned previously. The proposed relative timing between structural elements is shown in Table 2.

A syntectonic timing of the granites appears unlikely in the Pine Creek Inlier, and indeed in other provinces. If compression was interrupted to allow granite intrusion from depth, overprinting evidence of changed stress orientations would be likely around the granite intrusions. In addition, in the Pine Creek Inlier, sedimentological evidence suggests that basement highs existed before compression, and similar deformation patterns occur around the definite basement highs at Rum Jungle and postulated, granite-centred basement highs elsewhere.

As compression continued, burial increased during the deposition of the thick sequences of Finniss River and El Sherana Groups. Regional metamorphism consequently occurred. Temperatures of 400 to 500°C and pressures of 2 to 4 kb (Ferguson, 1980) were attained in the rocks now exposed on the surface of the Pine Creek Inlier. The mobile bodies of light, sialic basement would have been hotter than this as they were buried deeper in the Lower Proterozoic sedimentary pile or were contained within the basement sequence, at this stage. The strain produced during upward movement may also have increased temperatures within the diapirs.

13.4 Granite Emplacement

When the regional compression relaxed, burial stopped, and diapiric movement of the basement diapirs relative to the earth’s surface increased (Figure 23). Decreasing pressure in these bodies could have caused melting. Temperatures of about 700°C and pressures of 2 to 4 kb are sufficient to melt granitic material (Carmichael et al., 1974). Pressure release has been proposed as a major cause of magma generation (Carmichael et al., op cit; Figure 20). These conditions are likely to have been attained in the diapiric sialic basement, except perhaps where geothermal gradients were lower; burial depths (or overall basement subsidence) were insufficient for the basement material to reach sufficient temperatures or heat loss from the rising bodies was too fast. This may have occurred in Rum Jungle material where little or no granite appears to have been generated (at least at the current level of exposure).
The melting resulted in a lowering of viscosity of the sialic material and a consequent increase in the rate of uplift. Diapirism approached equilibrium with the formation of sill-like bodies high in the sedimentary pile (Talbot 1974; Ramberg 1972). These are represented by the discordant granites. Granite magma frozen in the neck of the diapirs is represented by the concordant granites.

13.5 Later Faulting

The South Alligator, Giants Reef and perhaps north trending structures represent later periods of brittle deformation. The extent of some of these structures and extensions into neighbouring provinces suggests some reactivation of older, basement structures.

13.6 Stratiform Mineralisation

A synsedimentary (- diagenetic) origin for stratiform mineralisation is evidenced by:-

- finely bedded, deformed textures;
- close association on a prospect scale with stratigraphic changes along and across the stratigraphy;
- lack of association with prospect scale, post lithification structures;
- and the similarity of the Inliers stratiform mineralisation with a number of well known types of mineralisation of an accepted synsedimentary origin.

These types include the Whites Formation deposits which closely resemble the stratiform copper type deposits (Gustafson and Williams, 1981) and many of the others fall into the category of shale-hosted Pb-Zn deposits (Gustafson and Williams, 1981; Large, 1981). Stratiform gold deposits have had both synsedimentary (Fripp, 1976; Fleischer and Routhier, 1973; Sawkins and Rye, 1974; Nicholson and Eupene, 1984; Mayer, 1990; Alexander, et al, 1990) and later syn- to post-deformational, epigenetic origins proposed (Phillips et al, 1884; Thompson et al, 1990; Caddey et al, 1991). However, as the Pine Creek Inlier has numerous stratiform gold showings, is less deformed and has better outcrop than most other regions containing this style of mineralisation, it should perhaps allow insights into occurrences in other provinces. A synsedimentary origin is preferred here because:

i) High grade ore can occur in linear, unfaulted and unfolded lenses (eg Golden Dyke). Prospect scale folding and faulting is not a prerequisite control. However, where later structural complications occur gold is redistributed into high strain zones.

ii) The occurrence of ore grade lenses in iron-poor, ductile lithologies as well as more brittle iron formation indicates that control by iron-rich, brittle units as proposed by epigenetic proponents is invalid. The iron formation deposits contain some vein and sulphide textures similar to those considered by Thompson et al, (1990) and Caddey et al (1991) as indicating an epigenetic origin. The adjacent and nearby mudstone and carbonaceous mudstone mineralisation rarely contain these veins. This would suggest that the veins represent a post mineralisation event not critical to mineralisation distribution.

iii) The stratiform gold deposits have a strong spatial association with stratiform tourmaline beds (Nicholson and Eupene, 1984), which are considered to be evidence of synsedimentary hydrothermal activity (Fliescher and Routhier, 1973; Ethier and Campbell, 1977; and Slack, 1982).
iv) There are a number of examples of transitions between stratiform Fe-As-Au deposits and stratiform Pb-Zn deposits. The Davies No.1/Afghans Lode is a stratified pyrite-arsenopyrite-gold-minor sphalerite, galena and chalcopyrite lens with an along-strike envelope of siderite. It is hosted by a thin lens of carbonaceous mudstone. This mineralisation occurs amongst a cluster of typical stratiform, iron formation-hosted Fe-As-Au deposits (Golden Dyke, Langley’s, Davies No.2, Fisher’s Lode, Northern Costeans) and is only 2 km from the Mt Bonnie deposit. The Mt Bonnie mineralisation is stratiform, black shale hosted, contains Pb-Zn-As-Au-minor Sn, and occurs within an envelope of Fe-Mg silicates and carbonates.

The stratiform deposits and their host sediments were deposited during a period of waning basin subsidence and formation of topographic highs over the diapiric basement (Section 10.10, Figure 23). The rising basement, which if it retained its heat would have been hotter than the surrounding sediments, could have caused convective fluid movement in adjacent areas. Additional heat may also have been generated by radiogenic decay within these U-rich granites (Solomon and Heinrich, 1992). The fluids were discharged through structures (Henley and Thornley 1979), between and around the highs. The extra heat generated between close spaced highs may explain the particular favourability of this setting. Greater structural complexity may also have provided more discharge structures. An early thermal event is perhaps evidenced by some metamorphic textures (Section 9.1).

13.7 Polymetallic Vein Mineralisation

13.7.1 Timing of Polymetallic Veins

The location of these veins within, and their deformation by, concordant and transpressional faults indicates polymetallic veins were emplaced during the compressional deformation. The similar composition and compositional changes that veins and stratiform deposits show through the stratigraphy suggests the polymetallic veins were formed from the same type of fluids at the same time as the stratiform deposits, although deeper within the sedimentary pile. This is supported by the fluid inclusion work of Smoloney (1988) which indicates sphalerite at Woodcutters formed under 0.7 – 1kbar-pressure, or 2.6 to 3.8 km depth. This approximately represents the spacing between stratiform and polymetallic veins of similar compositions. Early copper-rich discordant deposits were not deposited as the host structures were not formed until during deposition of the Koolpin Formation. Late copper-tungsten-tin-rich stratiform deposits are not found because suitable quiet, anoxic depositional environments were not available during the accumulation of the Burrell Creek Formation.

13.7.2 Relationship Between Hydrocarbons and Polymetallic Veins

It is proposed that hydrocarbons may have precipitated polymetallic vein mineralisation in the Pine Creek Inlier. Where a continuing supply of hydrocarbons was not available, mineralising fluids continued to migrate upwards until precipitation occurred upon mixing with seawater at or close beneath the seafloor.

Assuming that hydrocarbons played a significant role in forming polymetallic vein type mineralisation, the following three factors needed to coincide to form significant deposits.

1. Continuing supply of metal bearing fluid.
2. Continuing supply of reducing agent (hydrocarbons).
3. Continuing supply of sulphate to be reduced.
By further assuming that the supply of both metal bearing fluid and sulphate was reasonably common, the continuing supply of hydrocarbons to the site of deposition becomes the critical element. Hydrocarbon generation and accumulation in the Pine Creek Inlier has previously been discussed and Table 5 summarises the key elements involved. These factors will now be examined on both a regional and prospect scale to investigate their possible influence on polymetallic vein formation.

13.7.3 Regional Scale

Four of the main elements listed in Table 5 - of source, reservoir, seal and trap are widespread throughout the Pine Creek Inlier and place few constraints on the potential distribution of hydrocarbon supply. On a regional scale, timing of hydrocarbon generation with respect to basin compression (and hence structure formation) and the advent of the metal bearing solutions appears to be the critical factor.

As discussed previously, the main polymetallic mineralising phase in the Pine Creek Inlier probably began after the onset of deposition of the Koolpin Formation, and at approximately the same time as the very beginning of basin compression. Consideration of time-depth of burial curves such as Figure 30, has also shown that hydrocarbon generation can be expected to have occurred considerably earlier in the central portions of the basin where the sedimentary sequence is thicker than the outer margins.

It is possible that significant hydrocarbon generation had effectively ceased in the central portions of the basin prior to the onset of compression (and hence main structure formation) and the introduction of the main mineralising fluids. This scenario may explain the absence of significant polymetallic vein deposits in the central Burrundie and Golden Dyke Dome areas. Conversely, the availability of mature, hydrocarbon generating source rocks in the basin margin could account for the predominance of polymetallic vein type deposits in these areas (over stratiform types). Metal and sulphate bearing fluids would not be able to reach the surface if they encountered abundant supply of reductant (hydrocarbons) along the way. Even if the source rocks were marginally immature for hydrocarbon generation in the basin margins the increased heat of the metal bearing fluids may have been sufficient to elevate them locally into the oil window.

The stratigraphic level at which polymetallic veins may occur is determined partly by the source rock maturity of the enclosing sediment and it's degree of lithification. Lithification is important for the formation of secondary porosity by fracturing and folding and faulting.

In most cases, the upper Coomalie Dolomite would define the lower stratigraphic limit at which hydrocarbons could have been encountered, and no significant polymetallic veins have yet been found below this level in the Pine Creek Inlier.
13.7.4 Prospect Scale

After consideration of the regional constraints on polymetallic vein formation, Table 5 can also be utilised to examine favourable factors on a prospect scale. The Woodcutters Mine illustrates this point.

Woodcutters

Isotope studies and fluid inclusion studies on the Woodcutters Mine have yielded results which are not inconsistent with the following proposed role of hydrocarbons in the precipitation of sulphides. Sulphur isotope studies carried out by the Baas Becking Geological Laboratory of the BMR reportedly yielded values of +10\%/oo, suggesting reduction of seawater sulphate as a source for sulphur (Taube, 1990). Taube (1990) also reports that preliminary conclusions from the study were that Woodcutters mineralisation resembles Mississippi Valley type. Fluid inclusion studies by Smolonogov (1988) indicate that mineralisation was precipitated from a hypersaline (>23.3 wt% NaCl equiv.), CO\textsubscript{2} rich brine. Salt other than NaCl was indicated by low ice melting temperatures. Smolonogov (1988) also noted the presence of a clathrate hydrate (CO\textsubscript{2},5\%/H\textsubscript{2}O) in primary sphalerite inclusions. Whilst CO\textsubscript{2} hydrate is the most likely type, clathrate hydrates can also form from a variety of molecules including CH\textsubscript{4}, H\textsubscript{2}S, SO\textsubscript{4}, N\textsubscript{2} and O\textsubscript{2} (Hollister and Barruss, 1976).

The carbonaceous, dolomitic shales of the Whites Formation provide the obvious source for hydrocarbons at the Woodcutters Mine. Study of fluid inclusions indicates sulphide deposition temperatures of 221°C to 294°C and a depth of 2.6 to 3.8 km of overburden (Smolonogov, 1988). These temperatures are well above what would be expected from geothermal gradient alone (they indicate a gradient of approximately 80°C/km) and therefore were probably achieved by the introduction of anomalously hot mineralising fluids. Consequently it is likely that prior to mineralisation, the Whites Formation was an immature to mature source rock for hydrocarbons (Figure 30) and hence had ample hydrocarbon generating capacity remaining at the time of mineralisation.

There is strong evidence to suggest that the Pb-Zn-Ag mineralisation at Woodcutters was mainly deposited during deformation (Nicholson et al, 1990), in a transpressional structural regime. Underground mapping and core observations show that the more competent dololulite beds within the Whites Formation shales fractured in a brittle manner during deformation, whilst the shales tended to be more ductile. Thus secondary porosity and permeability were developed in otherwise tight dololulite beds along fold hinges and adjacent to significant faults. Continual movement along faults in the transpressional regime resulted in local dilatant zones along the faults themselves, which transect all lithologies (Figure 26). Intersections of crosscutting faults and north-south trending faults also created sub vertical pipe-like permeable zones.

Metal and sulphate bearing solutions were introduced to the Whites Formation along the fault zones, particularly the permeable fault intersections. Continual hydrocarbon generation in the surrounding rocks provided an on-going supply of reducing agent to the fault zones resulting in a continual supply of hydrogen sulphide and hence precipitation of sulphides. The heat of the mineralising solutions ensured that all hydrocarbons were gaseous by this stage.

Where the faults intersected sufficiently fractured dololulite beds, the mineralising fluids moved along them, again depositing sulphides on contact with reducing gasses. Continual fault movement and folding and possibly dissolution of carbonate, ensured adequate local permeability.
A significant proportion of the mineralisation at Woodcutters was contributed by replacement of dolomutite beds. The sub-horizontal components of mineralisation evident on longitudinal section (Figures 24 and 25) are predominantly dolomutite controlled. This control is particularly strong along anticlinal hinge zones in the upper levels of the mine, where fold amplitudes are greatest as shown in Figures 13 and 14. The anticlinal control is also apparent in long section (Figures 24 and 25). In both long sections not only is the larger anticline reasonably central to the overall mineralisation but also local culminations appear to influence the location of the northernmost orebodies (3N Extended and 5N). These features are suggestive of trapping of the buoyant reductant gases. In addition, on the 5 orebody long section (Figure 25) the relatively flat base of the upper dolomutite controlled orebody may reflect a palaeo-hydrocarbon/water contact. The efficient trapping precipitation mechanism at Woodcutters has resulted in nearly all of the metals in solution being deposited below the top of the lower sequence (the highest carbonate rich unit). The apparent absence of domal anticlinal fold closures along strike where other favourable factors are also present (ie. N-S faults, cross faults, carbonate units) may explain the occurrence of only local fault-related mineralisation found to date.

Only a small number of diamond drill holes have intersected the Coomalie Dolomite below the Woodcutters Mine, and trace mineralisation has been found. The upper Coomalie Dolomite could be mineralised, although the narrower fold amplitude and greater thickness of this unit may have reduced its capacity to be fractured and hence its permeability. Karstic topography developed elsewhere in the Coomalie Dolomite is probably of post mineralisation age. A possible decollement along the Coomalie Formation-Whites Formation contact, may however be mineralised.

Given all the other necessary prerequisites (eg. regional location, structures, stratigraphy, metal bearing fluid pathways), the critical feature in localising the Woodcutters orebodies appears to have been the presence of a domal anticline. Considerable thickening is associated with the anticlinal folding, and methods for locating this thickening elsewhere such as detailed gravity should be investigated for exploration in similar situations.

13.8 Stockwork - Concordant Gold-Quartz Mineralisation

Vein sets which crosscut S₂ cleavage indicate this mineralisation postdates regional compression. Fluids derived from compacted, interstitial pores and metamorphic dehydration reactions are likely to have contained anomalous gold concentrations, particularly in areas underlain by stratiform and polymetallic vein concentrations. These criteria fit the Frances Creek and Finnis River Groups around and between basement highs. The rising sialic basement/granites may have also acted as a heat source causing recirculation by convection. Fluid movement probably concentrated up previously existing vertical structures including transpressional faults, faults within the Pine Creek shear and the Shoobridge fault. Although these zones are continuous, individual faults often die out within an en echelon pattern. Fluids may have accumulated below impermeable beds in unfaulted anticlines above terminated faults. Water retained during the peak of metamorphism may build up pressure due to thermal expansion (Norris and Henley, 1976). Resultant hydraulic fracturing can then occur along planes of previous weakness and perpendicular to the axis of least principal stress (Hubbert and Willis, 1957; Secor, 1965). The fracturing enhanced permeability and helped upward fluid movement through the ore zones. A common timing for this type of mineralisation across the Inlier is suggested by the subparallel orientation of discordant (to S₁ and S₂) vein sets in different deposits (Figure 39). Fracturing favoured brittle and permeable lithologies (Secor, 1969). Mudstones tended to trap fluids, particularly when fracturing along weak bedding planes would not allow fluids to escape up through the sequence. This lithology may have favoured mineralisation in flat or double plunging anticlines due to the larger retention time of mineralising fluids.
13.9 Unconformity Related Uranium-Gold-Platinoid Mineralisation

Many different origins have been proposed for this style of mineralisation. However, a common theme involves the descent of oxidised mineralising fluids into conduits in the Early Proterozoic sequence. Deposition occurred upon mixing with reducing fluids or reaction with carbonaceous lithologies. The mineralising solutions and conduits were formed during diagenesis of the overlying Middle Proterozoic sediments. Constituent metals may have been derived from the nearby Archaean basement.
14. COMPARISON WITH OTHER PROVINCES

14.1 Introduction

This study has arrived at the following empirical relationships:

i) The location of basement highs within basins can be recognised where a few of the following are coincident: doming, elliptical upfaulting, lesser fold intensity, gravity lows and divergence of fold axial planes.

ii) Base metal-gold deposits that were formed during or soon after basin sedimentation (for example stratiform, polymetallic vein and Mississippi Valley deposits) are preferentially located adjacent to, above or particularly between closely spaced basement highs.

iii) Syn-or post-deformation gold quartz veins are arranged along arcs on either side of and way from basement highs, in the direction perpendicular to prevailing cleavage/fold axial planes.

iv) Stratiform mineralisation occurs within stratigraphic units that were not deposited over all basement highs and show evidence of local unconformity or emergence.

In this section these observations are tested in a number of different mineral provinces.

14.2 McArthur River

Leaman (1992) has interpreted the thickness of successive units in the Batten Trough Region from geological and geophysical data. Figure 42 shows the location of centres of persistent minimal sedimentation. These probably represent basement highs. The McArthur Group hosts most known mineralisation, has a patchy distribution (Leaman, 1992) and contains sedimentological evidence for local tectonically controlled emergence (Jackson, Muir and Plumb, 1987). Base metal occurrences (from Jackson, Muir and Plumb, 1987) are found adjacent to basement highs. The major HYC deposit occurs between closely spaced highs within the McArthur Group (Figure 42).

14.3 Mt Isa

Geological and gravity data was obtained from Blake (1987). Base metal mineral occurrences were also obtained from Blake (1987) and various press reports. Figure 43 shows the position of interpreted basement highs using Bouguer gravity; fold-bedding trends, areas of mapped doming, concordant granites; the subcrop of the stratigraphic units known to host stratiform mineralisation (the Mt Isa and Mary Kathleen Groups); and known base metal occurrences. Favourable stratigraphy between closely spaced (interpreted) basement highs appears particularly prospective.

14.4 Glengarry Basin

Geological and mineralisation data were obtained from Elias and Williams (1980), Gee (1987) and the Homestead Gold of Australia Prospectus. Bouguer gravity data was obtained from BMR 1:250,000 contour sheets (1974). Figure 44 shows the position of interpreted basement highs, the Glengarry Group, areas of mapped doming, axial plane/cleavage trends and known gold and copper mineralisation. The mineralisation appears to more commonly occur between and adjacent to closely spaced basement highs in the Glengarry Group.
14.5 Broken Hill

The Willyama Supergroup has insufficient outcrop to treat in the same manner as the Pine Creek, McArthur or Mt Isa provinces. However detailed gravity in the mine area (Figure 45 from Tucker, 1983) indicates that this major deposit occurs within an 'embayment' defined by gravity lows.

14.6 Mississippi Valley

Figure 33 and Figure 46 illustrate the distribution of Pb-Zn deposits within the Mississippi Valley, relative to basement highs. These show a preferred relationship of mineralisation adjacent to, above and particularly between closely spaced masses of basement high.

14.7 Zambian Copper Belt

Fleischer, Garlick and Haldane (1976) describe the geology of this Province. Figure 47 illustrates possibly similar spatial relationships between mineralisation and basement highs to those described above. Figure 48 shows that mineralisation is mainly hosted by stratigraphic units which lens out over these highs.

14.8 Reefton

The Reefton goldfield is situated near Greymouth on the South Island of New Zealand. It has produced several million ounces of gold from quartz veins hosted by early Palaeozoic greywacke and mudstone. The veins are contained within fault zones orientated subparallel to fold axial planes (Cage, 1949). Figure 49 shows that mineralisation appears to be preferentially located in an elongate zone of smaller wavelength folds. Although outcrop is not continuous it appears that to the east of the favourable zone a larger wavelength syncline occurs adjacent to an elongate zone of granite outcrop. This pattern is similar to the diapir/granite-broad syncline-compression zone/gold stockworks pattern seen in the Pine Creek Inlier.

14.9 Bendigo/Ballarat

Figure 50 shows a simplified geology of this province obtained from the 1:250,000 scale maps of the Geological Survey of Victoria. Gravity data was obtained from the BMR. The figure shows that most gravity lows are overlain by outcrops of Devonian granite/granodiorite. Fold axial planes appear bent around some of these granite outcrops, but not those away from the gravity lows. The major gold producing centres are located adjacent to the gravity lows in the direction approximately perpendicular to the prevailing strike of the fold axial planes.

14.10 Forrestania

The geology of this province is shown in Figure 51. The location of known gold mineralisation was provided by Rutherford (pers comm). The mineralisation appears preferentially located adjacent to "syntectonic" granites, particularly in the direction perpendicular to fold axial planes.
15. EXPLORATION STRATEGY

15.1 Commodities and Mineralisation Style

The size of the resource at Woodcutters confirms the Inlier’s potential to host substantial deposits of Pb and Zn. Additional discoveries that could be trucked to the Woodcutters plant would increase the efficiency of mining the Woodcutters orebody and increase the value of the Woodcutters operation. The presence of the plant also allows the mining of smaller resources than would otherwise be possible. Both stratiform and polymetallic vein styles are realistic targets.

The Pine Creek Inlier has produced relatively small amounts of copper, however it contains examples of the very productive stratiform copper style and is considered prospective for the same. As copper sulphide mineralisation could be treated at the Woodcutters plant, the same advantages for Pb-Zn discoveries apply.

Tin is in a similar situation to copper. The similarity between the polymetallic vein mineralisation and the Renison Bell deposit together with encouraging exploration results from Little Mary indicate the Inlier’s potential.

The Pine Creek Inlier has total production and present resources of over 8 million ounces of gold. Significant deposits of stratiform, polymetallic vein, stockwork/concordant gold-quartz and unconformity-related styles occur, and are worthy of exploration.

15.2 Districts

The prospectivity of districts within the Inlier is discussed in relation to mineralisation styles, tenement holdings and previous exploration. The location of these districts is shown in Figure 51.

15.2.1 Lloyd Creek

This district contains an interpreted compressional zone, Whites Formation and Acacia Gap Quartzite and is close to the Acacia High. It is therefore prospective for polymetallic Pb-Zn deposits. Although outcrop is poor and soil cover generally thick, Pb-Zn stream anomalies on Aztec tenements are worthy of followup.

15.2.2 De Monchaux Creek

This district contains a doubly plunging sequence of Whites Formation and Acacia Gap Quartzite within an interpreted compressional zone. Auger/RAB geochemistry indicates the north of the area has significant Au-base metal anomalism, and deserves diamond drilling. The southern half of this zone deserves RAB drilling across the poorly outcropping Whites Formation. The district deserves priority due to its proximity to Woodcutters mine. It may be downgraded as it is outside, rather than between basement highs and the favourable Whites Formation dololultes may not occur above 300m depth.

15.2.3 Woodcutters

The Woodcutters district is obviously favoured with known mineralisation, favourable stratigraphy for polymetallic veins, a compressional zone, doubly plunging anticlines and location between basement highs. A number of prospects have similar characteristics to the mine (L6, Huandot, Flaming Fury and Seismic Anticline) and deserve further exploration. Mineralisation could also occur along D, breccias above the Coomalie Dolomite. The ‘2’ mineralisation at the mine could be controlled by such a structure.
The Area 44 prospect has the following favourable features for stratiform Cu mineralisation: stratigraphy, proximity to cosmic faults and embayment location. However, the potential for a moderate resource has been reasonably tested.

15.2.4 Waterhouse

The district does not appear to contain a compressional structure. However, numerous Pb-Zn anomalies could mark polymetallic mineralisation veins hosted by concordant breccias, perhaps localised adjacent to contracts of metadolerite sills. Previous drilling has been targeted down dip rather than down plunge, which now appears more appropriate.

The presence of the Sundance mine and wide areas of interpreted Coomalie Dolomite under surficial cover indicate some potential for unconformity-U-Au mineralisation.

15.2.5 Kylie-Mt Mabel

Favourable indications for unconformity U-Au-Pb mineralisation are:-

i) large areas of concealed Coomalie Dolomite,
ii) large areas of exposed Middle Proterozoic Tolmer Group,
iii) evidence of both post-Middle Proterozoic faulting and karst collapse,
iv) known U occurrences, and
v) no previous Au exploration.

These favourable indications are partially countered by the poor drainage and thick soil cover which will hamper exploration.

15.2.6 Tumbling Waters

This large area could represent the transpressional zone to the west of the Rum Jungle/Waterhouse/Acacia diapir. The Burrell Creek Formation, which is favourable for stockwork-concordant vein style Au mineralisation, occurs throughout. BMR mapping indicates a possible increase in deformation in the district. Minor gold has been discovered along the north of this trend. A lack of previous exploration in the south of the district and reasonably developed drainage supports the districts prospectiveness of this district.

15.2.7 Rum Jungle Embayment

Stratiform Cu-style mineralisation is the most obvious target in this district. It possesses known occurrences, embayment between basement highs, cosmic faults and lower Whites Formation stratigraphy. Recent intersections in the Area 55 prospect by Compass Resources could add further encouragement.

15.2.8 Darwin River/Acacia

The Acacia North area hosts similar mineralisation to that at Waterhouse, and deserves further testing for the same reasons. Acacia South contains a number of geochemical anomalies on the northern end of the Woodcutters compressional zone. The stratigraphy/lithology are similar to Woodcutters and the area occurs between basement diapirs. The only drawback to this area’s potential is the possible depth to target zones.
Favourable indicators of stratiform mineralisation in the adjacent Darwin River area are:

i) South Alligator Group stratigraphy.
ii) embayment between basement highs.
iii) known minor occurrence and widespread anomalous geochemistry.

Unfavourable criteria are soil cover and predominance of polymetallic veins in the Acacia/Rum Jungle/Waterhouse area.

15.2.9 Maureen - Mt Woods

This district covers the compressional zone on the east side of the Acacia/Rum Jungle/Waterhouse diapir. In the north, most of the favourable zone contains sediments too low in the stratigraphic sequence whilst in the south, large areas are covered by soil. Areas of outcrop have been reasonably explored with mixed success.

15.2.10 Adelaide River

This district contains known shows and favourable stratigraphy for stockwork-concordant quartz-gold mineralisation. However, its relationship to basement highs and lack of compressional zones downgrade it.

15.2.11 Mt Bundey

Numerous mineral showings occur in this district including stratiform Au, stockwork-vein Au, concordant-vein Au and polymetallic vein or stratiform Pb-Zn. Proximity to the Toms Gully plant and Rustlers Roost resource has resulted in a relatively exhaustive testing of the gold potential. The base metal potential has been reasonably tested, although is worthy of continued review as models further develop.

15.2.12 Plateau Point-Green Ant Creek

South Alligator Group stratigraphy, known mineral occurrences and proximity to a basement high define the potential for stratiform base metal mineralisation in the Plateau Point area.

In the Green Ant Creek area a compressional zone in the Lower Proterozoic rocks to the west of the Fenton basement high is likely. Although mostly covered by Daly River basin sediments, this is supported by aeromagnetic data. Economic viability is downgraded by the cover. However, the high gold productivity of neighbouring compressional zones in the Inlier (eg Howley anticline, Brocks Creek anticline and Golden Dyke-Yam Creek zone) justify further investigation.

15.2.13 Howley

The Howley anticline and subparallel structures define a compressional zone 4 km wide and 35 km long. This hosts numerous gold deposits. It has been well explored and is covered tightly by existing, foreign tenements.

15.2.14 Ringwood

A number of stockwork gold prospects in Burrell Creek sediments are located along a compressional zone in this district, which occurs to the northeast of the Burnside granite/basement high. The northwest and southeast extensions of this zone are worthy of further attention.
15.2.15 Brocks Creek-Golden Dyke-Burrundie

This district occurs between the closely spaced Fenton, Burnside and Prices Springs basement highs. The Golden Dyke-Yam Creek and Brocks Creek compressional zones are gold productive and have generally been well explored. A possible exception is the southern end of the Brocks Creek zone in the Hayes Creek area and the northern end of the Yam Creek/Priscilla Line. Local structure and stratigraphy also appears favourable.

The district also has good potential for stratiform base metal mineralisation. This is suggested by the numerous known examples, the wide outcrop area of the Frances Creek Group and the situation close between basement highs.

A number of partially tested prospects including Yellow Track, Emerald Springs, Heatley's and a stream anomaly in the north-west Golden Dyke Dome are worth follow-up.

15.2.16 McKinlay River

BMR mapping in this district suggests the presence of a compressional zone formed on the north-east side of the Prices Springs basement high. Favourable stratigraphy is present although it is generally covered by soil. Previous exploration results should be investigated.

15.2.17 Frances Creek-Jessops

This district hosts numerous small showings of base metals and tin. Proximity to the Mary River basement high, favourable stratigraphy, evidence of widespread concordant breccias, and well drained topography are all favourable. A more detailed evaluation of previous exploration is justified.

15.2.18 Allamber

Favourable indication for stratiform copper mineralisation include:- embayment situations between lobes of basement high/granite, favourable lower Whites Formation stratigraphy, known showings, and extensive stream sediment Cu, Pb, Zn and Mn anomalism.

Although compressional zones don't appear to be present, polymetallic veins could occur in concordant structures.

Abundant carbonate, scattered Middle Proterozoic sandstone occurrences, chloritic alteration, uranium mineralisation, adjacent granite/basement highs and a lack of previous gold exploration justify exploration for unconformity related deposits.

15.2.19 Mary River

This district contains all the favourable criteria for polymetallic vein deposits, apart from location adjacent to, rather than between, basement/granite highs. It also contains a number of known occurrences. Unfortunately it is within the Kakadu National Park and is currently inaccessible to exploration. However, it is possible that this problem may be overcome within the life of the Woodcutters operation, particularly if the NT government is given management of Kakadu.
15.2.20 Union Reefs-Pine Creek

Compressional zones, the Pine Creek shear and outcropping Burrell Creek Formation combine in this district to make it obviously favourable for stockwork/concordant quartz vein gold mineralisation. However, known present and future producers have made the tenure situation very tight.

15.2.21 McCarthy’s-Moline-Little Mary

Widespread outcrops of the Frances Creek and Finniss River Groups, well defined transpressional and concordant structures, and location between and around basement highs confirms the potential for polymetallic vein mineralisation.

Probable downplunge, rather than down dip, control in the McCarthy’s concordant prospects should be tested. The discordant zones at McCarthy’s may be more related to stockwork gold-quartz mineralisation. The relatively low sulphide concentrations in these deposits probably downgrades their base metal potential.

15.2.22 Driffield-Mt Todd

Windows of Frances Creek Group overlying basement highs in this area are prospective for polymetallic vein and stratiform base metal mineralisation.

Tenements along the Pine Creek structure overlying the highs are tightly held due to the presence of the Batman stockwork gold deposit.

15.2.23 Daly River

A number of the features of this district differ from others within the Inlier:

i) The host volcanics are far more proximal than their probable correlatives in the central Pine Creek Inlier, viz, the Gerowie Tuff.

ii) The mineralisation, although apparently shear controlled and syn-deformationally emplaced, is associated with more wall rock alteration than other polymetallic vein deposits in the Inlier.

iii) The co-existence of significant Cu and Zn mineralisation is unusual, although not unique.

The prospectivity of the district is indicated by its situation between two large, closely spaced gravity lows; a number of prospects containing ore/sub-grade Zn mineralisation; the occurrence of several significant soil anomalies that have only been weakly tested; and the proximity (only 120 km by road) of these prospects to the Woodcutters plant. The acquisition and exploration of tenements over this district must be a high priority.

15.2.24 Fletchers Gully

This district is considered favourable for stockwork-concordant quartz gold deposits as it contains the Burrell Creek Formation and a likely compressional zone. Previous exploration work should be assessed.
15.2.25  Eva Valley

The regional setting of this district is not fully understood due to the presence of surrounding cover rocks. However, the occurrence of polymetallic vein deposits in South Alligator and Finnis River Group rocks suggests that exploration is warranted.
16. REFERENCES


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TEMPORAL RELATIONSHIP OF STRUCTURAL ELEMENTS
IN THE PINE CREEK INLIER
<table>
<thead>
<tr>
<th>Deposit</th>
<th>References</th>
<th>Commodities</th>
<th>Production/ Resources</th>
<th>Stratigraphic Unit</th>
<th>Stratified</th>
<th>Deformed by D2 Cleavage</th>
<th>Adjacent to Cosmic Fault</th>
<th>Within Compressional Zone</th>
<th>Budded Toroidal -like Nearby</th>
<th>Extensive Pervasive Alloformation</th>
<th>Association with Along Strike Facies Changes</th>
<th>Location at Stath Creek Meyer Strikemodel 1 Change</th>
<th>Stacked Leses</th>
<th>Clustering Along Strike</th>
<th>Fe-structures and Carbonates Along Strike</th>
<th>Host Lithology</th>
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<td>Discordance</td>
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<td>Kanavagh and Voysa, 1990</td>
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Guest 29 2020 09 (March 1995)
Mound Creek 3.4mt @ 3.1 g/t (Feb 1996)
Kazi 1.01 mt @ 1.93 (Oct 1995)
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<th>Carbonates in Host Sequence</th>
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<td>Paterson, VonPeckman and Bornhoff, 1984; Fraser, 1980</td>
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<td>Fraser, 1980</td>
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<td>Sundance</td>
<td>0.02mt @ 10g/t Au</td>
<td>yes</td>
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<td>no</td>
<td>yes</td>
<td>yes</td>
<td>?</td>
<td>?</td>
<td>yes</td>
<td>Nicholson, 1986,1987</td>
</tr>
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<td>Kylie</td>
<td>?</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>?</td>
<td>Pagel, Bornhoff and Coles, 1984</td>
</tr>
<tr>
<td>El Sherau</td>
<td>0.06mt @ 0.6% U₃O₈</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>Crohn in Walpole et al 1968; Valenta, 1991</td>
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<td>Coronation Hill</td>
<td>4.85mt @ 4.3g/t Au, 0.2g/t Pt, 0.6 g/t Pd including 0.026mt @ 0.26% U₃O₈, 10.4g/t Au</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>Carville et al, 1990; Valenta, 1991</td>
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<td>Koongara</td>
<td>3.45mt @ 0.44% U₃O₈</td>
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<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>Snelling, 1990</td>
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<tr>
<td>Ranger</td>
<td>~75mt @ 0.2% U₃O₈</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>?</td>
<td>?</td>
<td>Kendall, 1990; Eupene, 1980</td>
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<tr>
<td>Jabiluka</td>
<td>53mt @ 0.39% U₃O₈ including 1.1mt @ 10.7g/t Au</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>?</td>
<td>?</td>
<td>Hancock, Maas and Wilde, 1990</td>
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<td>Narbarlek</td>
<td>0.56mt @ 1.86% U₃O₈</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>Wilde and Noakes, 1990</td>
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<tr>
<td>Ranger 68</td>
<td>1.5mt @ 0.36% U₃O₈</td>
<td>?</td>
<td>yes</td>
<td>yes</td>
<td>?</td>
<td>yes</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>Browne, 1990</td>
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</table>
DISTRIBUTION OF THE ZAMU DOLERITE, COSMIC FAULTS AND THRUST FAULTS - PINE CREEK INLIER

Figure 4
Tight to isoclinal folding  with fold wavelengths < 0.5 km  
Open to tight folding — fold wavelengths generally < 0.5 km  
Open folding  
Faults? marking margin of Younger Lower Proterozoic Sequence  
Cosmic Faults / Margins of Basement Diapirs Interpreted  
Older Early Proterozoic / Archean Basement  
Concordant Granites  
D2 Fold axial planes with dip direction  
D2 Fold axial planes

THE GEOLOGY IS PRE-GIANTS REEF FAULT MOVEMENT

Fold geometry was determined from TM images, 90MIR mapping and aeromagnetics. Fold axial planes bend around basement and concordant granites. Folding tightness and intensity is greater in arcs and elongate zones adjacent to basement and concordant granite bodies in both directions perpendicular to the prevailing S3 strike direction.

CONCORDANT GRANITES, BASEMENT, COSMIC FAULTS AND D2 FOLDING - PINE CREEK INCLIER

Figure 5
NOTE: Data is from detailed surveys by BMR and Urenco. Contouring has Giants Reef Fault and regional gradient removed. Peripheral contouring interpreted from regional gravity data.
Hematite bodies are interpreted to occur in D1 breccias and shears (Johnson, 1964). These shears were often located in sulfide stratigraphic intervals. The brecciation probably enhanced supersgene enrichment of iron to form the widest hematite bodies. Hematite and brecciation, particularly the widest zones exploited in open pits, appear preferentially located on the limbs of D2 folds.

**DISTRIBUTION OF D1 FAULTING AND D2 FOLDING IN THE FRANCES CREEK AREA**

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**DISTRIBUTION OF D1 FAULTING AND D2 FOLDING IN THE MCCARTHY'S AREA**

Limonite shears and sulfide breccias represented by hematite outcrops on the surface appear to be preferentially located, and thickest, on the limbs of D2 folds.
1. Folding is initiated during thrusting by the formation of detachment (or décollement) folds (Jamiison, 1987). Concordant breccias are preferentially located on fold limbs. Upright folds with increased amplitude moving up the sequence, are produced.

2. 'D1' faults are folded and earlier folds accentuated during regional 'D2' compression.
a) Principle - stress distribution for one - half of a model.

A. Lateral walls are unconstrained.

B. Lateral walls are constrained, top surface is free.

Model B shows greater compression adjacent to the diapir with maxima about 0.5 to 3.0 radii away from the diapir.

b) Differences in normal stresses, \( \sigma_1 - \sigma_3 \), for a model constrained lateral walls and a free top. The direction and magnitude of stresses reflect the net flow of material in the model.

DEFORMATION AROUND CONSTRAINED AND UNCONSTRAINED DIAPIRS

(after Berner et al, 1972)

Figure 18
The middle of the three layers consists of interbanded competent and incompetent units.
The upper and lower layers consist wholly of incompetent layers.
Folds overlying domes in more competent units are less well developed. Folding in upper layers has greater emplitude than that in lower layers.

FOLD AND THRUST STRUCTURES
(after Dixon and Tirrul, 1991)
A granitic system with a fixed water content will have a positive slope to the PT melting curve. Decreased pressure of a solid, rising body with accompanying minimal temperature loss will lead to melting.

MAGMA GENERATION
WITH PRESSURE RELEASE
(after Carmichael et al, 1974)

Figure 20
The changes in the composition of mineralisation show similar trends for the two different styles of mineralisation. Stratiform mineralisation with certain compositions appear to occur 2 to 3 km stratigraphically above polymetallic vein equivalents.
THE GEOLOGY IS PRE-GIANTS REEF FAULT MOVEMENT

These styles of mineralisation appear to be preferentially located adjacent to, and particularly between closely spaced bodies of interpreted diapiric basement.

DISTRIBUTION OF DIAPIRC BASEMENT, Polymetallic vein and stratiform deposits - Pine Creek Inlier

Figure 22
Overall basin subsidence rates were interpreted from sedimentological evidence and curves from other basins illustrated in Klein (1998). Basement high uplift rates were assumed to be constant until melting lowered the viscosity of the dike, causing an increase in rate. Subsequently, rates slowed down as an equilibrium situation was approached. The curve for basement high movement relative to the earth's surface is approximately the overall basin subsidence curve with basement high uplift added to it.

Figure 23

PINE CREEK INLIER - BASIN SUBSIDENCE AND DIAPIRC BASEMENT UPLIFT RATES OVER TIME
Mineralization favors dolostone-rich stratigraphic intervals. On a 100 metre scale in a N - S direction, the mineralization appears localized within a zone of apparent stratigraphic thickening. This is due to the intersection of an axial-thickened anticline with the mineralized fault.
Mineralisation favours dolostone-rich stratigraphic intervals. On a 100 metre scale in a N-S direction, the mineralisation appears localised within zones of apparent stratigraphic thickening. These are due to the intersection of the structure with axis-thickened anticlines.

Note the coincidence between ore and anticlinal closure in long section.
WOODCUTTERS MINE
645 LEVEL PLAN

SCALE: 1:2500

LEGEND

- Underground Development
- Major N-S structure with interpreted movement
- Cross Structure
- Mineralisation with associated arrangement relative to fault
- Lamprophyre dyke

WOODCUTTERS MINE
Detail of 835 R.L. level

SCALE: 1:1000

WOODCUTTERS MINE - MINERALISATION IN DILATIONAL SITES IN OR ADJACENT TO FAULTS

Figure 26
McCARTHY'S PROSPECT
THICKENING OF MINERALISATION
IN DILATIONAL ZONE

Pdz  Zamu Dolerite
Psk  Koolpin Formation
     (cbc mudstone/siltstone)
Ppm  Mundogie Sandstone

Concordant
brecciated gossanous
limonite structure (with inferred movement)
Discordant brecciated siliceous
weakly gossanous structure
The orientation of the thickened zone of gossan is
consistent with dilation during upper block towards
anticline axis movement.
Mineralisation thickens adjacent to crossfaults. Ag, Pb and to a lesser extent Zn concentrations are higher near crossfaults while As, Fe and Sb concentrations tend to decrease in these areas.

Client: Woodcutters Joint Venture

Scale: 1:1000  Compiled: W. Ormsby  Date: June 1991

WOODCUTTERS MINE
Geochemical Zonation
3N Orebody 950 RL Level

Figure 29
The stratigraphic section on the right hand side depicts current day formation thicknesses from the Woodcutters area. To achieve these thicknesses, the depth of burial of particular stratigraphic levels are shown (Koolpin Formation, Lower Whites Formation, EVOG Formation). Through time, the period prior to significant erosion. These lines were constructed using the time constraints of 4-5000m (age of Rum Jungle grates) +1800m (time of magmatism), and the assumed average sedimentation rates shown. The intercept of the stratigraphic horizons with the surface lies represents the time of commencement of sedimentation of that particular unit. The period during which polymetallic vein mineralisation is postulated to have occurred is shown by the dashed vertical lines.

The depth range of the approximate oil window is also shown for various paleo-geothermal gradients. The horizontal lines represent 130°C and hence the approximate end of oil generation for the various geothermal gradients shown. Consequently, the more of which the Whales and Koolpin Formations passed through the oil window can be read off the horizontal scale for various paleo-geothermal gradients. Other stages of oil generation are also shown (as 4) for the base of the Lower Whites Formation as calculated using the Latapin method (Waples, 1986) assuming a paleo-geothermal gradient of 5/100m.

The diagram illustrates three main points:
1) For all assumed paleo-geothermal gradients, the Whales and Koolpin Formations were within the oil window prior to metamorphism.
2) For paleo-geothermal gradients < about 6%/100, the Whales Formation was still in the oil window at the postulated time of mineralisation.
3) The strong dependence of timing of hydrocarbon generation on depth of burial and hence current stratigraphic thickness. For example, for a geothermal gradient of 4%/100m, the end of oil generation occurred at approximately 2045m at the base of the Lower Whites Formation compared to about 1900m at the base of the Koolpin Formation - i.e. oil generation at the base of the Koolpin Formation ceased 145 my later than for the Whales Formation due to it being buried 250m shallower.

WOODCUTTERS MINE AREA
TIME - DEPTH BURIAL HISTORY
Simplified representation of a regional dome-shaped gas cap over the mineralized areas in southeast Missouri. The ruled surface extending out to a circular perimeter represents the top of the Bonnette Formation. The irregular polygons in the center represent the outline of the St. Francois Mountains at sea level and at 1,000-ft elevation. The stippled surface represents the gas-water interface at sea level. The outline of the barite-lead district (which lies above the top of the Bonnette Formation) is from Kisvarsanyi and Howe (1963). The principal lead mining areas are shown as more densely stippled areas and they lie in the plane of the gas-water interface. Vertical exaggeration ×20. A. Plan view. B. Perspective view. The ruled surface representing the top of the Bonnette Formation has been omitted for clarity.

A north-south section through the Viburnum trend mineralized area. Compiled from Kisvarsanyi (1979), Anderson (1979), articles on mine geology, and personal communication with mine geologists. An attempt was made to place the orebodies accurately with respect to elevation, but the information is sketchy and not totally consistent. The shapes and extent of the ores are diagrammatic only. The western edge of the Lamotte pinchout surface (Fig. 8) is projected onto this plane. Crosses = Precambrian, stippled = Lamotte Formation, blank = Bonnette Formation. Vertical exaggeration ×20.

SOUTH EAST MISSOURI, U.S.A. - REGIONAL GAS TRAP
(from Anderson, 1991)

Figure 31
Oil and Mississippi Valley Type ore deposits occur in the same or similar stratigraphic horizons.

CENTRAL SHIELD OF NORTH AMERICA - PALAEOZOIC STRATIGRAPHIC TABLE SHOWING OIL AND ORE DISTRIBUTION (after Dozy, 1970)
Note: The correlation between the Mississippi Valley type ore districts and the basement highs as indicated by pre-Mississippian aged sediments and granite.

1. The antithetic relationship between ore and oil occurrences.

DISTRIBUTION OF OIL AND ORE OCCURRENCES AROUND THE OZARK UPLIFT, NORTH AMERICA (after Dozy, 1970)

Figure 33
The Sorby Hills deposit occurs adjacent to the Pre-Cambrian Pincombe Inlier

SORBY HILLS - LOCATION AND GEOLOGY OF ONSHORE BONAPARTE BASIN
(from Jorgensen et al, 1990)

Figure 34
Ore distribution on section 25700N is controlled by two subtle anticlines. The control on section 23650N appears to be stratigraphic.

SORBY HILLS - GEOLOGICAL MAP AND CROSS SECTIONS
(from Jorgensen et al, 1990)

Figure 35
The Coxco deposit is situated adjacent to the Masterton Dome, along a regional anticlinal axis.

COXCO LOCATION AND McARTHUR RIVER DISTRICT GEOLOGY
(from Walker et al, 1983)

Figure 36
Hydrocarbons may have played a role in the stage II mineralisation which is mainly hosted in the Reward Dolomite.

COXCO DEPOSIT - GEOLOGY
(from Walker et al, 1983)
Veins parallel to bedding.
Veins parallel to cleavage.
'Ladder' veins perpendicular to bedding striking parallel to cleavage.
Veins discordant to bedding and D2 fabrics.
Cluster of discordant veins.

Data was collected from Mt Woods, Goodall, Tom's Gully, Rustler's Roost, Pelican, Woolwonga, Wandle, Batman, Quigley's, Enterprise, Sandy Creek and Union Extended.
Poles plotted on a Wulff net.

STEREOMETRIC PROJECTION OF POLES TO
STOCKWORK / CONCORDANT GOLD - QUARTZ VEIN SETS
- PINE CREEK INLIER

Figure 39
TIN DEPOSITS AND DISCORDANT GRANITE - PINE CREEK INLIER

Figure 40

THE GEOLOGY IS PRE-GIANTS REEF FAULT MOVEMENT

Vein and greisen tin deposits appear to be preferentially located adjacent to discordant granites.
Base metal occurrences apparently favour locations adjacent to, and particularly between, closely spaced basement highs. The McArthur Group appears to be a preferred stratigraphic host.

DISTRIBUTION OF INTERPRETED BASEMENT HIGHS, McARTHUR GROUP AND BASE METAL DEPOSITS - BATTEN TROUGH, McARTHUR BASIN

Figure 42
Bouguer gravity low with accompanied concordant granite and/or doming: Interpreted Basement High

Fold axial plane

Outcropping Mt Jea, McNamara and Mary Kathleen Groups

Base metal mineralisation. Large resource to small occurrence.

Major base metal occurrences apparently favour situations adjacent to, and particularly between, closely spaced basement highs. Certain stratigraphic units also appear favoured.
SPATIAL DISTRIBUTION OF GOLD AND COPPER MINERALISATION AND INTERPRETED BASEMENT HIGHS, GLENGARRY SUB BASIN W.A.

Copper and significant gold mineralisation appears more likely to occur adjacent to or above the position of the interpreted basement highs.
Principle Lead Mining Areas

Lamotte Sandstone Pinchout

Depth to Basement. Contour interval 200 feet.

Mineralisation apparently favours locations between closely spaced basement highs.

DISTRIBUTION OF BASEMENT MINERALISATION AND BASEMENT DEPTH - SOUTH EAST MISSOURI, U.S.A

(after Anderson, 1991)

Figure 46
The mineralisation occurs in stratigraphic units interpreted to lens out over basement highs. Basement high uplift rates probably exceeded overall basin subsidence during the deposition of these units.

ZAMBIA COPERBELT - STRATIGRAPHIC SECTION AND FACIES DIAGRAM
(after Fleischer et al, 1976)
Lenses of copper mineralisation are shown in black.

Figure 48
Gold mineralisation preferentially occurs in an elongate zone of closely spaced folds which subparallel a zone of granite outcrops. Detailed mapping in the south west indicates the granite is separated from the closely spaced folds by a syncline with much larger wavelength than the folds in the apparently more mineralised zone.

REEFTON GOLDFIELD, NZ.
(Simplified geology after Gage, 1948)
The gravity lows are sometimes centred with granitic intrusives. Fold axes often bend around the lows. Major gold producers are preferentially located adjacent to the lows in the direction perpendicular to fold axial planes.
Gold deposits appear to be preferentially located adjacent to 'syntectonic' granites.