RELATIONSHIP OF THERMAL EVOLUTION TO TECTONIC PROCESSES IN A PROTEROZOIC FOLD BELT: HALLS CREEK MOBILE ZONE, EAST KIMBERLEY, WEST AUSTRALIA.

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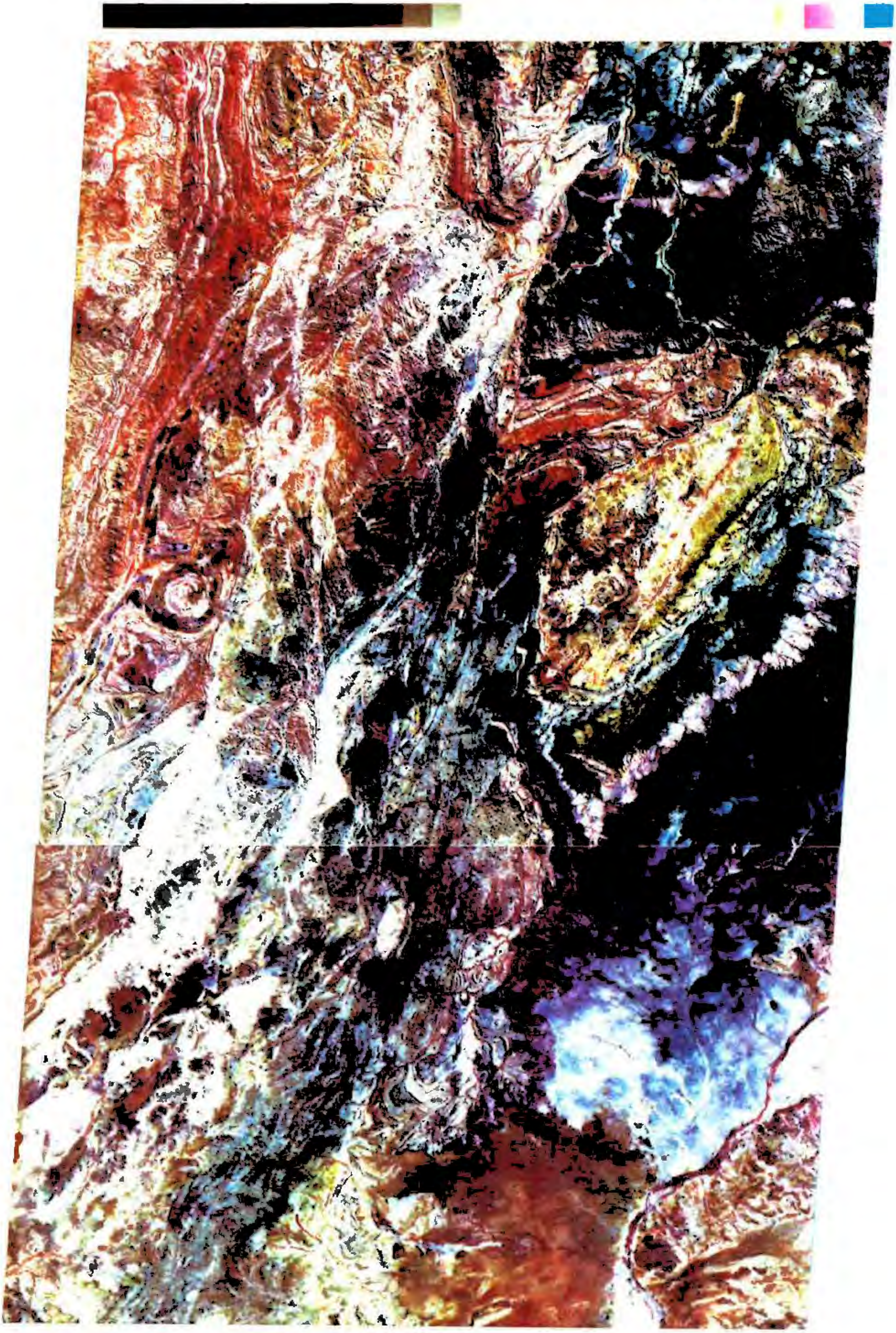

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SUMMARY

The Halls Creek Mobile Zone, East Kimberley, is part of the Northwestern Australian Province, of Lower Proterozoic orogenic domains and younger platform cover. The Kimberleys (East and West), the Pine Creek Geosyncline, and the Granites-Tanami are considered as one initially contiguous domain subject to the same tectonic history. These areas formed marginal to an Archaean continent to the northwest, which crops out as basement to the Pine Creek Geosyncline. A volcanic island arc is proposed, which intermittently erupted calc-alkaline acid tuff and island arc tholeiitic basaltic lava, with eventual convergence between arc and continent.

It is suggested that a system of mantle convection cells initiated about 1870 Ma produced thermal updoming with concomitant crustal thinning. A marginal basin evolved, filling with arc volcanic detritus, and clastic and chemical sediments. A hot spot developed , producing an array of rhyolite domes with associated volcanics. Continued crustal extension ruptured the brittle upper crust, and basaltic magma rose through the deep faults into the partly lithified sediments. The rising hinterland to the west shed a wedge of sediment across into the newly generated sub-marine canyons.

Deformation commenced with isoclinal, overturned, folding about northeast axes. Sinistral transform faulting, initiated in the south, facilitated emplacement of layered basic and ultrabasic sills. A change from extensional to compressional tectonics accompanied rotation of the principal stress direction. Compression from the SSE on to the rigid block to the northwest caused upright fold trends to swing from NNE in the north into the WNW trends of the West Kimberley. Post-orogenic sinistral faulting in the north, separated the Kimberleys from the Pine Creek area.

Granitic magma intruded syntectonically as a linear

unconformity controlled, heterogeneous, tonalitic pluton, and as an extensive post-tectonic granite batholith. The end of orogenesis was signalled by eruption of huge volumes of sub-aerial acid volcanics.

Syntectonic regional metamorphism was superimposed on the high geothermal gradient initiated in the crust by convecting mantle and enhanced by diapirism, shear heating and magmatic intrusion, thus producing an anomalously high geothermal gradient for this tectonic setting. Metamorphic temperatures increased and migrated north with time, varying from low greenschist facies in the south, syntectonic with the first period of extensional folding, to granulite facies in the north after the last period of compressive folding, reaching a peak of 800°C. and 5.5 kb.

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INTRODUCTION

1.1 Preamble

This investigation of the evolution of the Halls Creek Mobile Zone was undertaken in conjunction with a structural study by S. Hancock, and a study of the granites by M. Ogasawara, with the object of gaining a better understanding of the thermal history and structural style of the Halls Creek Mobile Zone, its relationship to the King Leopold Mobile Zone, and thereby tectonic processes in the Early Proterozoic. The major effort was directed towards the East Kimberley, with detailed mapping of specific areas on the Dixon Range, Gordon Downs, and Lansdowne 1:250,000 sheets. Short safaris to the Cummins Range and McClintock Range area on the Mount Ramsay sheet were made by two of us (Allen and Hancock), and a brief reconnaissance trip to the West Kimberley was followed by a four week programme of mapping and sampling in the Lennard River area by C. Giles and N. Mancktelow. Throughout this thesis, reference is made to the work of the other members of this group, and work done by the author on samples collected by others is indicated where appropriate. Major topographic features, and geological structures, and all place names mentioned in the text are located on Fig 1.1, with an index to the relevant 1:250,000 sheets.

1.2 Previous Investigations in the Area

The Kimberley Region was mapped by combined teams from the Bureau of Mineral Resources and the Geological Survey of Western Australia from 1962 to 1967. A programme of isotopic age determination was carried out concurrently with the mapping project by V.M. Bofinger. Maps at a scale of 1:250,000 and explanatory notes on the area currently under investigation in the East Kimberley were published in 1967 (Dixon Range and Lansdowne) and 1968 (Gordon Downs, Mount Ramsay and Lissadell). The results of the first three years mapping were incorporated in B.M.R. Bulletin 106 by Dow and Gemuts, published in 1969. That bulletin deals primarily with the Lower Proterozoic rocks of the East Kimberley, and more briefly with the Carpentarian rocks of the Kimberley plateau. The metamorphic and igneous geology of the mobile zone is presented in somewhat more detail by Gemuts in B.M.R. Bulletin 107, published in 1971. Thom (1975) compiled all available previous work for the section on the Kimberley Region in West Australia Geol. Survey Memoir 2.

Prior to this major mapping programme, a number of geologists made valuable contributions to geological knowledge of the East Kimberley. The first geologist to describe the area was Hardman in 1855. His remarkably accurate report laid the basis for all future work in the area. Over a century later (1969) Dow and Gemuts state "the main rock groups shown on his map are much the same as the broader divisions in this bulletin." It was Hardman who confirmed the original discovery of gold in the vicinity of Old Halls Creek by Hall and Slattery in 1883, which sparked the gold rush to Halls Creek and the Grant's Patch area in the 1890's. During the 1920's and 1930's various geologists, notably Finucane, Blatchford and Jones reported on mining activities and prospects, generally gold, but also tin-columbite and silver-lead. As part of the regional mapping of the Fitzroy Basin by the B.M.R. Matheson and Guppy (1949) mapped the Proterozoic rocks near Halls Creek. In 1949 and 1952 Traves mapped the Ord-Victoria region, and his comprehensive report (1955) includes the area currently under investigation. Rock relations as seen by these authors, in comparison with the later subdivision by Dow and Gemuts, are tabulated by Gemuts (1971) and illustrated overleaf in Fig. 1.2.

HARDMAN (1884, 1885)	MATHESON & GUPPY (1948)	TRAVES (1955)	DOW & GEMUTS (1969)	
Varieties of gneiss and schist intruded by granite syenite; and trap rock	Lamboo Complex (granite, gneiss, and metasediments)	Lamboo Complex (granitic rocks)	Basic and acid plutonic rocks	Lamboo Complex
	Halls Creek Group (metasediments and volcanics)	Halls Creek Metamorphics	High-grade metamorphic rocks (Tickalara Metamorphics)	
	McLintock Greenstones (mainly basic lavas)		Halls Creek Group (unmetamorphosed and low-grade metamorphic, sedimentary, and volcanic rocks)	

M(S)79

More recent investigations include those by Ruker (1961), Herbert (1971), Neville (1974) and Hamlyn (1977). A mineralised basic intrusive body in granulite facies rocks is currently under investigation (Thornett). Latterly a number of mining companies have been active in the area exploring for various commodities including diamonds, nickel, copper, silver-lead zinc, platinum, tin-tantalite, uranium, tungsten, scheelite and rare earth minerals. This activity has culminated in discovery of the very rich diamond deposit at Lake Argyle.

Despite the above, little detailed geological work has been done in this remote and isolated area. The preliminary mapping by the B.M.R. and G.S.W.A., although of excellent quality, was necessarily on a broad scale. Dow and Gemuts (1969) state "the mapping was no more than a detailed reconnaissance, and can only be regarded as a broad framework for more detailed work."

1.3 Objectives.

The aim of this study is to establish the thermal history in the Early Proterozoic and its relation to tectonic processes. The evolution of the Halls Creek Mobile Zone provides the base-line example from which broader implications are drawn. This area has good outcrop of very variable lithologies, both sedimentary and igneous, displaying a wide range of metamorphic grade. A number of problems are identified, as listed hereunder :-

A. The stratigraphic relationship of the Tickalara Metamorphics to the un-metamorphosed Halls Creek Group.

B. The detailed timing of metamorphic events and peak temperatures with respect to deformation.

C. The chemistry and petrogenesis ofthe metamorphic rocks and their constituent mineral phases.

D. The time of formation and emplacement of igneous bodies relative to metamorphic events and grades in the vicinity.

E. The chemistry and petrogenesis of the extrusive igneous rocks as they relate to tectonic processes.

F. The local, regional, and global tectonic setting, and therebycrustaland mantle involvement intectonicprocesses during the Early Proterozoic.

1.4 Approach

Areas for detailed study have been carefully selected to provide solutions to the specific problems outlined above, within the constraints of overall significance, while recognising the importance of local variation.

A. Stratigraphic Relations

The approach to the problem of the stratigraphic position of the Tickalara Metamorphics is the selection of an area in the Tickalaras for detailed mapping, for comparison with the Halls Creek Group. Prerequisites of the selected area include —

(a) good outcrop

(b) a sequence with adequate marker beds

(c) structure sufficiently uncomplicated to allow detailed stratigraphy to be erected.

Units within the high grade area are now confidently correlated with their Halls Creek Group equivalents.

B. Relationship Between Deformation and Metamorphism

The area mapped to establish stratigraphic relationships has trends paralleling the regional strike of the Halls Creek Mobile Zone, and thus can be taken as structurally typical. A fabric datum is delineated from which earlier and later deformations are recognised using overprinting criteria. Pelitic rocks at amphibolite grade in this area are ideal for fabric studies. Regional metamorphic events are correlated with different deformations by interpreting the internal and external fabrics of porphyroblasts with respect to the fabric datum.

C. Petrogenesis of the Metamorphic Rocks.

Interpretation of microfabrics is used to determine the paragenetic sequence of metamorphic mineral nucleation and growth. Metamorphic reactions are deduced from these fabric studies, in concert with analysis of the chemistry of the rocks and their constituent mineral phases. These reactions in turn are used to ascertain the physical and chemical parameters operative in different places at different times. Fabric studies are notoriously liable to a plethora of conflicting interpretations, and the sequence outlined above compounds the possibility of error. Nevertheless, it is considered that the limitations inherent in this approach are outweighed by their advantages.

D. Relationship Between Igneous Intrusion and Metamorphism

Igneous intrusive rocks both basic and acidic, crop out widely in the mapped area. These form part of the Lamboo Complex (Fig 1.2) various aspects of which are discussed in Chapters 2 and 5. Field relationships of these intrusive rocks and overprinting criteria, using the fabric datum mentioned above, are used to establish relative emplacement times, and allow their incorporation into the thermal history of the area. Thus, their influence on the thermal regime is determined.

E. Geochemistry of the Extrusive Igneous Rocks.

Major and trace element chemistry of basic and acidic lavas and tuffs are examined and compared with the chemistry of recent extrusive rocks from known tectonic settings. These geochemical studies assist in establishing crustal and mantle involvement in tectonic processes during the Early Proterozoic.

F. Tectonic Framework

The local tectonic setting of the Halls Creek Mobile Zone is revealed by the interaction of numerous components. These include the sequence of lithologies in the stratigraphic column, the sedimentary environment, the styles and history of deformation, and the thermal regime in the area.

The regional tectonic framework is established by correlation of the Halls Creek Mobile Zone with the intersecting King Leopold Mobile Zone, and the relationship of these to other areas in the North Australian Proterozoic Province.

The regional picture is fitted into a global tectonic setting by comparison with other Proterozoic fold belts.

1.5 Analytical Methods

Metasediments were generally analysed for major elements only; igneous rocks were analysed for a wide range of trace elements also, including those with compatible and incompatible characteristics.

Major elements (excluding Na_2O in some instances) were determined using a fully automated X-ray fluorescence (XRF) spectrometer (Norrish and Hutton, 1969). Na_2O was determined by flame photometry initially, and later in the research programme by XRF. Total iron only was measured, which is quoted as ferric iron. Trace elements were also determined by XRF using a pressed powder technique (Nesbitt et al, 1976). Repeat analyses, and internal (University of Adelaide) and external standards were measured routinely. Values obtained for international standards at the University of Adelaide Laboratories are presented in Appendix 1, Table 1.1. It is estimated (Sun et al, 1979) that errors for all trace elements excepting Nb are within one or two percent.

Minerals were analysed using Electron Microprobe Analysers at Melbourne University, Macquarie University Sydney, Perth C.S.I.R.O., and Adelaide University. The majority of the analyses were done at Melbourne University, and a range of samples analysed on this equipment was re-analysed on the other instruments to ensure comparibility.

1.6 Data Presentation

Whole rock analyses are tabulated and presented on microfische in appendix 5, and some in appendix 2 as indicated in the text. For igneous samples, analyses are presented as variation diagrams to establish trends (Chapter 5). Both major and trace elements have been plotted initially against SiO_2. This facilitates comparison with igneous rock categories determined on the basis of hand specimen and thin section characteristics (qualifying terms indicate textures). The summation effect (Chayes, 1964) can not be applied as a serious objection to this approach, where the trace elements, which are in relatively low abundance compared with SiO_2 follow the trends of the major elements. Other plots are used in conjunction with the variation diagrams which are independant of the summation effect. The effect of alteration due to metamorphism is guaged by comparing rocks from the same stratigraphic horizon at low and high grade where possible, and by comparison with the field of little altered Cainozoic analogues. Significant departures from these fields are checked for secular variation against Proterozoic volcanics from other provinces in Australia and elsewhere. Tectonic setting is inferred by comparison with recent rocks from known tectonic environments. Limitations in using geochemical data to test genetic hypothesis are further discussed in Chapters 5 and 6.

Analyses of minerals in metasediments are presented on microfische in appendix 6. A selection of analyses of garnet - biotite pairs, and the geothermometry calculations for which they were obtained, is presented in appendix 4. AFM diagrams show changing mineral composition and parageneses with increasing metamorphic grade (Chapter 4). The corresponding whole rock analyses are plotted on the relevant diagrams. Various other diagrams are also presented which are designed to illustrate ranges in chemical composition of different mineral species.

Specimen numbers referred to in the text are, unless otherwise indicated, prefixed by the accession number K498/ . Thus (123) refers to hand specimen and/or thin section, polished thin section, rock powder, pressed pellet, labelled K498/123. Specimen numbers prefixed in the text by 540/ were collected by S. Hancock, those prefixed by Ki and KM were collected in the West Kimberleys by C. Giles and N. Mancktelow respectively. All specimens are housed in the Department of Geology and Geophysics, University of Adelaide, South Australia.

STRATIGRAPHY and PETROLOGY

2.1 Introduction.

Ruker, in 1961, erected a stratigraphy in the Halls Creek Metamorphics in the Saunders Creek area. His work forms the basis of the subdivision by Smith (1963) of the Halls Creek Group into four formations as follows -

Olympio Formation.
Biscay Formation.
Saunders Creek Formation.
Ding Dong Downs Formation.

Dow and Gemuts (1969) modified this nomenclature slightly (they preferred the name Ding Dong Downs Volcanics) and codified and defined the units in the stratigraphic sequence. They designated type areas and described the lithologies in those areas in broad outline, and indicated the stratigraphic relationships and the distribution of the units in the Halls Creek Mobile Zone. A type section was measured in the Saunders Creek Formation. No type sections were measured in the other three units because of tight folding and/or poor outcrop.

These two authors also established the 'Tickalara Metamorphics' (Fig 1.2). While there may have been some justification for introducing this term when the position in the stratigraphic sequence of the high grade rocks was unknown, and the structure and metamorphic history largely undeciphered, its continued use can serve only to confuse. Thom (1975) alleged the designation of the 'Tickalara Metamorphics' was an attempt to solve the 'demarkation dispute' between 'granite gneiss' and 'gneissic granite'. Not only did this problem remain unsolved but new problems were created;

(a) Another boundary was erected further down grade such that there is "metamorphic overlap between the most altered rocks included in the

Halls Creek Group, and the least altered 'Tickalara Metamorphics'" (Thom 1975).

(b) A category was designated in one fold belt which was not applied to rocks of similar age and grade in the other associated fold belt.

(c) A subsidiary problem was thus created in differing limits to the 'Lamboo Complex' (Ch. 5) in the two mobile zones.

In this chapter the stratigraphic equivalence of the Halls Creek Group and the Tickalara Metamorphics is established, and the latter term is abandoned. The rocks are henceforth referred to by their lithology or formation name. This step removes the confusion between stratigraphic nomenclature and metamorphic grade. It also removes a meaningless and contentious boundary.

The problem of stratigraphic equivalence is most obviously solved by mapping along strike, from the Halls Creek Group rocks in the south, to the Tickalara Metamorphics in the north (Fig 2.3). As mentioned earlier (section 1.4) a different approach was used, because of the presence of a large area of alluvium blanketing outcrop in the south of the Black Rock Anticline, and basic and acid igneous intrusive bodies largely obliterating stratigraphy to the west (Fig 2.3). The erosion resistant Saunders Creek Fm. forms topographic highs, and is sufficiently distinctive to be used as a regional marker bed recognisable by photo interpretation. The presence of Saunders Creek Fm. rocks in the high grade area was recognised by the author in outcrops, previously mapped as Mabel Downs Granodiorite, west of the western splay of the Halls Creek Fault, which defines the western boundary of the Black Rock Anticline (Fig 1.1). The stratigraphy youngs west with the Biscay Fm. overlying the Saunders Creek Fm. A NNE-SSW belt to the west of this fault, fulfils basic requirements for correlation ie. good outcrop, adequate marker beds, and reasonably uncomplicated structure. This area has been mapped in detail (Fig 2.1 & 2.2). The Biscay Fm. has been informally subdivided into four units of member status (Fig 2.4), which may be compared with the sub-division of the Biscay Fm. established by Hancock (1985) in the low grade Biscay Anticlinorium. (Fig 2.5). A similar stratigraphy has been established in this latter area by Pyke (pers. comm.)

In addition to describing the detailed stratigraphy in the Biscay Fm. at high metamorphic grade, new work on the other three formations in the Halls Creek Gp. is also presented in this chapter, and the overlying Whitewater Volcanics are introduced. The formations are described below in stratigraphic sequence.

2.2 Ding Dong Downs Volcanics.

The oldest rocks exposed in the area are the Ding Dong Downs Volcanics. Rocks of this formation crop out in the Biscay Anticlinorium in the core of the Saunders Creek Dome, and in a small domal culmination some kilometres east of this (Pyke, pers. comm.), also in the Cummins Range area in the cores of two anticlines east of the Woodward Fault (Fig 1.1). The base of the Ding Dong Downs Volcanics is nowhere exposed. The most complete sequence is in the Saunders Creek Dome , the designated type area (Dow & Gemuts,1969), and consists of a series of interbedded basic and acid volcanics, comprising up to 1,000 metres of section. Gemuts and Smith (1968) reported basic tuffs, metasediments (quartz mica schist and slate) and minor rhyolite from this area. Dow and Gemuts (1969) also reported intercalated sediments. Of the acid rocks they state "though some have a brecciated appearance and could be volcanic, they are more probably intrusive and co-magmatic with the much younger rhyolite dykes of the Lamboo Complex." Samples which were identified by the author in the field as basic tuffs and metasediments, on thin section examination, were revealed as highly deformed metamorphosed amygdaloidal basalts. The acid rocks examined by the author are all fragmental and identified as tuffs. Three felsic tuff units interbedded with basalts together comprise the known Ding Dong Downs Volcanics (Allen, 1982). Brief thin section descriptions of the acid and basic volcanic rocks are presented in Appendix 2, Tables 2.1 and 2.2. Geochemical data are presented in Appendix 5. Selected photographs are presented in Figs 2.6 & 2.7. A general petrographic desciption of the acid and basic volcanic rocks of the Ding Dong Downs Volcanics is presented hereunder.

2.2.1 Acid Volcanic Rocks.

The acid rocks from the type area of the Ding Dong Downs Volcanics examined by the author are all altered rhyolitic crystal lithic tuffs, some with a vitric component. In outcrop they are pink, grey, or buff coloured, fine grained and porphyritic with no internal stratification. Phenocrysts comprise 10%-15% of the rock. These occur as fine to coarse grained euhedral to subhedral crystals of plagioclase, with subordinate amounts of K-spar and occasional quartz grains. The felspar sometimes occurs as glomeroporphyritic aggregates. The texture is indicative of synneusis or aggregation of crystals in a melt (Vance, 1969). Contact between individual crystals in the aggregate is along euhedral crystal faces. Lithic fragments comprising 15%-25% of the rock consist of rounded clasts of medium to coarse grained basalt and porphyritic rhyolite. The basalt fragments are well defined and dominantly represented by fine to very fine grained plagioclase laths in an extremely fine grained matrix. Occasionally (213) the basalt fragments are amygdalar, the amygdales being infilled with quartz, epidote, chlorite, and calcite. Fragments of porphyritic rhyolite have diffuse margins and are generally partially resorbed. They consist of quartz and/or feldspar phenocrysts in a quartz and sericite matrix. The basal acid volcanic horizon (Fig 2.4) was not sampled, but lithic fragments from this bed occur in the second horizon of felsic tuff. One specimen (232) contains numerous fragments of original glass, with spherulitic devitrification texture, generally partially resorbed (Fig 2.8). The matrix is very fine grained quartz and sericite. In most cases original matrix textures are completely obliterated, but occasionally (230) the characteristic shape of shards is discernable. Rocks from this area of the mobile zone fequently develop a slaty cleavage, axial plane to D1-2 folds, (Ch. 3) which wraps feldspar phenocrysts. These rocks have been metamorphosed to the biotite grade of the greenschist facies. Phenocrysts of sanidine frequently show patchy unmixing to orthoclase and albite (Tuttle, 1952), as revealed by electron microprobe analyses (Fig 2.7 and Appendix 2). The felsic tuffs are generally rhyolitic. Where the composition is less acidic (eg 210), the lower SiO2 content is related to a higher percentage of basalt fragments. The tuffaceous nature of these rocks is inferred from incorporated lithic fragments, and the presence of crystal chips.

2.2.2 Basic Volcanic Rocks.

The basic volcanic rocks from the type area of the Ding Dong Downs Volcanics examined in the field and the laboratory by the author, are all basalts. In outcrop, they are generally amygdaloidal. Pillows with bleached rims and amygdalar cores can be identified in the lower basalt horizon in relatively less deformed areas (Fig 2.6a). The basalt is greatly altered, spilitised (see Ch.5), and epidotised, and in places highly deformed with schistose zones of shearing and mylonitization. In thin section, they consist of fine to very fine grained plagioclaths laths, and fine grained anhedral to subhedral opaques, and granular sphene, disseminated through a recrystallized matrix of chlorite, epidote, quartz, and actinolite. Late formed minerals include interstitial pools of calcite, veins of quartz and/or calcite, and/or epidote, and lenses of white mica. Original igneous mineralogy is represented by plagioclase and opaques. All other minerals are of metamorphic origin. Matrix minerals comprise approximately 40% plagioclase, 10% opaques + sphene, 10% quartz, and 40% chlorite + actinolite + epidote (hence their green colour). Some specimens, as mentioned, are highly epidotised, eg 217 contains 65% epidote. Amygdales comprise from 10% to 50% of the rock. They are infilled with quartz, epidote, chlorite, and white mica in that order. At times (eg 205) the amygdales are virtually completely infilled with quartz; in other specimens (eg 207) epidote occupies most of the amygdalar cavity.

Some features of original texture, such as the amygdales, are generally apparent in hand specimen. However in a few specimens, finer and fewer amygdales initially were thought to be lithic fragments, and the rock mis-identified as a basic tuff. Spec. 219 is a mylonitised amygdaloidal basalt (Fig 2.6c). It was identified in the field as fine grained metasediment, and its true nature only revealed on thin section examination. This could equate with "sheared ahd recrystallised rocks which appear to have been originally tuffacious greywacke"(Dow and Gemuts, 1969). Other textural features become obvious on microscopic examination, eg in spec. 215 and 220 trachytic texture is preserved, with minute plagioclase laths aligned in a flow structure around the amygdales. However in the majority of specimens original texture is strongly altered by deformation and metamorphism. A tectonic fabric is developed to varied extent. This is expressed by alignment of linear and platy minerals eg. actinolite, chlorite and white mica. Spec. 206 is strongly schistose. White mica wraps the amygdales in a fabric which is considered to be S2 (axial plane to large and small scale folds, Ch.3). The amygdales have a suggestion of a weak internal fabric, defined by diffuse strings of granular sphene, which is randomly aligned with respect to S2 suggesting variable rotation of amygdales during deformation.

As indicated, the original mineralogy is largely replaced by metamorphic minerals. Two generations of metamorphic minerals can be discerned. Up to 25% of some rocks (eg 206) consists of fine grained actinolite. No hornblende was identified in any of these rocks. Although the basalts are described together, the two horizons Fig(2.4) have some distinguishing features. The lower horizon contains spilitised pillow basalts, and is frequently extensively silicified, with a ramifying system of quartz veins.
(Fig 2.6b).

Concluding Remarks.

(1) There is a very similar sequence of bimodal volcanics in two widely separated areas, the Biscay Anticlinorium and the Cummins Range (even after restoration of proposed movement along the Halls Creek Fault system - see Ch.3)

(2) The rocks are generally altered chemically - by spilitization at relatively low temperatures, and are frequently altered mechanically - by mylonitization along shear zones.

(3) There is little, if any, original sediment.

(4) Pillow structure is evident in the lower basalt horizon, indicating deposition under water. The acid volcanic horizons appear un-bedded which, coupled with the lack of sediments, could suggest these four small domal areas represent palaeo- highs emergent during the latter phases of volcanic eruption. A shallow marine environment of deposition is suggested as the best fit for the available data.

2.3 Saunders Creek Formation.

Stratigraphically overlying the Ding Dong Downs Volcanics is the Saunders Creek Formation. The type area for this formation is the Saunders Creek Dome, where the type section was measured.

2.3.1 Distribution.

The Saunders Creek Fm. crops out NE of Halls Creek in the Biscay Anticlinorium flanking the Saunders Ck. Dome and the domal culmination to the east (Pyke, pers.comm.), and on the northern margin of the Sophie Downs Dome. In the Cummins Range area it occurs around parts of the Mc.Clintock Dome, and the adjoining Bulara Dome. This has, until recently, comprised the total extent of known Saunders Creek Fm. It has now been mapped by this author in a thin discontinuous strip, west of the Black Rock Anticline, from east of White Rock Bore to east of Sally Malay Bore, a distance of some forty kilometres (Figs 1.1, 2.1 & 2.2). This highly resistant quartzite ridge defines the western margin of the western splay of the Halls Creek Fault.

2.3.2 Petrography.

The type section (Dow and Gemuts,1969) indicates that the Saunders Ck. Fm. in the Biscay Anticlinorium consists dominantly of quartz sandstone, generally thinly bedded and fine grained, with intercalated beds of felspathic sandstone. The sandstones are commonly cross bedded, defined by accumulations of detrital magnetite, ilmenite, and zircon. The type section as described does not include conglomerate.The formation is, however, defined as indurated quartz sandstone, quartz conglomerate and felspathic sandstone, and conglomerate is noted near the base of the unit in beds between 1 and 5 feet thick, (Dow and Gemuts, 1969). The pebble conglomerate contains rounded clasts of vein quartz, chert, and magnetite, as well as lithic fragments of the underlying Ding Dong Downs Volcanics. Selected photographs and photomicrographs are presented in Fig 2.8.

In the Cummins Range area, the Saunders Creek Fm. consists dominantly of quartz arenite, with subordinate thinly bedded, fine grained, sub-litharenite, and minor development of clast-poor pebble conglomerate. The sandstones show frequent cross bedding outlined by heavy mineral bands. Here, as in the Biscay Anticlinorium, the conglomerate is a sporadic and local development, apparently confined to scour channels and gravel beds.

The outcrops west of the Black Rock Anticline consist of well sorted, well rounded, supermature quartzites. Because of the absence of cross bedding outlined by heavy mineral bands, and pebble conglomerate, which are so characteristic of this formation in the outcrops in the south of the Halls Creek Mobile Zone, another discriminant was sought to distinguish it from sandstones and quartzites higher in the sequence. Thorogummite has been identified in the Saunders Creek Fm. at Saunders Ck. Although no radioactive minerals were identified with a geiger counter in the Northern quartzite, it was hoped that had they been sufficiently ubiquitous in the source area, they may have left a 'fingerprint' throughout the quartzites of this formation. Consequently, thermo-luminescence studies were done on quartz grains extracted from conglomerate and sandstone of the Saunders Creek Fm. from the Saunders Creek area, and from quartzites from the northern area. Standards included in the sample set were conglomerates of the Red Rock Beds (Carpentarian) and a quartzite of unknown age infilling a circular diatreme. These latter two samples came from north of the Black Rock Anticline close to the Halls Creek Fault. The results are presented in Fig 2.9. The signature sought is not apparent. It has subsequently been determined (Hockman, pers comm.) that thermoluminescence patterns are not very useful as stratigraphic indicators in uraniferous sandstones of this age. Radioactive material in concentrations as low as 10ppm affecting the quartz grains subsequent to deposition can completely alter the inherent thermo-luminescence pattern.

There is, however, no reasonable doubt that this horizon represents the time equivalent of the Saunders Creek Formation. In all areas this formation is conformably overlain by sequences of the lowermost Biscay Fm.

2.3.3. Environment of Deposition.

The Saunders Creek Formation is a shallow water deposit. In the Biscay Anticlinorium and Cummins Range areas, the environment of deposition is perceived as fluviatile. The conglomerate lenses represent rapidly deposited material in a braided stream system (Allen, 1981). The moderate sorting, pebbly, in places felspathic to lithic character, with ubiquitous cross bedding suggest a braided fluvial to shallow marine depositional environment. In the northern outcrops west of the Black Rock Anticline, the good sorting and roundness, and high quartz content, indicate shallow marine to high energy beach conditions (Allen, 1985).

2.3.4 Provenance.

Transport of material from a source area to the north- west has been established for the Saunders Creek Fm.in the Biscay Anticlinorium by various company geologists, and supported by the study of Hancock (in prep.). This area to the north and north-west of the Kimberley Proterozoic mobile zones was a persistent source of sediment during deposition of the turbiditic Olympio Fm.(Hancock, in prep.) and sandstones of the Kimberley Group in the Kimberley Basin (Gellatly, Derrick, and Plumb, 1970). The provenance area suggested by the latter authors is the Precambian of central Burma, and by Hancock and Rutland (1984), a small continent of presumed Archaean crust.

2.3.5 Stratigraphic Relationships.

There has been some confusion about the stratigraphic relationship of the Saunders Creek Fm. to the underlying Ding Dong Downs Volcanics. Gemuts and Smith (1968) state "the Saunders Creek Fm. overlies the volcanics apparently conformably." The next sentence reads "... there may have been a distinct break in sedimentation after the volcanics were extruded and folded." Dow and Gemuts (1969), and all subsequent authors until now, have referred to the Saunders Creek Formation as conformable on the Ding Dong Downs Volcanics. The contact is sharp, and in places erosional, with scour channels cut into the volcanics. While the evidence does not support an interpretation of a conformable contact, there remains some uncertainty about the nature of the erosional surface. Hancock (in prep.) maps a slight angular discordance, and suggests minor tilting of the underlying surface prior to the deposition of the Saunders Creek Formation. The present author favours an interpretation of marked unconformity for the following reasons :-

(1) Within the Saunders Creek Dome the volcanic horizons are at a high angle to the overlying Saunders Creek Fm.

(2) There are totally different lithologies immediately below and above the unconformity (Figs 2.4 and 2.5).

(3) Although bimodal volcanics recur in Units 1 and 2 of the Biscay Formation, the primary chemistry appears distinctly different (Ch. 5).

(4) There are vastly different styles of alteration below and above the unconformity, even at the same metamorphic grade in closely contiguous areas, eg. within and flanking the Saunders Creek Dome. Biscay Unit 1 basalts are not spilitised (Ch. 5).

(5) Clasts of chemically very mature material eg. chert, vein quartz, and magnetite, in the conglomerates of the Saunders Creek Fm. suggest a regolith surface in the provenance area.

(6) Deformation within the Saunders Creek Dome is more intense than in the surrounding areas and "displays a particularly strong

upright cleavage" (Hancock & Rutland, 1984).

(7) Faulting appears to be continuous though the unconformity. However, where the basalt has become mylonitised and ductile folds are evident, the overlying sandstone has suffered brittle fracture. In general, quartzose rocks mylonitise more readily than mafic rocks (Oliver, pers.comm.). The reverse situation seen above suggests that mylonitisation was initiated prior to deposition of the Saunders Creek Fm., possibly concurrently with tilting or folding, and then reactivated later.

Dating of Ding Dong Downs Volcanics material could resolve this problem. However this presents a difficulty because these rocks are badly altered.

2.4 Biscay Formation.

The Biscay Formation conformably overlies the Saunders Creek Formation. The core of the Biscay Anticlinorium, north of the Saunders Creek and Sophie Downs Domes is the type area (Dow and Gemuts,1969). The thickness is poorly constrained, being estimated in the type area by the above authors as 5,000 to 10,000 feet, by Hancock and Rutland (1984) as "in excess of 4,000 metres", and by Hancock (1985) as 2,000 to 3,000 metres. In the high grade areas the Biscay Formation is estimated by the present author to be 2,800 metres thick.

2.4.1 Distribution.

The distribution of the Biscay Fm. in the East Kimberley is noted by Dow and Gemuts (1969) as "the core of the Biscay Anticlinorium, and south of Halls Creek in the core of the same ? anticlinorium displaced south by the Halls Creek Fault, also in the area immediately north of Halls Creek." The formation is now recognised in the high grade area (previously mapped as 'Tickalara Metamorphics') in the Black Rock Anticline, and west-ward approximately to the eastern margin of the Mabel Downs Granodiorite in a SSW strip, south of Alice Downs Homestead and north of the Corkwood Bore to Turkey Creek (Allen, 1981. Figs. 1.1, 2.1, and 2.2). In the West Kimberley, unpublished company reports indicate that the sequence in the inlier southeast of the King Leopold belt (Fig 2.15) correlates with the Biscay Fm.

2.4.2 Stratigraphy.

The sedimentary sequence established by Dow and Gemuts is defined as "basic volcanic and intrusive rocks with intercalated sediments, generally metamorphosed to low greenschist facies." There is obviously little difference in the stratigraphic sequence from low to high metamorphic grade in widely separated areas (cf. Figs 2.4 and 2.5). The major distinction is in the position, extent, and nature of volcanic horizons, and in facies variation, particularly in acid volcanic horizons associated with local vent systems. The base of the formation has been set, arbitrarily, at the top of the quartzite of the Saunders Creek Formation by both Allen and Hancock (1985). The top of the Biscay Fm. is defined by a thick horizon of calcareous beds, or its facies equivalent - thick pillow basalts. In places, up to 50% of the succession in the Biscay Fm. is replaced by the pre-tectonic Woodward Dolerite. This basic magma intrudes as sills, sometimes tens of metres thick, or as areally extensive bodies transgressing and obliterating large sections of the stratigraphic sequence. It is restricted to the Biscay Fm. and the base of Units 1 and 2 of the Olympio Fm. in the East Kimberley, and intrudes Unit 2 of the Olympio Fm. (Hancock and Rutland, 1984) and probably the top of the Biscay Fm. in the West Kimberley. It is considered by Hancock (1985), to be an integral part of the stratigraphic succession.

In the amphibolite and transitional granulite facies areas (Fig

2.1 & 2.2),the basalts and acid tuffs are metamorphosed respectively to amphibolites and plagiophyric rocks. The pelitic rocks are all highly schistose, coarse grained (except in shear zones), and contain the appropriate index minerals. The carbonates are metamorphosed to marbles, and the sandstones to quartzites. Petrography and geochemistry of the metasediments is presented in Appendix 4, 5, and 6. Selected photographs and photomicrographs of field relationships and texture are illustrated in Fig 2.10, 2.11, 2.12, 2.13, and 2.14. A general petrographic description of the metasediments and metavolcanic rocks is presented here in stratigraphic sequence.

2.4.3. Petrography.

Unit 1.

In the high grade areas, the Biscay Fm. generally opens with renewed volcanism. The lowermost unit immediately overlying the Saunders Ck.Fm. south of the westward bow of Wills Creek near its junction with the Ord River (Fig 2.2), consists of a series of flows of basaltic pillow lava, with intercalated leucocratic material (Fig 2.10), capped by a carbonate bed. Stacking relationships of the individual pillows indicates that the volcanic pile youngs west. The pillows are deformed and stretched, with a length to breadth ratio of up to 10:1. The lowest bed is felsic tuff. The individual beds are quite thin, ranging from 0.5m. to 5m for the thickest basalt flow. The leucocratic rock (125 & 1452) is light grey, massive and compact, with sparse, manganese rich garnets (up to 14% MnO - Appendix 2), original plagioclase phenocysts (An_{26} - Fig 2.11), and lenses, up to 5mm long, of white mica. Occasional bottom 'rip-up' structures are evident (Fig 2.10). These interbedded felsic and basic volcanics are informally named 'The Wills Creek Suite' (Allen, 1985).

North of the Ord River (Fig 2.1), the basal sequence of Unit 1 consists entirely of acid volcanics, informally named 'The Corkwood

East Suite' (Allen,1985). In outcrop the rocks are pink, fine grained, and massive, with no internal stratification. They are sparsely plagiophyric, (Fig 2.12). Weathering out of large (up to 1cm. diam.), rounded, felspars (An_{15}) gives the outcrops a characteristically pitted appearance. The carbonate bed at the stratigraphic top of Unit 1 is tens of metres thick in this area. Southward along strike, it varies from 0.5m to 2m thick.

Southward up Wills Creek, east of Dougals Bore (Fig 2.2), a silty sequence metamorphosed to sillimanite schist and garnet sillimanite schist overlies the Saunders Creek Formation. This is similar to the sequence in the Biscay Anticlinorium (Fig 2.5).

In the Mc.Clintock Dome area in the Cummins Range, Unit 1 consists entirely of basalt in the lower volcanic horizon underlying the carbonate bed.

Unit 1 thus consists of two horizons :-

(a) a lower volcanic horizon, or its silty facies equivalent,

(b) a carbonate horizon, laterally fairly continuous, but of variable thickness.

Unit 2.

Unit two is a thick, richly volcanogenic sequence, with a conspicuous carbonate horizon and pelitic interbeds. In the Wills Creek area, the lower portion of Unit 2 consists of bimodal volcanics. The character and chemistry of the pillow basalts and the interbedded felsic volcanics is distinguishable from the 'Wills Creek Suite' in Unit 1 only by its position in the stratigraphic sequence. In the core of the Black Rock Anticline, the stratigraphically lowest succession is a sequence of bimodal volcanics lithologically very similar to the 'Wills Creek Suite' and mapped as Unit 2 of the Biscay Fm. North of the Ord River, the 'Corkwood East Suite' occupies an horizon which reaches a thickness of approximately 100m. This deposit is laterally extensive, and spreads south of the Ord River where it caps the 'Wills Creek Suite'. Here, it has been mylonitised, and has a schistose fabric (Fig 2.12) which wraps the few, rounded, felspar megacrysts, (1452, Appendix 2) and is overgrown by tiny almandine garnets. North of the Ord River, the 'Corkwood East Suite' is overlain by pillow basalts, and pelitic and semi-pelitic beds, now metamorphosed to garnet and/or sillimanite schists, followed by a relatively thick and continuous marble (+/- gossan) horizon.

In the White Rock Bore area (Fig 2.2), Unit 1 is cut off by the Halls Creek Fault, and the lowest bed outcropping in Unit 2 is an acid volcanic of uncertain affinity, which is very rich in plagioclase phenocrysts. Overlying this bed is a 5m - 20m thickness of banded iron formation, and an iron rich pelitic bed and carbonaceous schist. These lithologies, now folded, re-folded, and metamorphosed to amphibolite facies, are illustrated in Fig 2.13. The geochemistry is presented in Appendix 5.

In the Cummins Range area, a pelitic sequence occupies the basal part of Unit 2. The Biscay Formation is anomolously thin in this area (Allen, 1981), partly due to faulting, and much of the upper units are replaced by Woodward Dolerite. In the Saunders Creek area, pelitic beds separate a felsic volcanic sequence from thick amygdaloidal basalts which underlie the carbonate horizon (Hancock and Rutland, 1984).

Unit 3.

Unit 3 is generally dominated by fine grained meta-sediment, and laterally persistent carbonate beds, which may attain a thickness of 20m. Some of the carbonates are ferruginous and a further horizon of B.I.F. has been noted in Unit 3 in the low grade areas (Hancock,1985).

In the Sally Malay Bore area, a thick horizon of felsic volcanics, of unknown affinity, occurs towards the top of Unit 3. They have a high concentration of felspar phenocrysts, similar to the deposit lower in the sequence in the White Rock Bore area. Thick pillow basalts (Fig 2.14) underlie the two carbonate beds at the top of Unit 3 in this latter area. East of Dougals Bore the lower half of this Unit is intruded by great thicknesses of Woodward Dolerite.

In the south of the Halls Creek Mobile Zone, in the Saunders Creek area, and south of the Saunders Creek and Sophie Downs Domes, volcanic material reappears in the sequence at the top of Unit 3 (Figs 2.4 and 2.5). These rocks are grey, very fine grained, and either massive and compact, or finely flow banded pumiceous rhyolite. In thin section they consist of tiny euhedral quartz phenocrysts in a glassy matrix (Fig 2.14). The rhyolite is associated with tuffs, most units of which as Hancock (1985) notes "are highly felsic with quartz (0-20%), alkali felspar, and albitic plagioclase being dominant constituents". These acid tuffs and rhyolites are associated with discrete, probably sub-volcanic, rhyolitic domal structures. This is a distinctive suite of acid volcanics, informally named the 'Alkaline Suite' (Allen, 1985).

Impure quartzites are noted for the first time in the stratigraphic column of the Biscay Fm. (Fig 2.4) at the very top of Unit 3, immediately below the two laterally persistent, but thin, carbonate beds which mark the top of Unit 3.

Unit 4.

North of the Ord River, the base of Unit 4 consists of a series of impure quartzites, which form ridges, and interbedded pelitic horizons. Up sequence, carbonate beds increasingly dominate the stratigraphy. A very thick carbonate horizon, in places consisting of seven individual beds finely intercalated with carbonaceous schist, is taken as the top of the Biscay Formation. Along strike to the south in the White Rock Bore area, thick pillow basalts again recur in the succession in this area (Fig 2.2), replacing the carbonate at the top of Unit 4. They are beautifully preserved, with glassy rims and amygdalar cores (Fig 2.14). The interstices between the pillows are infilled with pure white quartzite, or clean carbonate.

In the low grade areas in the south of the mobile zone, Unit 4 is less carbonate rich than it is north of the Ord River. In the Cummins Range, the top of the Biscay Formation is defined by a thick, continuous, carbonate horizon (Fig 3.1). In the Biscay Anticlinorium, this carbonate horizon is somewhat poddy, and occurs "within turbiditic successions otherwise indistinguishable from the Olympio Formation." (Hancock, 1985).

2.4.4 Petrology

The thin acid volcanic beds in the 'Wills Creek Suite' have been interpreted as sub-aqueous deposits (Allen, 1985). It was suggested that they were tuffs, either very distal from the vent, or that secondary phreatomagmatic eruptions could have occurred, "most of the volcanic material becoming re-airborne and leaving very little deposited sub-aqueously." These secondary eruptions are caused by interaction of the hot, mobile, ash cloud with water (Cass and Wright, 1982). The lenses of white mica in these felsic tuffs were interpreted as metamorphosed glass lapilli flattened parallel to bedding. However, Allen (1986) cautions that extensive devitrification and subsequent foliation of rhyolite lavas can produce an "appearance of welded ignimbrite" with phyllosilicate patches "misinterpreted as altered pumice clasts in a pyroclastic rock." Thus, an alternative, and preferred, hypothesis suggests that the acid volcanics in the 'Wills Creek Suite' could be thin beds of rhyolitic lava extruded in a shallow marine environment, and subsequently devitrified, foliated, and metamorphosed.

The felspar megacrysts in the 'Corkwood East Suite' probably represent metamorphosed pisolites. This northern area is interpreted as emergent at the time of eruption, and the voluminous ignimbritic material deposited sub-aerially by "continuous collapse of a plinian eruption column" (Wright et al, 1980). The thickness variation in the carbonate bed is due partly to syn-sedimentary faulting (Chapter 3), and partly to later mylonitization. In addition to these structural controls, palaeo-topography probably influenced thickness of the ignimbrite i.e. ponding in palaeo-valleys and thinning over palaeo-highs.

The plagiophyric rock at the base of Unit 2 in the White Rock area is interpreted as a crystal tuff. The mechanism by which phenocrysts were concentrated may have been aeolian fractionation, i.e. the winnowing out of the fine ash from the plume. The deposit is massive and un-bedded, which suggests subaerial deposition. The overlying B.I.F. is considered to have been laid down in shallow water, possibly a protected barrier environment, a near shore trough or bay paralleling the ancient shore line. The B.I.F. apparently has a volcanic exhalative affiliation, for it occurs in this area where much of the Biscay Fm. is occupied by great thicknesses of pillow basalt. B.I.F's are not seen in the northern areas, where basalt horizons are fewer and thinner, and carbonate horizons predominate in Upper Unit 2, and in Units 3 and 4. An anaerobic environment is suggested by associated carbonaceous schists.

In Units 1 and 2 of the Biscay Formation, the combination of shallow marine and subaerial features suggests a possible volcanic archipelagic setting. An increasingly deep water environment of deposition is suggested for the upper units of the Biscay Formation, particularly in the southern, low grade areas, where turbiditic features are preserved in upper Unit 4. The succession is predominantly volcanic in the lower two units of the Biscay Fm., with basic extrusive rocks exceeding acidic. The upper two units consist of a variety of metasediments, with volumetrically minor, but tectonically important volcanics (Ch.6) of the 'Alkaline Suite' localised around specific vent systems. Unpublished company reports, supported by the analyses of Hancock (in prep), indicate that they are highly fractionated, and characterised by extreme enrichments in incompatible trace elements, eg. Zr, Nb and Y. Hancock (1985) interprets this suite as the "products of highly fractionated A-type rhyolite".

Metapelites throughout the Biscay Formation have an abundance of iron rich phases (e.g. chlorite, chloritoid, garnet, staurolite, magnetite, - see Ch.4. Occasionally pelitic rocks are so strongly magnetic that structural measurement with a compass is precluded). The felsic volcanics throughout the Biscay Formation, as well as in the Ding Dong Downs Volcanics and the Whitewater Volcanics, have higher iron values than their Cainozoic counterparts (Ch. 5). These characteristics, in concert with the development of B.I.F. horizons, attest to the iron rich nature of the entire province.

2.5 Olympio Formation.

2.5.1 Distribution.

The Biscay Formation is overlain by the Olympio Formation. It is areally the most extensive formation of the Halls Creek Group in both the East and West Kimberley. The entire outcrop area of Halls Creek Gp. rocks in the West Kimberley, with the exception of the inlier mentioned previously in the southeast of the King Leopold Mobile Zone, consists of Olympio Fm. metasediments (Fig 2.15). Geophysical data suggest the presence of further high grade metasediments of the Biscay Fm. in the south of this fold belt. However, they are concealed beneath Palaeozoic rocks of the Lennard Shelf and the Fitzroy Trough (Hancock and Rutland, 1984).

Thickness has been estimated at over 4.000 metres for the incomplete, lower part of the sequence in the East Kimberley, by Dow and Gemuts, 1969, and Hancock and Rutland, 1984. In the West Kimberley, Derrick and Playford (1973), estimate a thickness of "probably 6,100 metres" for the Halls Creek Group, while Hancock (1985) estimates that the Olympio Fm. is "greater than 9,000 metres in the West Kimberley". This discrepency is largely balanced by a decrease in thickness of the Whitewater Volcanics relative to previous estimates, due to re-positioning the boundary up sequence by Giles and Mancktelow (1979).

2.5.2 Petrography.

These two authors (Giles and Mancktelow) have informally subdivided the more complete succession in the West Kimberley into three units.

2.5.2.1 West Kimberley (Type Area).

Unit 1 is characterised by a monotonous succession of coarse to medium grained sublitharenite, with interbedded pelitic intervals, particularly towards the top of the sequence. Unit 2 is defined as a volcanogenic sedimentary unit, and consists of fine grained, finely bedded schists and phyllites (some with a volcanogenic component), and locally, lithic crystal tuffs. Tuffaceous material dominates the sequence in Unit 3, which is defined as an acid volcanic unit. The crystal lithic tuffs grade from dacitic and rhyodacitic at the base to rhyolitic at the top of the sequence. A diagrammatic stratigraphy of the Olympio Fm. in the West Kimberley is presented in Fig 2.17.

2.5.2.2 East Kimberley.

In the south of the Halls Creek Mobile Zone, the Olympio Formation is a monotonous succession of predominantly arenaceous sediments, lacking good marker units. In the Biscay Anticlinorium, the lower part of the sequence is medium grained, and is overlain by a conglomeratic interval, transitional to phyllite (Dow and Gemuts,1969). The top is not exposed. The incomplete succession in the East Kimberley is correlated with Unit 1 of the Olympio Fm. in the West Kimberley by Hancock and Rutland, 1985.

North of the Ord River, the generally metapelitic, carbonate dominated, Unit 4 of the Biscay Formation passes abruptly upwards into the basal sequence of the Olympio Formation, with various intercalated carbonate horizons, and schistose lenses, in otherwise monotonous paragneisses of an original sandy, sublitharenite sequence (Fig 2.1). The sedimentary sequence is intruded by Woodward Dolerite, which in turn is intruded by the syntectonic Mabel Downs Granodiorite. Rafts of country rock indicate an original lithology quite distinct from the underlying Biscay Formation. These quartzo-felspathic gneisses contain rare, minute, rounded, almandine garnets as inclusions in coarse grains of quartz and felspar (Fig 2.17b). They appear to be unrelated to the equilibrium metamorphic assemblage, and are seen as sedimentary in origin. This confirms Dow and Gemuts's characterization of the provenance region as "an actively rising landmass of metamorphic and plutonic rocks".

Further up sequence in the high grade area, a thick carbonate horizon abuts the western edge of the main body of Mabel Downs Granodiorite north of the Ord River (Fig 2.1). Further west, the 'Highway Gneiss', east of the Great Northern Highway is a monotonous quartzo-felspathic gneiss considered to be Unit 1 of the Olympio Fm., although none of the distinctive sedimentary features which characterise this unit at lower grade have been observed by the author, or reported by others.

In the Sally Malay Camp area, further west up sequence, the acid granulites indicate an original lithology less sandy and more pelitic than lower in the stratigraphy. This sequence is here correlated with Unit 2 of the Olympio Fm. in the West Kimberley, on the grounds of similar lithological sequences at an equivalent position in the stratigraphic succession (Fig 2.16). Unit 1 is separated from Unit 2 by a wide mylonite zone, along which the Great Northern Highway is constructed. The base of the sequence is intruded by abundant mafic granulites, of three different generations (Thornett, 1983, and in prep.). Stratiform, pre-tectonic horizons represent basalts within the sequence, or Woodward Dolerite sills. The latter is the more likely since basalt flows have not been recorded in the Olympio Fm. A differentiated ultrabasic and basic body was intruded post-dating the metamorphic peak. A final pulse of magmatic intrusion is represented by a suite of post-tectonic norites.

Further south, east of Dougals Bore and White Rock Bore, great thicknesses of Woodward Dolerite obliterate most of the base of the Olympio Formation (Fig 2.2). Unit 1 is similar in character to outcrops further north, consisting of a general sandy sequence, metamorphosed to paragneisses (Allen, 1985). A carbonate horizon occurs, as rafts within the 'granite' pluton south of the Ord River, and further south in the Melon Patch Bore, and Mc.Kenzie Bore areas. (Fig 2.17c). Unit 1 is intruded by 'granites' as in the northern area. In addition, much of the sequence west and southwest of White Rock is obliterated by the mafic and ultramafic Panton and Mc.Intosh sills (Chapter 5).

2.5.3 Environment of Deposition.

In sublitharenite units throughout the Olympio Formation, in the Biscay Anticlinorium, in the Cummins Range area, and the West Kimberley, base of bed structures such as flute casts, load casts and scour channels are common, together with such features as slump structures, graded bedding, and climbing ripples. There is widespread partial (and occasional complete) preservation of Bouma sequences (Giles and Mancktelow,1979). The character of the sequence is diagnostic of a deepwater, turbidite succession, which Hancock (1985) suggests accumulated "on an extensive submarine fan complex..in broad, open midfan channels and lobes." Giles and Mancktelow (op. cit.) suggest that the fine volcanogenic shales in Unit 2 "may not have been deposited in deep water in a eugeosynclinal environment, but rather in a shallow water lacustrine environment."

2.5.4 Contact Relationships.

The base of the Olympio Formation is not exposed in the West Kimberley. In the East Kimberley the contact between the Biscay Formation and the overlying Olympio Formation is frequently obliterated by Woodward Dolerite. Where the contact is exposed, the transition from shallow water deposits to deep water turbidites is generally quite sharply defined. The distinction between Biscay Fm. and Olympio Fm. metasediments is also obvious in distinctly different radioactivity levels (Pyke, pers.comm.). Similarly, the transition from Unit 1 to Unit 2 of the Olympio Formation is "very abrupt... suggesting a marked change in the sedimentary regime" (Giles and Mancktelow,1979). These "distinct shifts in vertical facies associations" (von der Borch, et al. 1986) are analogous to the "sequence boundaries" proposed by them in the Proterozoic Wilpena Group, Adelaide Geosyncline. Christie-Blick (1986) suggests that these sequence boundaries are equivalent to regional unconformities, which are here proposed at these two levels in the stratigraphic column of the Halls Creek Group.

2.6 Whitewater Volcanics.

The Halls Creek Group, in both the East and West Kimberley is unconformably overlain by the Whitewater Volcanics. These, in turn, are unconformably overlain by the Kimberley Basin succession. Thickness of the Whitewater Volcanics has been variously estimated at 6,000 to 7,000 feet (Dow and Gemuts,1969), up to in excess of 12,000 metres (Derrick and Playford, 1973). Felsic tuffs included in the above estimate have been re-allocated by Giles and Mancktelow (1979), along with Dyasons Granite, to Unit 3 of the Olympio Formation. They could find no evidence of an unconformity in the position indicated by Gellatly et al,(1974). A much reduced estimate of "up to 3,500 metres" is suggested by Plumb, (1985).

In outcrop, the rocks are buff-brown to grey-green to purple. They are generally massive, fine grained, structureless, ignimbrites. Lapilli tuffs have been reported, as have lenses of agglomerate, and volcanic conglomerate (Gellatly and Derrick, 1967, Dow and Gemuts, 1969). Texturally the volcanics are porphyritic, with phenocrysts of quartz and felspar in the more acid rocks, and chlorite and biotite pseudomorphs after pyroxene in the more basic rocks. The fragmental nature is suggested by the presence of crystal chips and splinters, and glass shards in some specimens. Photographs and photomicrographs of the Whitewater Volcanics are presented in Fig 2.18. The geochemistry is discussed in Chapter 5.

In the East Kimberley, the Whitewater Volcanics, and the associated Castlereigh Hill Porphyry, are only mildly deformed. However, in the West Kimberley, the volcanics, along with the Bickleys Porphyry and equivalents, are strongly deformed and metamorphosed by two events. As Giles and Mancktelow, 1979, indicated, their allocation to Transitional Tectonism in the Tectonic Map of Australia and New Guinea is thus questionable.

2.7 Comparison of Stratigraphy in the East and West Kimberley.

In the East Kimberley, in the high grade area previously mapped as 'Tickalara Metamorphics', a complete sequence of Biscay Formation can be confidently correlated in detail with the stratigraphic sequence established in the type area. This includes previously unrecognised bimodal volcanics mainly at the base of the sequence in Units 1 and 2. It is conformable between newly recognised Saunders Creek Formation quartzites, and gneisses and granulites of the Olympio Formation, of which all of Unit 1, and probably most of Unit 2, are exposed. This is at variance with the views of Hancock and Rutland, 1984, who claim for the high grade area "only a limited stratigraphic thickness appears to be exposed", and who recognise only "Upper Biscay and Lower Olympio successions." These authors propose diachroneity of the Olympio Fm., and suggest that the "flysch facies is entirely older in the extreme west than in the extreme east." The recognition of large thicknesses of the Olympio Fm., including Unit 2, rather than "some remnants of the facies" allows more accurate correlation between the East and West Kimberley, which does not support an hypothesis of diachroneity of this facies.

STRUCTURE

3.1 Introduction

A history of polyphase deformation has been recognised throughout the Halls Creek Mobile Zone by previous authors. Dow and Gemuts (1969) considered that the rocks of the Halls Creek Group in the low grade areas were "tightly folded by at least two episodes of intense deformation." The high grade Tickalara Metamorphics, it is suggested, "probably had the same tectonic history as the Halls Creek Group until their metamorphism and intrusion by granite and gabbro, but in the high grade rocks earlier structural trends have been obliterated". Hancock and Rutland (1984) recognised three periods of deformation in both the low and high grade areas of the East Kimberley. Thornett (in prep) has recognised four fold episodes in an area of granulite facies rocks. These equate in style, orientation, relative timing, and association with metamorphic events, with those described in Allen (1985), and presented hereunder. This sequence can also be related to the fold events of Hancock and Rutland (op. cit.) depicted for the Black Rock Anticline, with the omission of the third foliation, which is not recognised by these authors. However, Hancock (pers. comm.) describes structures in low grade areas which have the same orientation and relative timing as the third foliation of Allen and Thornett.

Dow and Gemuts (1969) defined the Halls Creek Mobile Zone as bounded to the east and west by the Halls Creek Fault and the Greenvale Fault respectively. Thom (1975) included the Biscay Anticlinorium and the Osmond Ranges in the Halls Creek Mobile Zone, the same formations in these two areas having undergone the same deformational events as the rest of the fold belt. This broader definition is adhered to below.

In this chapter the number and sequence of ductile deformations is clarified, fabric elements developed in the different events are described and documented, and deformation mechanisms are examined. Discrete fold episodes are correlated between the low and high grade areas, using style, orientation, associated fabrics and over-printing criteria. Brittle deformation is also addressed in this chapter. Dislocation along major faults is considered by Dow and Gemuts to have been initiated in early Carpentarian times, representing a major change in the structural regime of the East Kimberley. However, they also cite evidence for pre-Carpentarian movements on major faults "during the metamorphism and igneous intrusion along the Mobile Zone". Further evidence is adduced by this author bearing on the timing of faulting, shearing, and mylonitization.

3.2 Deformational Events.

Four periods of folding are deliniated with structures and fabrics recognisable at a variety of scales (Allen, 1985).

3.2.1 The First Deformation, D_1.

In low grade areas, macroscopic folds with an amplitude of many tens of kilometres are the most obvious structural element. These large scale structures fold bedding, and are assigned to D_1 deformation.

The Garden Creek Anticline in the Mc.Clintock Ranges (Fig 3.1), mapped by Dow and Gemuts (1969), is an isoclinal overturned fold with restored amplitude of 30 kilometres. In thin sections from the Olympio Formation in the anticline, "two distinct foliations can be distinguished" (Dow and Gemuts, op cit). The first, they describe as defined by aligned mica flakes parallel to bedding, and the second is defined by a second generation of mica flakes, "parallel to the axial planes of the later folds". This structure is interpreted (Allen, 1985) as a macroscopic F_1 fold refolded by D_2 (also on a macroscopic scale) on the following evidence :-

1. The stratigraphic sequence is repeated across the fold closure.
2. Vergences, appropriate to this fold closure (ie. sinistral on the western limb and dextral on the eastern limb) plunge steeply to the S.W. These are at variance to the later F_2 vergences, all of which are sinistral (cf. folded axial trace - Fig 3.1) and plunge at 25^o - 70^o to the N.E.
3. The regional schistosity axial plane to the macroscopic F_1 fold is S_1. S_1 is folded by D_2 to the west of the major anticlinal structure. The Woodward Dolerite and the axial trace of the F_1 fold are also folded by D_2. A new schistosity is developed overprinting the earlier layer parallel fabric. Both S_1 and S_2 are defined by muscovite-biotite. However S_1 overprints only in the core of the major F_2 structure closing south. The most likely interpretation of the original F_1 structure, prior to the later fold event, is an isoclinal reclined fold with limbs dipping moderately (probably approx 30^o) to the east, and plunging steeply in a general south-westerly direction. Both F_1 and the overprinting F_2 verge west.

F_1 folds are developed on all scales (Fig 3.2), and are characteristically isoclinal, generally with an associated penetrative cleavage. They are reclined to recumbent, except where axial planes are steepened by later deformation.

Dow and Gemuts (1969) suggested that the Biscay Anticlinorium has been truncated, and the western section has been shifted southwest by left lateral transform fault movement on the Halls Creek Fault. This southwest section is the large anticlinal structure, of which the Garden Creek Anticline is the southern extension. The correlation is based on similarity of stratigraphy (within the Biscay Formation), and structure. This interpretation is widely accepted, and the pre-slip configuration is illustrated in Fig 3.3. The Biscay Anticlinorium consists of two broad anticlines separated by a pinched in syncline. Bedding is isoclinally folded, with an amplitude of some tens of kilometes, and "throughout the Biscay Anticlinorium there is evidence that the rocks have undergone two separate periods of severe folding" (Dow and Gemuts, op. cit.). These are equated with F_1 and F_2 described above for the Garden Creek Anticline.

The strata in the Black Rock Anticline are recumbently overturned (Figs 2.2 and 3.4). This high grade area also exhibits the two periods of folding, with structures of a similar style, wavelength, and amplitude, to that described above in the low grade areas to the south. Both limbs of the isoclinal F_1 folds in the core of the major structure have a sinistral vergence, having been refolded by F_{2a}. The structural style in the Black Rock Anticline is completely different from that in the adjacent area to the west, across the western splay of the Halls Creek Fault (Fig 2.2). The Black Rock Anticline is anomalous in that in no other high grade area have macroscopic or mesoscopic folds of S_0 (bedding) due to D_1 deformation been observed. The high grade Black Rock Anticline is structurally similar to the low grade Biscay Anticlinorium to the south. It is proposed here that the Black Rock Anticline has been transposed some 90 kilometres north by movements along the Woodward Fault and Halls Creek Fault (Section 3.2.2.2).

In high grade areas (eg. Figs 2.1 and 2.2), even in the absence of macroscopic and mesoscopic F_1 folds, good evidence for F_1 exists in the form of a layer parallel schistosity folded about F_2 axes (Allen, 1981, 1982, 1985). This D_1 fabric, S_1, is illustrated in Figs 3.5, 3.6, and 3.7, from a selection of rocks from the White Rock Bore area (see figs 1.1 and 2.2). A number of lines of evidence suggest this fabric is of tectonic origin -

1. The layer parallel fabric in the hinges of F_{2a} folds is very strong in rocks of appropriate composition (369 in Fig 3.5c).

2. This early fabric is temporally associated with metamorphic minerals eg. garnet (372 and 377 in figs 3.6 and 3.7b).
3. S_2 is a crenulation cleavage implying a strong pre-existing anisotropy of probable tectonic origin. (377 and 413 in Fig 3.7b, and 3.5 a & b).
4. Porphyroblasts wrapped by S_2 sometimes display a rotational S_i, finer than and discontinuous with S_2. (Fig 3.7a).
5. D_2 folds a tectonic fabric in some igneous rocks (Fig 3.17a, and Chapter 5).

In these high grade areas, S_1 is strongly overprinted by a later, coarser grained schistosity, S_2, and can be distinguished in the field and in thin section only where S_1 is oblique to S_2. In the hinges of F_2 folds, as illustrated, S_1 is easily identified and very widespread. S_1, wherever it has been observed in these high grade areas is layer parallel, indicating that F_1 folds are isoclinal. Younging directions around F_2 folds are everywhere consistent. When unfolded, beds invariably young west, in conformity with the regional westward younging of the Saunders Creek Formation, through the Biscay Formation, to the Olympio Formation, shown in Figs 2.1 and 2.2, and described in Chapter 2. This suggests that macroscopic F_1 folds have a very large amplitude, and this area is entirely on one limb of an F_1 fold. The early schistosity, S_1, in the high grade areas, is correlated with the first schistosity, S_1, axial plane to F_1 folds in the low grade areas (Allen, 1982, 1985).

It is possible that the mechanism responsible for these early folds is gravity sliding in a high strain decoupling zone at basement/cover contact (not exposed in the Kimberleys), analogous to that proposed for early recumbent folding with widespread concordant foliation in the Pine Creek Geosyncline (Johnston, 1984).

3.2.2. The Second Deformation, D_2.

The second deformation is a composite event, which has generally developed in two stages; widespread folding followed by shearing, designated F_{2a} and D_{2b} respectively (Allen 1982, 1985).

3.2.2.1. The Fold Event F_{2a}.

F_{2a} folds a fabric (generally a layer parallel schistosity) everywhere, and at all scales. These folds are near co-axial with F_1 and thus modify existing structures only slightly, except where hinges of the two fold generations interfere. The Garden Creek Anticline provides an example. The F_1 fold closure is crumpled by a parasitic fold on the limb of a major F_{2a} structure (Fig 3.1). Where axial planes are not co-incident, the effect of F_{2a} refolding is the imposition of minor folds with the same vergence on both limbs of pre-existing F_1 fold structures. This is evidenced in the Garden Creek Anticline and the Black Rock Anticline. Folds of F_{2a} generation are recognised in all areas mapped in detail. Very tight to isoclinal, generally reclined to recumbent folds, fold a layer parallel schistosity, S_1, about predominantly N.E. to N.N.E. axes (Allen, 1982, 1985; Hancock and Rutland, 1984; Hancock, 1985). Mesoscopic F_{2a} folds are widespread in high grade areas, and are illustrated in Fig 3.8. Planar and linear fabrics, developed on all scales, are characteristically associated with the F_{2a} fold event. In high grade areas, a new schistosity, S_2, is developed, which is ubiquitous, penetrative, and prograde. In greenschist facies areas, S_2 is of similar grade to S_1 and is generally penetrative. However, in some areas eg. the Mc. Clintock Ranges, S_2 is more weakly developed than S_1. As indicated, S_2 forms by crenulation of the penetrative slaty cleavage, S_1. Thus S_2 is a spaced crenulation cleavage (Powel,1979). Except at very low grade, it is a prograde schistosity, and is therefore coarser grained than S_1. The situation is analagous to the two prograde schistosities in the Willyama Complex, New South Wales (Glen and Laing 1975), and the Adelaide Fold Belt (Allen, 1977, Mancktelow, 1980, and others). S_2 is the regional schistosity in the high grade areas. It is well developed in a wide range of lithologies, and is easily recognised both in the field and the laboratory. S_2 forms the datum from which earlier and later events (structural, metamorphic, and igneous) are recognised and put into a relative time scale (Allen, 1981, 1982, 1985). As illustrated in Figs 3.5 and 3.6, a crenulation axis develops in rocks of suitable composition at appropriate positions in the fold geometry. This L_2 is generally a fine, small wavelength crenulation, with S_2 axial plane to the crenulations, and parallels the plunge of major F_2 folds. An elongation lineation also commonly develops in association with F_{2a}. This is defined in the high grade rocks by oriented metamorphic minerals, eg. hornblende in metabasites and sillimanite in metapelites. During this deformation, boudinage is also developed (sometimes on a scale of many metres) in competant bands enclosed in a less competent matrix (Fig 3.9). Mesoscopic folds from the high grade areas approximate Ramsay's (1967) Class 2 (similar) folds, "which are generally found in the central parts of belts of regional folding and metamorphism". In some localities in the Saunders Creek area, recumbent folds fold bedding and are therefore assigned to D_1 deformation. However, in other localities recumbent folds fold a fabric (in some cases an elongation lineation, in others an intersection lineation, and in areas of slightly higher grade a cleavage), and are thus of the later (D_{2a})generation.

3.2.2.2. The Shearing Event, D_{2b}.

This deformational event is associated with shearing along the base of F_{2a} folds, transposition, and widespread though locally discrete mylonitization (Allen, 1982, 1985). It records major movement on the Halls Creek Fault system, and rotation of pre-existing structures in its vicinity into parallelism with the fault. Fold axes are rotated into a NNE trend from the NE orientation which is the regional trend away from this fault. Steepening of axial planes, sometimes to near vertical, occured concurrently with rotation as the result of D_{2b} shearing. Major structures eg. the Biscay Anticlinorium, as well as minor, show these effects, which are evident in low and high grade areas, and are described and illustrated below on macroscopic, mesoscopic, and microscopic scales.

Detailed mapping and sampling west of the western splay of the Halls Creek Fault which marks the western boundary of the Black Rock Anticline, and in the White Rock Bore area west of the fault, has revealed a large number (tens) of ductile shear zones. These are zones of mylonitic rock; "foliated fault rock, in which the deformation is accompanied by a reduction in grain size, without loss of cohesion of the rock" (Belliere, 1982). The usage of the term 'shear zones' follows that of White et al (1980), ie. "zones of inhomogeneous deformation in which strain softening has occurred. The mylonites which form in ductile shear zones are the softened medium." The D_{2b} shear zones range from 0.5m to 50m wide, and can encompass within one zone, wide areas of cataclasite, protomylonite and mylonite, enclosing thin bands of ultramylonite. The largest of these are mapped on Figs 2.1 and 2.2. In the highly tectonised area east of White Rock Bore, they trend N-S, parallel to bedding and the regional schistosity, S_2. Further to the north, trends of D_{2b} shear zones swing through a more easterly azimuth east of Dougals Bore, to NE in the vicinity of the Ord River, in sympathy with the changing trends of S_0, S_2, and the Halls Creek Fault (western splay, which defines the western boundary of the Black Rock Anticline) north from White Rock Bore to Sally Malay Bore.

In the Sally Malay Bore area, much of the D_{2b} strain was taken up by movement on a system of orthogonal faults and shear zones trending ENE, WNW, and N-S. Fig 2.1 shows beds greatly thickened in lozenge shaped areas bounded by these orthogonal faults, indicating syn-sedimentary extensional faulting (discussed in Chapter 2, and further in Chapter 6). The sense of displacement of S_0 by D_{2b} indicates that reactivation of the earlier fault system took place under the same stress regime as that which controlled syn-sedimentary extension. This stress field is indicated on Fig 3.10.

Where they can be directly observed, D_{2b} shear zones throughout the fold belt are vertical or nearly so (Allen 1985 and Fig 3.11). Others can be inferred to be very steep from their straight traces across topography. While there may well have been tectonic steepening during D_{2b} and later (and this argument is used to correlate fold structures with steeper axial planes near the Halls Creek Fault than those more distant), there is no evidence either directly observed or indirectly inferred from sequence repeats, that any of the shear zones were initiated as low angle thrusts. Evidence is presented below which indicates that these major strike slip faults have acted as transform faults from very early in their history. Episodic compressive and shearing stresses were accommodated by further lateral movement on these high angle zones of weakness, which are expressed as long straight fault traces. In contrast, low angle thrusts and mylonite zones, in the Harts Range area of the Northern Territory, are regionally folded into sweeping curves by later events (Ding and James, 1985).

There are various lines of evidence which support the timing of this deformation as post dating D_{2a} folding, and pre dating D_3 folding.

A. Macrostructural.

(1) In the Biscay Anticlinorium, large scale folds paralleling the

Halls Creek Fault have axial traces gently folded about E-W axes (Fig 3.12). Dow and Gemuts (1969) note "The whole structure has been domed along an east-west axis, and it plunges to the south-southwest at 30° to 50°, and to the north at about 20° to 25°." These structures are interpreted as folds of D_1 / D_{2a} generation rotated into parallelism with the Halls Creek Fault by D_{2b}, and folded by D_3. (D_3 structures have an east-west orientation, and are described in Section 3.2.3). Hancock and Rutland (1984) also note the parallelism of D_1 and D_2 with the Halls Creek Fault, and suggest rotation of these fold structures. Had this rotation occurred after D_3, the east-west structures would also have been rotated. Thus D_3 was superimposed on structures already rotated by D_{2b}.

(2) A 40 kilometre left lateral offset on the Halls Creek Fault, evidenced by the division and dislocation of the Biscay Anticlinorium, is indicated above (Fig 3.12, A-A', and Fig 3.3). In addition, Hancock and Rutland (1984) suggest probable sinistral strike slip movements, of similar magnitude, on the Woodward Fault, and the western splay of the Halls Creek Fault which defines the Black Rock Anticline (Fig 3.12, B-B', C-C'). Changing metamorphic grade (Chapter 4) associated with the deformational events described above imposes tight constraints on the time of re- positioning of the Black Rock Anticline in its present location. The metamorphic grade indicates that C' (Fig 3.12) could not have been closely contiguous to C any later than D_{2a}. Metamorphic parageneses and temperatures during D_{2a} are appropriate to that position. However, the grade in the Black Rock Anticline during D_3 is anomolously high for that locality, and it must have moved further to the north into a higher grade area by D_3 time.

This restoration of the Black Rock Anticline southward to its D_{2a} location, automatically re-joins the two halves of the Biscay Anticlinorium, as in Fig 3.3, which indicates that that displacement also took place during D_{2b}. Restoration along the Woodward Fault to bring B and B' (Fig 3.12) into adjacent positions across the fault, imposes the geometrical constraint that the Black Rock Anticline move a further 50 to 60 kilometres south. (Fig 3.13). The metamorphic grade during D_2 is anomolously high for this area, which indicates that this dislocation must predate D_2. The structural similarity of the Black Rock Anticline to the rejoined Biscay Anticlinorium during D_1 is appropriate for terrain which, on the above reconstruction, is but 10 kilometres distant. Thus, movement on the Woodward Fault (post D_1) predates movement on the southern sector of the Halls Creek Fault (D_{2b}). The metamorphic evidence supporting these arguments is presented in Chapter 4.

B. Mesostructural.

(1) Shearing along the base of D_{2a} folds is illustrated in Fig 3.8. It has no large scale expression, and is therefore considered of minor import. However, the "possible slide" mapped by Hancock in Hancock and Rutland, 1984, in the Black Rock Anticline (Fig 3.4) could be seen as an expression of this event. Fig 3.17a illustrates folding of the attenuated limb by D_4.

(2) In areas where very different lithologies were finely interleaved, a plethora of rootless folds of D_{2a} generation indicates transposition (Fig 3.9). This is a major effect of D_{2b} deformation, the large scale expression of which is the parallelism of pre-existing structures and fabrics already noted.

(3) Complex folding and refolding of sheath folds occurs in some D_{2b} shear zones during mylonitization, which is unrelated to regional foliation events. However, undoubted mesoscopic F_3 folds do sometimes fold a mylonitic fabric (Fig 3.15). This represents a locking up of the shear zone due to reorientation of the external stress field, so that a majority of the grains are no longer oriented for easy slip (White et al, 1980).

C. Microstructural.

Mylonitization on the D_{2b} shear zone array is synmetamorphic. A mylonitic fabric wraps pre-existing D_{2a} porphyroblasts, and is overgrown by later metamorphic minerals, relatable to D_3 or to the period of tectonic quietus pre-dating D_3 (Allen, 1982, 1985). This is a very definitive and incontrovertible piece of evidence for the relative timing of the D_{2b} event. It is widespread in the amphibolite facies areas (see Petrographic Descriptions in Appendix 4). Fig 3.16 shows a selected sample. Further examples are described and illustrated in Chapter 4.

The microstructural, petrofabric, and transmission electron microscopy work of Bell and Etheridge (1973), White (1973), Lister et al. (1977), supported by many recent studies, indicate that mylonitic recrystallization is syntectonic. White et al (1980) identify a number of softening processes during mylonitization leading to mechanical weakness. They indicate that "the existence of well defined crystallographic fabrics in most mylonites suggests that geometric (fabric) softening, and continual crystallization are the most important ofthese." In the Halls Creek Mobile Zone, metamorphic studies in the Fig 2.1 and Fig 2.2 map areas suggest a number of the other processes are also important.

(1) Reaction softening occurs with syntectonic metamorphism due to stresses induced by volume changes and increased diffusion rates during reaction and phase transformation (Nicolas and Poirier, 1976; White and Knipe, 1978).

(2) Chemical softening occurs consequent on the ingress of water and volatiles, due to dilatancy accompanying cataclasis, leading to neomineralization and pressure solution processes which resulted in the initial mylonite foliation. Apart from metamorphic reactions related to increased f_{H2O} and a_K, which are documented in Chapter 4

and covered in (1) above, lattice bound 'water' has a dramatic weakening effect (Carter, 1976; Post, 1977; Ross and Nielson, 1978).

(3) Pore Fluid effects produce significant softening in shear zones such as these, which act as fluid pathways (Rutter, 1972).

As noted above, the D_{2b} shear zones frequently parallel the regional S_2 schistosity, developed during D_{2a}, for some or all of their length. Within the mylonite zones also, the fabric generally parallels S_2. Means (1981) questioned the stability of a foliation, and suggested that a steady state foliation stable to large strains, is associated with steady state flow in rocks. White (1982) notes evidence for the co-existence and superposition of dislocation, pressure solution, and cataclastic processes in mylonites from the Moine Thrust Zone, and also the Alpine Fault Zone in New Zealand. He proposes that the mylonite foliation is the "nett product of cyclic cataclastic and ductile processes", and concludes that "the effect may be to reinforce an existing foliation if deformation occurs near the ductile - brittle transition."

3.2.3. The Third Deformation, D_3.

This is the first period of upright folding in the East Kimberley. Macroscopic folds of D_3 generation are most obvious in the high grade areas around the Ord River, north to Mabel Downs homestead and south to White Rock Bore (Thornett, 1983, Allen, 1985). These are illustrated in Fig 3.14. However, F_3 structures occur throughout the fold belt. As indicated above, F_3 is the fold event responible for doming of the Biscay Anticlinorium, and for warping of axial traces of its constituent folds about E - W axes (Fig 3.12). Folds of this generation in the high grade areas verge west (Fig 3.12); another interesting exception (along with the Garden Creek Anticline) to the eastward vergence suggested by Hancock and Rutland (1984) for structures in the East Kimberley.

Mesoscopic, tight to open, upright folds fold S_2 about E-W axes (Fig 3.17). F_3 refolds F_{2a} folds, with the production of a Type 3 interference pattern (Fig 3.18). No new schistosity is developed axial plane to F_3 folds, but a crenulation (generally coarser than that associated with F_{2a}) sporadically forms in rocks of appropriate composition.

Major faults, tens of kilometres long, sometimes develop into fault zones many metres wide. As indicated above, these dextral faults striking east, with vertical or near vertical dips (Fig 3.19) are considered to be D_3 structures. They are particularly prolific in the area of the Ord River, where it is crossed by the Great Northern Highway (Fig 3.14), but are evident throughout the Halls Creek Mobile Zone. Major E-W faults occur in the Cummins Ranges, intruded by pegmatite dykes, which are stanniferous and tantalum bearing. These pegmatites along with swarms of quartz dykes, are considered to be related to the post tectonic Bow River Granite which shallowly underlies the Mc.Clintock Range and Cummins Range areas (Chapter 5). Doming associated with batholith intrusion along the long axis of the mobile zone, could have been responsible for opening pre-existing faults. This dilatancy facilitated pegmatite intrusion. The displacementon a swarm of E-W faults can be considerable,eg. a2 metre nett slip was measured in an 11 metre length of a quartz-hornblende dyke cross cut by E-W faults, north of the Ord River (Fig 3.19).

The D_3 event records a fundamental change in the orientation of the stress field in the East Kimberley. The WNW - ESE axis of compression is relaxed, and the maximum principal stress swings around to west of north (Fig 3.10), with resultant folds and faults on an E - W azimuth. This is the stress system proposed by Hancock and Rutland (1984) for the Kimberleys. They suggest that the "boundaries of the main orogenic domains are broadly controlled by strike-slip faults related to a maximum principal stress oriented just west of north."

This accords with the proposal below (Section 3.3) of post orogenic reactivation of the stress system initiated during D_3, to account for strike-slip movements on major faults in the East Kimberley during later Proterozoic and early Phanerozoic times. However, the ENE and NE trending faults and shear zones in the East Kimberley cannot be related to this stress system, because the sense of movement is dextral (Fig 2.1 and 3.8), and not the "sinistral en eschelon pattern" which these authors suggest.

While this period of deformation has little effect on the outcrop pattern except in the high grade areas, it is considered very important for the following reasons :-

(1) It is associated with peak metamophic temperatures (Thornett, 1983; Allen, 1985), and thus has implications for heat sources during metamorphism (Chapter 6).

(2) It is a very important structural trend controlling uplift, erosion, and deposition through the Proterozoic and into the Phanerozoic (Chapter 6). While this is recognised by Hancock and Rutland (1984), they do not recognise a controlling influence on structure and metamorphism on an E - W azimuth during orogenesis.

Hancock and Rutland (1984) indicate that the Whitewater Volcanics "overstep both to the east and south over progressively deeper levels of the underlying rocks". It is considered here that this uplift and erosion, prior to deposition of the Whitewater Volcanics, is a consequence of vertical movement (south block up) on the Little Gold Fault and the continuation of this fault into the high grade area, during D_3 deformation. This brought the southern sector into higher crustal levels at this time, during associated and later metamorphism (Chapter 4). (Deposition of post-orogenic sediments to the south of this fault system requires reversal of movement, with relative uplift of the northern block). It is thus envisaged that D_3 involved components of vertical and horizontal movements on an en echelon series of E-W to ENE trending faults (including the Little Gold Fault) with associated folding and metamorphism. The fact that structures on this azimuth, at this time, are ubiquitous throughout the mobile zone, justifies their allocation to a separate deformation event.

3.2.4. The Fourth Deformation, D_4.

Macroscopic, upright, open to tight, F_4 folds trend northeast in the high grade areas. F_3 axial traces are folded by this event (Fig 3.14). As illustrated, these F_4 folds are tighter in the centre of the mobile zone than they are further west (or east - cf. Fig 3.4). This accords with the proposition of Hancock and Rutland that this zone "has concentrated the early strain during convergance".

Mesoscopic F_4 folds are widespread in the high grade areas (Fig 3.20). They plunge at small angles, generally to the NE to NNE, but occasionally to the SSW (probably where there has been prior doming by F_3). This regional shallow plunge of L_4 is due to the folding by F_4 of a near flat-lying S_2 surface. This observation refers to the regional scale, and is not valid for rotated structures in the vicinity of the Halls Creek Fault system. In Fig 3.21, an F_4 fold is illustrated with a vertical plunge. This example is from the White Rock area in a locality where F_{2a} structures are strongly rotated (see Sect.3.2.2.2). Exceptions to the regional shallow plunge of L_4 occur where S_2 departs significantly from the horizontal, where it is affected by D_{2b} rotation or F_3 folding. F_{2a} folds are refolded by F_4, with the production of a Type 3 interference pattern (Fig 3.22). L_4 crenulation lineations parallel the plunge of F_4 folds, but no new schistosity is developed in this event. F_4 folds appear to be closely coaxial with F_{2a} folds in the high grade areas. This may represent a return to the stress field orientation of initial extension and early folding. Alternatively, it may be seen as maintenance of the newly imposed D_3 stress field, but with a strain rate sufficiently low to be able to be accommodated by reactivation of existing folds, even though they are not perpendicular to the maximum compressive stress. No shear zones are known to have been initiated during D_4 deformation, and no major reactivation of existing shears can be documented, indicating that the strain rate was probably able to be accommodated without resource to localised mylonitization.

D_4 was a period of compressive folding with trends varying in sympathy with the established basement trends. The antiforms follow the flexure at the confluence of the two mobile zones, curving around into the West Kimberley. A similar effect in the Adelaide Fold Belt was considered by Mancktelow (1979), to have resulted from late compressive folding towards a rigid block to the northwest of the fold belt. Although this deformation is considered to have had a contouring effect, moulding the final shape of the fold belt, it was accompanied by retrograde metamorphism in the highest grade areas, and occured when the rocks were everywhere already on an uplift and cooling path.

3.2.5. Correlation Between Low and High Grade Areas.

Structural correlation between low and high grade areas of the Halls Creek Mobile Zone is problematical because near coaxial later structures and fabrics overprint earlier structural elements (Allen, 1984). The problem is exacerbated by a strong linearity imposed by major faulting, and the rotation of structures in the vicinity of these faults. These trends are emphasised by later compressive folding, and the emplacement of fault controlled linear batholiths. As a result of these difficulties, three models of structural evolution have been proposed, two of which are quite similar, but the third differs in major elements. The tectonic model proposed in Chapter 6 has its structural base in the correlations documented above. The tectonic model presented in Hancock and Rutland (1984) does not necessitate close structural correlation between their proposed imbricate thrust sheets.

Model 1 Allen.

Detailed above.

Model 2. Hancock and Rutland.

Hancock and Rutland (1984) consider that D_1 and D_2 in the low grade areas are represented by minor structures only. They are characterised as "D_1 ? localised in stratiform zones", and "D_2 ? Sub-listric slide-zones...defined by mesoscopic isoclinal folds and a penetrative schistosity." The regional anticlinoria and synclinoria in these areas, they relate to D_3 (equivalent to D_4 described above), "on the basis of similarity of style and orientation". There are major problems which arise from this correlation.

1. Lack of correlation of associated fabrics.

D_3, in low grade areas, is defined by these authors as "late, upright NNE to ENE trending, flatly plunging, tight folds, associated with upright to gently east vergent cleavage (S_3)". There is no schistosity associated with their D_3 in high grade areas. Also, no schistosity associated with D_1 is documented in low grade areas, although S_1 is recognised at high grade. While a fold event at high grade might fail to generate new metamorphic minerals at shallow crustal levels, the reverse situation proposed above for D_3 is less readily acceptable.

2. Lack of correlation of overprinting structures and fabrics.

The Garden Creek Anticline (Fig 3.1) is the southern extension of the continuation across the Halls Creek Fault of the Biscay Anticlinorium. If these are D_3 structures as proposed, the refolding on a macroscopic scale, with associated superimposed schistosity, documented for the Garden Creek Anticline, has not been recognised. This event post-dating D_3 has no high grade equivalent. Similarly, the doming of the Biscay Anticlinorium about an E-W axis has not been recognised, and has no high grade correlative, if this event postdates D_3.

3. The eastward vergence proposed by Hancock and Rutland for structures in the East Kimberley, does not appear to be applicable in the area between the Halls Creek Fault and the Springvale Fault (Allen, 1985, and above).

Model 3. (Hancock).

Hancock (1985) presents a somewhat different structural model, which permits closer correlation between low and high grade areas.

D_1 structures are defined as "tight to isoclinal folds, penetrative cleavage, and sporadic mineral lineations". The regional and mesoscopic "upright folds and associated cleavage of crenulate to penetrative form" are assigned to D_2. A rotational component of D_2 strain is recognised "compatible with a nexus between D_2 folding and left lateral strike slip shear." Shear zones associated with the initiation of the Halls Creek Fault system are categorised as D_3. E - W structures post dating D_2 are recognised (pers. comm.), but in keeping with their relatively minor import in low grade areas, are not assigned to a separate event.

This scheme is similar to Model 1, with D_{2b} in Model 1 equivalent to a "rotational component of D_2 strain ... and left lateral strike slip shear" and D_3 in Model 3. Regional folding in low grade areas is assigned to D_2, rather than the interaction of D_1 and D_2. However this is implied for the Black Rock Anticline by the recognition of S_1 and S_2. The later steepening of axial planes close to the Halls Creek Fault is not apparently recognised. D_2 folds are upright only close to major faults.

3.3 Large Scale, Brittle Deformation.

The Halls Creek Mobile Zone is characterised by an anastomosing system of major strike-slip faults tens of kilometres long (Fig 1.1), some composite sets attaining regional dimensions, being many hundreds of kilometres long. The wide shear zones, long sinuous traces, and near vertical dips, are typical of fundamental strike-slip faults, as are their long history of intermittent movement, with large vertical displacements, periodically reversed (Plumb, 1985).

The Greenvale Fault is linked to the Liamma Fault in the north (Fig 1.1). Further south, the NNE trend swings more easterly through the Little Gold Fault, towards the Sandy Creek Shear, sub-parallel to the King Leopold Mobile Zone. The westerly offshoots of the Halls Creek Fault south of Halls Creek, the Angelo and Woodward Faults, appear to swing around into the trend of the King Leopold Mobile Zone as the Pinnacle Fault, in a similar fashion. The Springvale Fault, intermediate between the Greenvale and Halls Creek Faults, also changes trend at the confluence of the two mobile zones, and swings into an easterly azimuth as the Glidden Fault. These trends parallel the changing orientation of the traces of the upright folds. They may similarly be related to compression from the SE during early orogenesis swinging around to the SSE during late orogenesis and post-cratonization deformation, towards a rigid block to the NW.

While more than half of the movement on these fault systems is demonstrably post-cratonic (Plumb, 1968; Plumb and Veevers, 1971; Plumb, 1985), approximately 90 kilometres of aggregate syn-metamorphic, Early Proterozoic, sinistral displacement on the Halls Creek Fault and the Woodward Fault can be demonstrated with a high degree of confidence (Fig 3.13). Separation of the Biscay Anticlinorium across the Halls Creek Fault suggests a left lateral displacement of some 40 kilometres, and displacements of similar magnitude are indicated across the Woodward Fault, and across the western splay of the Halls Creek Fault which defines the Black Rock Anticline.

Plumb (1985) suggests that these movements are "quite compatible with being part of the post-cratonization system .... and objective analysis cannot positively constrain any of it to being any older". The sense of movement on these NNE faults is in accord with the post-cratonization pattern indicated by Plumb ("northeasterly thrusts and folds cut by more northerly strike-slip faults"), and the stress field suggested by Hancock and Rutland, and also by Allen (above) for D_3. However, this system (Fig 3.10) is not a unique solution for sinistral strike slip displacements on NNE trending faults. The orientation suggested for D_{2b} also permits the demonstrated dextral movement on the system of NE and ENE trending faults active during D_{2b} (Fig 2.1), as well as during initial extension. Evidence for movement on the Halls Creek Fault system continuing up to Late Devonian times has been recorded (Rod 1966, Veevers and Roberts, 1968). Restoration to a pre-slip configuration imposes metamorphic constraints on the time of movement, which indicates major dislocation on the Halls Creek Fault during D_{2b}.

A possible left lateral movement of 32 kilometres on the Springvale Fault is suggested by Dow and Gemuts. They indicate that a foliation in the Bow River Granite adjacent to the fault "was formed at high temperatures - probably at a late stage in the cooling of the granite." It has been noted that macroscopic D_3 folds are most obvious in the vicinity of the Ord River, and that faults associated with this event are prolific in this area. It is proposed that approximately 60 kilometres of strike slip movement on the Springvale Fault in a sinistral sense initiated during D_1, provided the structural weakness which concentrated later D_3 strain effects. This movement took place on the southern sector of the Springvale Fault, and is translated into left lateral movement of the Osmond Fault across the northern extension of the Halls Creek Fault above the Black Rock Anticline (Fig 3.23). The western section of the Osmond Fault thus becomes the Little Gold Fault, and the western side of the Springvale Fault becomes part of the Greenvale Fault and the sigmoidal fault joining the Greenvale and the Glidden Faults. This large block movement generated compressed and extended areas of crust occupied initially by the Mabel Downs Granodiorite during D_2 (Chapter 5), and later by the Toby Sill emplaced between the Little Gold and Greenvale Faults (syn D_3 or later) and the post tectonic and late metamorphic Bow River Granite (Chapter 5).

Thus movement took place first on the southern branches of major strike slip faults during the Early Proterozoic. These systems then locked up, and further movement occurred north of the Ord River during Later Proterozoic and early Phanerozoic times. This accords with the observation of Plumb (1985) that movement on the major faults in the north of the Halls Creek Mobile Zone was post orogenic. This northern area has been reconstructed into a pre-fault configuration, with the sense of movement suggested by Plumb and Gemuts (1976) and using, for most of the faults, their measured offsets (Fig 3.24). As can be seen, there is remarkably little overlap and very little gap between blocks. These geometric reconstructions accord with the orientation of the stress field at the proposed time of movement, and the relative time of emplacement of the two 'granites' and the Toby Sill, and the measured offsets. However the proposed D_1 movement on the Little Gold and Osmond Faults lacks the metamorphic constraints which apply to the time of movement on the Halls Creek and Woodward Faults.

METAMORPHISM

4.1 Introduction

The polyphase metamorphism in the East Kimberley noted by earlier workers (Dow and Gemuts, 1969, Gemuts 1971) is confirmed by this study, as is the overall areal distribution of low and high grade rocks depicted by them. The rocks outcropping at the surface show, as noted, an increase in grade from greenschist in the south to granulite in the north. The distribution of isograds as previously mapped, has been modified by the present writer, and the area has been further subdivided following more detailed metamorphic mapping. Also addressed in this chapter are two of the problems mentioned in Chapter 1, namely the relationship between deformation and metamorphism, and the geochemistry and petrogenesis of the metamorphic rocks (excluding meta-igneous rocks which are examined in Chapter 5).

4.2 Distribution of Isograds

Dow and Gemuts (1969) subdivided the Halls Creek Mobile Zone into three metamorphic zones. Detailed mapping in the higher grade areas has refined this original work, and six metamorphic zones are now mapped (Fig 4.1). Isograds are defined by metamorphic reactions, and/or the appearance of index minerals, as described in Section 4.4. The granulite/transitional granulite isograd to the west of the syntectonic acid intrusive was mapped by Thornett (in prep.). The positioning of this isograd to the east of the granite is in accord with the work of Neville (1974). The 'sillimanite in' isograd has been repositioned much further south, and this is supported by the work of Hancock (in prep). Dow and Gemuts's zones A and B are otherwise little modified. They note "the biotite zone also contains garnet and staurolite, but the density of sampling is not sufficient to outline zones by the appearance of these minerals." This situation still obtains, and more detailed metamorphic mapping than carried out by the writer in the lower grade areas is required to define almandine, staurolite, and andalusite zones.

Hancock and Rutland (1984) subdivided the Halls Creek Sub-province into four zones which are largely defined on metamorphic grounds. As indicated by Allen (1985), aspects of this sub-division are fundamentally at variance with the work of others as follows :-

(1) Zone IIa (medium grade) encompasses rocks ranging from the greenschist facies / amphibolite facies boundary, up to and including, granulite facies material, as outlined by the metamorphic studies of Gemuts (1971), Neville (1974), Hamlyn (1977), and Allen (1985 and this work).

(2) The mylonite zone which is used to define the boundary between zones IIa and IIc, lies in the middle of the Transitional Granulite Zone defined by metamorphic isograds. There is no grade change across the mylonite (Allen, 1985).

(3) Grade changes within the high-grade areas, where isograds have been defined by metamorphic reactions following accepted practice, are gradational (Gemuts 1971, Allen 1981, Allen 1982a, 1985a, 1985b, Neville 1974, Thornett 1983). There is no "tectonic abutment of very different metamorphic parageneses" within zones II and III. The only faults in the Halls Creek Mobile Zone across which significant grade changes can be demonstrated, are the Halls Creek Fault, and the un-named fault south of the Bow River Fault (Chapter 3).

Thus, the definition of zones I, IIa, and IIc on metamorphic criteria (low, medium, and high grade, respectively), and separated by major faults, is not justified.

4.3 Relationship between Deformation and Metamorphism.

Gemuts (1971) described "more than one period of metamorphism" associated with folding. This relationship is clarified following the recognition of four deformation events as documented in Chapter 3, with associated metamorphism, rather than the two recognised by Dow and Gemuts (1969). Micro-structural studies are used to establish the paragenetic sequence of mineral nucleation and growth with respect to the fabric datum, S_2, (Chapter 3) using overprinting criteria. These studies indicate a number of regional metamorphic events which can be correlated with different deformations (Fig 4.2). Metamorphism probably represents a continuum, commencing syn-tectonically with D_1, and waning progressively later in areas of increasing metamorphic grade. However, physical and chemical parameters, operative at various times during orogenesis, can be gauged from mineral changes which are correlated with the discrete and discontinuous deformation events. These 'mile posts' in the metamorphic history are designated as metamorphic events, M_1, M_2...etc., the micro-structural features of which are described and illustrated below, for metapelites in the high grade areas.

4.3.1 The First Metamorphic Event M_1.

The earliest event, M_1, is recognised by the presence of porphyroblasts with an internal fabric finer grained than, and discontinuous with, the wrapping matrix schistosity, S_2. Minerals of undoubted M_1 generation are not common except as remnant inclusions in later formed minerals. Where the fabric is preserved, these porphyroblasts are poikiloblastic with a rotational internal fabric. As explained and figured in chapter 3, biotite defining the S_1 schistosity is overprinted and obliterated except in the hinges of folds, and as inclusions in later porphyroblasts. No porphyroblasts, or remnants of porphyroblasts of M_1 generation occur in the Black Rock Anticline. Itwas proposed in Chapter 3 that this area was some 90km. further south at greenschist grade during M_1. Fig 4.3 illustrates micro-fabrics developed during the different metamorphic events.

4.3.2 The Second Metamorphic event, M_2.

M_2 is associated with the composite D_{2a} and D_{2b} folding and shearing deformation (see chapter 3), and assemblages formed during these two events are recognised.

4.3.2.1 Metamorphic Event M_{2a}.

During the first phase of D_2 deformation, a new generation of biotite grew axial plane to the D_{2a} folds (chapter 3). This coarse grained M_{2a} biotite wraps pre-existing M_1 porphyroblasts. New M_{2a} porphyroblasts crystallised syntectonic with the development of the S_2 schistosity. As indicated in Fig 4.2, M_{2a} porphyroblasts frequently show a rotational Si continuous with, and the same grain size as, the matrix schistosity, S_2.

4.3.2.2 Metamorphic Event M_{2b}.

The characteristic D_{2b} mylonitic or protomylonitic fabric described in Chapter 3 and Fig 4.2 is sometimes micaceous, depending on distance below the surface, and access to water and volatiles (see later). Tattered shreds of M_{2a} biotite are engulfed in a sea of fine grained muscovite. Fine quartz ribbons sometimes develop (Fig 3.16) defining the mylonitic fabric. Porphyroblasts are rotated, corroded, fractured, and sometimes sheared during the D_{2b} event. Other hydrous phases sometimes crystallise at this stage (Appendix 4).

The continuous (rather than episodic) nature of high temperature metamorphic conditions throughout D_2, is indicated by reference to inclusions in porphyroblasts. Some which have strain-free quartz inclusions in the core, have strained and recryatallised quartz inclusions at the rim. Some porphyroblasts include coarse grained M_{2a} biotite in the core, and mylonitised ragged remnants of biotite near the rim (Appendix 4).

4.3.3 The Metamorphic Event, M_{2c}.

M_{2c} is recognised by the presence of porphyroblasts overgrowing S_2. As indicated in Fig 4.2, these possess features characteristic of the static environment under which they nucleated and grew. They are either new minerals or overgrowths on pre-existing cores, and tend to be inclusion free with euhedral outlines. These M_{2c} minerals are described and figured in Section 4.5.2. Micro-fabrics are illustrated in Fig 4.3. Brief petrographic descriptions of metamorphic rocks are presented in Appendix 4.

4.3.4 The Metamorphic Events, M_3 and M_4.

As can be seen in Fig 4.2, M_3 and M_4 are syn-tectonic with deformation events, and are evident only at the highest grades. While structures and fabrics associated with these deformations (described in Chapter 3) are recognised throughout the Halls Creek Mobile Zone, new metamorphic minerals are not nucleated at this time in lower grade areas. M_3 is recognised by coarse grained prismatic minerals wrapping around M_{2c} overgrowths. Platy minerals do not crystallise at these high grades in the East Kimberley, and thus there is no new schistosity development. M_4 is recognised by the presence of corona textures.

4.4 Tectonothermal History.

The tectonothermal history is presented hereunder for metapelites in the amphibolite facies. For the purposes of this exercise, the Transitional Granulite Zone is here included, and the Low Amphibolite Zone encompasses the upper greenschist facies. No detailed fabric work was done by this author on rocks of the Granulite Zone, which is therefore dealt with briefly for completeness, using reconnaissance observations, and the detailed work of others (Neville, 1974, and Thornett, 1983 and in prep.).

4.4.1 Low Amphibolite Zone.

In the low grade area west of the Halls Creek Fault, the Garden Creek Anticline (Location 1, Fig 4.1) has been described as an isoclinal, overturned, D_1 fold, refolded by D_2 (chapter 3, and Fig 3.19). Both S_1 and S_2 are defined by muscovite-biotite. However, as indicated in Chapter 3, S_1 is the regional schistosity, and S_2 overprints only in the core of the major D_2 structure. No higher grade metamorphic minerals are produced during D_{2a}. The sporadic occurrence of euhedral, and randomly oriented andalusite overgrowing the regional schistosity, which was observed by the author during regional reconaissance in this area, is probably of contact metamorphic origin, associated with granite intrusions. This andalusite is probably analagous to that mapped by Gemuts (1971) in a contact metamorphic aureole around the post-tectonic Bow River Granite to the west of this area (Chapter 5). D_{2b} shearing is probably represented by the wide zone of cataclasis west of the fold structure - the high crustal level equivalent of the ductile mylonite zones in the high grade areas. No folds or crenulations referrable to D_3 were observed in the area. However, E-W faults many kilometres long are widespread, and stanniferous, tantalum-bearing, pegmatite dykes on this azimuth occur to the south and south-west. It is considered that the pegmatite dykes are a late development, related to the granite, infilling pre-existing D_3 fractures. The effect of the upright, compressional fold event, D_4, in these low grade areas, is considered to be steepening, re-orientation, and/or reactivation, of earlier structures, as discussed in Chapter 3. Thus peak metamorphic conditions are pre-D_2 (Fig 4.6), with an estimated maximum temperature of about 400°C for bi-mica schists.

4.4.2 Lower Sillimanite Zone.

Sillimanite is a very common mineral in pelitic rocks throughout the Figs 2.1 and 2.2 map areas. Thus Dow and Gemuts's sillimanite isograd (their zone C) would appear to be positioned some 15 - 20 km too far to the north. Sillimanite formed by a variety of reactions and processes (Allen, 1981, and Section 4.5). Entry to the Lower Sillimanite Zone is defined by the 'sillimanite in' isograd. In this zone, sillimanite is usually fine grained, commonly fibrolitic. Pelitic rocks from Location 2, Fig 4.1, show the following sequence of stable parageneses (illustrated in section 4.5. Also see Appendix 4).

M_1 Garnet and staurolite cores with rotational Si, and staurolite relicts in optical continuity in the core of M_{2a} garnets or plagioclase.

M_{2a} Biotite (S_2 schistosity), syntectonic garnets, and fibrolitic sillimanite generally nucleating on, or replacing, biotite.

M_{2b} Muscovite replacing biotite and fibrolitic sillimanite.

M_{2c} Andalusite and staurolite overgrowing fibrolite. The staurolite nucleates in muscovite, or on biotite or garnet.

There is no widespread metamorphic event after this time in the Lower Sillimanite Zone. Structural effects of D_3 are noted (Fig 3.12) - occasional macroscopic folds, sporadic crenulations, and some large scale faults - but new phases are not nucleated at this grade during D_3. D_4 crenulations are more widespread (Chapter 3), but there is no regionally developed S_4 schistosity. In Lower Sillimanite Zone rocks, micas crenulated in this event have their strains "frozen in" with no evidence of polygonization or recovery (Fig 4.3). This, however, gives no indication of prevailing temperatures. It has been found experimentally (Etheridge and Hobbs, 1974, and Tullis, 1976) that the kinetics of strain induced recrystallisation of phlogopite and biotite are very slow, even at temperatures close to the melting point.

Temperatures obtained from garnet - biotite pairs from samples in the Lower Sillimanite Zone are consistently too low to represent peak metamorphic conditions within the sillimanite stability field. These minerals are considered to have re-equilibrated at lower temperatures ($<500^{o}C$), and to represent conditions during D_{2c} ie. within the andalusite stability field. (Selected microprobe analyses of co-existing garnet-biotite pairs are tabulated in Appendix 4b. Geothermometric calculations are presented on microfiche). Hamlyn (1977) estimated re-equilibration conditions within the Panton Sill as $550^{o}C$. This estimate is deduced from stability fields of co-existing minerals on a petrogenetic grid. It is taken as being representative of peak metamorphic conditions in the Lower Sillimanite Zone. The thermal history of rocks from the different metamorphic zones is illustrated in Fig 4.4.

Down grade from the 'sillimanite in' isograd, in the un-mapped almandine - staurolite - andalusite zone in the Panton River area, M_{2a} andalusite, partly including M_1 garnets, has been observed. Rotational inclusion trails are preserved even though the andalusite is completely pseudomorphed by M_{2b} muscovite. These relationships possibly account for the observation (Hancock and Rutland, 1984) attributed to "Gemuts, 1971; Neville, 1974; and Allen, in prep." that in Zone 11a, "D_1 and D_2 deformations occured at similar high grade in the andalusite-staurolite to sillimanite zones". However, in none of the areas above the 'sillimanite in' isograd mapped by Allen does the situation as quoted above obtain, nor does she perceive it at low grade, but only in the narrow grade interval in the low amphibolite facies (intermediate between the Low Amphibolite Zone and the Lower Sillimanite Zone of Fig 4.4). Neville (1974) mapped the Granulite

Facies isograd in the Corkwood Bore area, and Gemuts mapped two deformations with associated metamorphism from greenschist to granulite facies in the area designated as Zone 11a.

4.4.3 Upper Sillimanite Zone.

Fig 4.5 illustrates parageneses stable at different times during orogenesis, from samples from various metamorphic zones in the Figs 2.1 and 2.2 map areas. In the Upper Sillimanite Zone (Location 3, Fig 4.2) effects of D_3 become more obvious, as described and figured in Chapter 3. The metamorphic effect at this grade is the maintenance of higher temperatures than in lower grade metamorphic zones, until a later period in the deformation history. Migmatites become common, with coarse grained biotite defining selvedges of leucosomes. The knotted schists have a strong S_2, with garnet porphyroblasts up to 1 cm. in diameter, and well defined sillimanite. Thin sections of pelitic rocks from this area frequently show two generations of sillimanite; the earlier fine grained and syntectonic with D_{2a}, and a later, coarser grained sillimanite replacing the S_2 biotite (Appendix 4). There is no development of retrograde mineral phases overgrowing S_2 (as in the Lower Sillimanite Zone). Peak metamorphic temperatures of 600-650°C were registered during M_{2c} (Fig 4.4 and Appendix 4b). There is no obvious metamorphic effect of D_4 at this grade, and no new schistosity is developed.

In the previous chapter metamorphic equivalence during F_{2a} of the Panton River area with the east of the Black Rock Anticline is noted. Almandine staurolite grade of the amphibolite facies is recorded. The west of the Black Rock Anticline attained higher grades in the upper amphibolite facies later in its history, which is appropriate to its present location in the Upper Sillimanite Zone (Appendix 4b. Specimens from the Black Rock Anticline are marked with a cross. The garnets are zoned, with almandine enrichment at the rim, and the lower temperatures register rim-garnet/biotite blocking temperatures during cooling). These observations form one of the critical pieces of evidence on which reconstruction of the pre D_{2b} configuration is based, by restoration along the Halls Creek and Woodward Faults (Chapter 3 and Fig 3.22).

4.4.4 Transitional Granulite Zone.

Cordierite is a very unusual phase at amphibolite grade in the East Kimberley. Although consciously sought in the field, it was never found, except at high grades well into the Upper Sillimanite Zone. Of hundreds of rocks thin sectioned for this study, seven only contain cordierite. No cordierite was identified by Hancock from samples from the low - mid amphibolite facies. Ogasawara reported cordierite in the migmatitic rocks west of 'Dougals Tonalite', a pluton west of Dougals Bore. Gemuts reported "The Mabel Downs Granodiorite masses north of the Ord River are surrounded by cordierite rich rocks with only a little sillimanite and garnet". This observation was not confirmed in the area mapped and sampled in detail by the author, and Neville (1974) reported the "absence of cordierite" in the area mapped by him at Corkwood Bore. Cordierite is, however, more abundant in granulite facies rocks west of the Great Northern Highway and north of the Ord River to Turkey Creek (Fig 1.1), as reported by Gemuts, and confirmed by the present author and Thornett (1983). Consequently the 'cordierite in' isograd in metapelites is used to define entry into the 'Transitional Granulite Zone' in the East Kimberley.

Garnet-cordierite-sillimanite gneisses (Location 4, Fig 4.1) contain no biotite except as remnant inclusions, and no other hydrous minerals. Potassium contents are very low. These gneisses are interpreted as restites after migration of H_2O and K+ into early minimum melts (see section 4.5). Thus metamorphic conditions at D_{2a} are estimated to be a minimum of 650°C and 4 kb. Further garnet growth occurs during D_{2c}, overgrowing the cordierite and sillimanite. A later generation of coarse grained sillimanite sometimes develops, and this can be observed to be wrapping the D_{2c} garnet overgrowths. This provides evidence of a further, high grade, metamorphic event, syntectonic with D_3. Coarse grained porphyroblastic perthitic K-felspar -sillimanite gneisses also appear in this zone. Coronas around cordierite of a simplectite of quartz-sillimanite and granular magnetite are considered to represent M_4 fabrics (Appendix 4).

Fe/Mg exchange geothermometry on metapelites from this area (Garnet-Cordierite pairs) registers temperatures of around 500°C. This is considered to be due to iron migration out of the cordierite (see below) and to be representative of M_4 cooling temperatures, indicating uplift of the southern block relative to the north during D_3, as discussed in Chapter 3. Shear heating probably represents one component of the high temperatures responsible for M_3 peak metamorphism in the Transitional Granulite Zone.

In the lower strain area west of the Mabel Downs Granodiorite, Thornett (1983) has estimated a metamorphic grade of 710°C and 4 kb. during the D_3 metamorphic peak in the Transitional Granulite Zone in this area (Location 5, Fig 4.1).

4.4.5 Granulite Zone.

Thornett (1983, and pers.comm.) uses a biotite - consuming - melt - formation reaction as a zone marker. He demarkates entry into the granulite zone west of the Mabel Downs Granodiorite (Location 6, Fig 4.1) by the reaction :-

$$\text{bio + cord + qtz} \rightarrow \text{gt + K-spar + melt} \qquad (1)$$

This reaction differs from the one proposed for entry into the Transitional Granulite Zone, in that cordierite appears on the product side of the equation at the lower grade (Section 4.5) rather than as a reactant in the equation above. In two pyroxene granulites, hornblende, which is ubiquitous in the Transitional Granulite Zone to the west, disappears in the Granulite Zone in the East. Thornett (1983) estimated peak metamorphic grade at 800°C and 5.5 kb. Neville (1974) also estimated temperatures of 800°C in the granulite facies rocks east of the Mabel Downs Granodiorite (Location 7, Fig 4.1), where two pyroxene granulites and charnockitic granite have been recorded, and which lies well within Dow and Gemuts's Zone C (high grade). Hancock and Rutland (1984) have mapped this as Zone 11a (medium grade). They have also indicated peak metamorphic conditions at 3-5 kb. and 500-600°C during D_2 metamorphism, and only 400°C during D_3 in Zones 11 and 111, in contrast to the foregoing.

4.5 Petrogenesis of the Metamorphic Rocks.

The physical and chemical conditions operative during the metamorphic events described above (section 4.3) are deduced from phase relationships. Textural evidence, supported by mineral and rock chemistry is used to determine the metamorphic reactions involved, and the prevailing chemical environment. Sillimanite (which, as mentioned, occurs commonly in metapelites throughout the map areas) is involved in many reactions both as reactant and product. These reactions are examined and used as the basis for determining the parameters controlling metamorphism, which imposes constraints on the tectonic framework.

4.5.1 Sillimanite Formation Reactions.

Sillimanite formed by at least seven different reactions in the Halls Creek Mobile Zone. These involve staurolite breakdown, reactions involving biotite as a reactant, also the pseudomorphic replacement of andalusite, the 'muscovite-out' reaction at high grade, and late stage, post tectonic precipitation from intergranular fluids.

4.5.1.1 Staurolite Breakdown Reactions.

Sillimanite formed by two reactions involving the breakdown of staurolite.

A. Fig 4.6 illustrates the reaction

$$\text{Staur} + \text{Qtz} \rightarrow \text{Alm} + \text{Sill} + H_2O \qquad (2)$$

The photomicrographs show thin sections of rocks from widely separated areas. The zoned M_2 garnets display an inner staurolite inclusion zone and an outer sillimanite inclusion zone. Many M_2 garnets have staurolite inclusions, and quartz inclusions are common. However, where inclusions of both occur in the same garnet, they are observed never to share a common boundary. The inference is that the reaction is arrested by depletion of staurolite in immediate contact with quartz.

This reaction has been experimentally performed and reversed in the Mg-free system (Richardson, 1968). It is probably the most frequently cited staurolite breakdown reaction. However, rarely are the reported occurrences accompanied by textural supporting evidence. Of this oft quoted reaction, Chinner (1965) states "the frequency of its invocation seems to be due more to the elegance of its simplicity than to any indications of its occurrence." Kwak (1974) also doubted its occurrence and concluded it to be "a theoretical expedient to balance hypothetical reaction".

However, this reaction (equation 2) is considered to occur quite commonly in the East Kimberley. An AFM plot (Thompson, 1976) of rocks showing evidence of this reaction (Fig 4.7) illustrates the Fe rich nature of all the phases involved, and suggests that perhaps this reaction only occurs in very Fe rich metapelites. A compositional plot of all analysed metapelites from the East Kimberley (Fig 4.8) shows the Fe rich nature of the province. (This was commented upon in

Chapter 2, and will be referred to again in Chapter 6). The staurolite bearing rocks in particular are Fe rich and Mg poor compared with an average shale and an average greywacke. A statistical analysis (Fig 4.9) of the FeO:MgO ratios of staurolite bearing schists from other metamorphic belts indicates the unusually Fe rich nature of these Kimberley rocks. Staurolite occurs in two of Miyashiro's (1973) three facies series, and is a reasonably common metamorphic mineral at intermediate grades. So also is cordierite, which, as has been pointed out, appears to be absent in the East Kimberley until much higher grades. This is related to the anomalously high Fe and low Mg content of these rocks. Cordierite can accomodate more Mg in its structure than staurolite. There is very limited substitution of Mg for Fe in tetrahedral coordination in staurolite. While bulk rock Fe content may exert the controlling chemical influence on staurolite formation and stability, it is not the only variable, or one would expect to encounter this reaction in metamorphosed B.I.F's. Al content is also important in staurolite - sillimanite bearing rocks. The precursor sediments necessary for this reaction (Equation 2) to take place are probably very Fe rich, alkali poor, aluminous metapelites.

This examination of the chemistry of the metasediments and the mineral phases involved in Equation 2, suggest that these have a restricted and unusual compositional range, which may explain the occurence of this reaction in the Halls Creek Mobile Zone, and its virtual absence elsewhere.

B. Fig 4.12 illustrates the second staurolite breakdown reaction.

$$\text{Staur } (+\ \text{Ca}_{2+}/\text{Na}_{+}) \rightarrow \text{Plag} + \text{Sill} + \text{Op} \qquad (3)$$

Similar reactions have been described and figured previously by many authors, eg Westra 1969, and Kwak 1974. Kwak suggests that they "seem to be particularly common at high temperatures but relatively low pressures". (These are the Temperature/Pressure conditions proposed herein for the Halls Creek Mobile Zone - see later). The excess aluminium from the breakdown of staurolite to plagioclase has presumably migrated away from the immediate vicinity, and formed some of the M_{2a} sillimanite which is ubiquitously associated with this reaction. (This is contrary to Carmichael's (1969) constant aluminium postulate. Negative evidence for this hypothesis has also been presented by Anderson and Burnham, 1983). While this would appear to be a reasonable assumption, there is no unequivocal evidence that any of the M_{2a} sillimanite has in fact formed from this reaction. (The sillimanite needles in contact with plagioclase, nucleating along grain boundaries, are a later phenomenon and are described anon). Kwak (op.cit.) indicates that biotite has sometimes formed as a product of a staurolite to plagioclase breakdown reaction, but there is no textural evidence for this in the Kimberley rocks. There is always, however, a concentration of metamorphic opaques (ilmenite - see facing page) within the reaction texture, and this, it is suggested, accounts for the excess Fe and Ti on the product side of this reaction. Clusters of minute staurolites have been observed nucleating on plagioclase grain boundaries during M_{2c}. This could possibly be the reverse of the staurolite breakdown reaction cited above.

On the basis of some dozens of staurolite analyses (see Appendix 7), East Kimberley staurolites do not appear to be particularly zinc rich. However, in staurolite breakdown reactions, the fate of Zn is of interest because very little of this element is present in rock forming silicates, except for staurolite. In the absence of specifically zincian minerals (eg gahnite and sphalerite) in these Kimberley rocks, an unusually high concentration of zinc might be expected to 'fingerprint' a 'non-zincian' product phase of staurolite breakdown. Consequently, minerals in the immediate vicinity of reacting staurolite were analysed for zinc (Fig 4.11). No such high concentrations were found. Apparently all nearby phases were saturated with the small amounts which can be accomodated in normal silicates and oxides. Interestingly, this element appears to have been released by its hosts and made available for M_{2c} staurolite in concentrations similar to that in M_1 staurolite.

Textural evidence for this reaction (Equation 3) is quite commonly seen in thin sections which show evidence also of Equation 2. Garnet - biotite pairs of M_{2a} generation were analysed in an attempt to determine a reaction temperature (Fig 4.12). The results, while internally consistent, are unacceptably low. It is believed that the temperatures recorded are cooling temperatures, as discussed in an earlier section.

4.5.1.2 Reactant Biotite.

Three sillimanite producing reactions which occur in metapelites from the Halls Creek Mobile Zone involve biotite as a reactant.

A. Fig 4.13 illustrates the replacement of biotite by sillimanite.

$$\text{Bio} \rightarrow \text{Sill} + \text{Op} + H_2O + K+ \qquad (4)$$

The constant association of biotite and sillimanite has been much commented upon, debate being centered on whether textures are better interpreted as epitaxial nucleation or replacement. Allen (1977) has commented on the excellent lattice fit of the two minerals. Both octahedra and tetrahedra substitute with good lattice registry, particularly along the b axis of biotite and the c axis of sillimanite. Given this ease of fit, the association is not surprising, and it would seem that there is no need to preclude either method of sillimanite formation. In fact, both nucleation on biotite and replacement of biotite appear to be very common, frequently even in the same thin section. Chinner, 1961, and Harte and Johnson, 1969, described sillimanite needles arranged at angles of 60 or 120 degrees to one another in the cleavage planes of biotite (as in Fig 4.13), the orientation of the sillimanite needles being controlled by the lattice structure of the biotite. They interpreted this regular arrangement as resulting from epitaxial nucleation of the sillimanite in the biotite. However in the example figured (Fig 4.13), many of the individual sillimanite prisms have their own cladding of ilmenite. It would seem reasonable to infer that the Fe and Ti probably came from the local source within the reaction texture, ie. biotite. Thus breakdown of biotite is indicated. The release of potassium presents no problem, as potassium is a highly mobile element during metamorphism, and de-alkalization of biotite is common in hydrothermal alteration, and even in the weathering process. At higher grades, Losert (1968) considers de-alkalization responsible for the formation of quartz-sillimanite nodules, and Eugster (1970) sees migmatites with which these rocks are frequently associated as a possible K^+ sink.

B. Fig 4.16 illustrates the M_{2a} assemblage

Cord - Gt - Sill (+ Opaques)

The cordierite bearing rocks presently under discussion are those from the 'Transitional Granulite Zone' in the Fig 2.1 map area. These rocks are sporadically distributed in this high grade area, contained in pelitic lithologies. They are intimately associated with migmatites, leucogranite, and the Mabel Downs Granodiorite. The mineralogy is unusual in that biotite is virtually absent, K-spar is absent, and cordierite occurs accompanied by large (and in some specimens very abundant) metamorphic opaques (generally magnetite).

The sequence of stable parageneses is shown in Fig 4.5, and mineral compositions plotted in Fig 4.15. Brief thin section descriptions appear in Appendix 4 and microprobe analyses in Appendix 7. This mineralogy reflects the high iron and very low alkali shown in Fig 4.8. (Note that specimen 784B contains some leucosome). These rocks are a little more magnesian than most Kimberley metapelites. The rare biotite occurs as coarse grained inclusions in garnet, and in the matrix in small amounts as corroded remnants. Garnet cores show fine grained rounded quartz inclusions surrounded by a zone of sillimanite inclusions which is continuous with matrix sillimanite in some cases, and in others, separated from the latter by an inclusion free rim. Sometimes garnet rims include cordierite but never vice versa. In the more iron rich of these rocks, magnetite is included in garnet, and in the matrix magnetite sometimes includes sillimanite. None of these rocks show obvious effects of D_{2b} shearing. Peak metamorphic assemblages show the effects of retrograde metamorphism. Cordierite is surrounded by coronas of quartz-sillimanite simplectite withgranular magnetite.

It is here proposed that the M_{2a} assemblage cord-gt-sill-op formed by the breakdown of biotite, K^+ and H_2O being involved in the formation of leucogranite and tonalite, leaving a relatively dehydrated and alkali poor restite. Harris (1976), discussing assemblages in Northern Ontario, came to a similar conclusion, viz "gneisses containing garnet and/or cordierite are in fact restites from semi-pelitic sediment which have lost potassium and an aqueous phase to a granite liquid." The timing is consistent with the formation of these anatectic melts (Chapter 5) as is the field association. Ashworth and Chinner (1978) observed that "cordierite and garnet are common in migmatites adjoining Caledonian (sensu lato) synorogenic intrusions in the Highlands of Scotland." The formation of the relatively Mg rich phase cordierite is counterbalanced by the crystallisation of metamorphic opaques, leaving the bulk rock FeO : MgO ratio relatively undisturbed. It is however likely that some migration of Fe and Mg ions into the melts took place. The leucogranite commonly crystallises garnet or clots of biotite, and small amounts of magnetite are ubiquitous in the three leucogranite variants (see Chapter 5), and the tonalite contains biotite and hornblende.

The breakdown of biotite and formation of cordierite may be represented by the equation:-

Bio + Fels -> Gt + Cord + Sill + Op + Melt (5)

As indicated, Fe/Mg exchange geothermometry determinations on Gt-Cord pairs (Thompson, 1976) register a post crystallisation cooling temperature of 466 - 506°C (Appendix 7). These minerals were carefully examined to determine the geometry and mechanism of ionic migration. Garnet textural zoning (Figs 4.3, 4.6, 4.10, 4.14) has quite sharp boundaries. However, analyses of garnets (and cordierite) with an electron microprobe (Appendix 7) failed to detect consistent chemical zoning patterns from core to rim (cf. Tracey et al, 1976). A scanning electon microscope was set up in a mode to display atomic number differences, ie using back scattered electrons and low vacuum on polished thin sections (Robinson and Robinson, 1978). The atomic number difference between Mg and Fe is sufficient for differences in percentage of these two elements to be visually obvious in this mode. Random inhomogeneity on a very fine scale was revealed, associated with micro-fractures in garnets from specimens 960 and 804 which were examined in this fashion (Fig 4.16). These extremely fine hair-line fractures would be sufficient to facilitate the post crystallization differential migration of Fe and Mg ions, homogenizing any gross core to rim zonation resulting from temperature differences during crystallization. Garnet composition, however, cannot be held responsible for the low temperatures recorded in these garnet-cordierite rocks. Pyrope contents are higher than in garnets from lower grade areas, and are appropriate to the Transitional Granulite Zone (Fig 4.17). When these garnet compositions are substituted for others which yielded the same temperature, in K_D determinations with biotite, the new temperature is at least 100°C higher, and generally much more. The problem must, therefore, lie in the cordierite composition, which (if Thompson's Gt-Cord geothermometer is reliable) is overly Mg rich to yield results within an acceptable temperature range. It is considered that Fe from the cordierite migrated into the symplectite corona, where it crystallized as granular aggregates of magnetite, rather than across the grain boundary into the garnet, exchanging lattice sites with Mg. Thus the relative Mg enrichment in the cordierite is due to Fe depletion by migration out of the exchange system. It is also possible in these magnetite rich rocks, that compositions have been partly controlled by oxygen fugacity (Chinner 1960, Wones and Eugster 1965, Hounslow and Moore 1967, Hsu 1968, Reinhardt 1968, Muller and Schneider 1971), and only partly grade controlled and temperature related.

C. Fig 4.18 illustrates the third method of sillimanite formation involving biotite as a reactant.

$$\text{Bio} \rightarrow \text{Plag} \rightarrow \text{Sill} \qquad (6)$$

M_{2a} biotite defining S_2 is replacd by sillimanite (as described in sub-section A) and concurrently embayed by plagioclase. The plagioclase occurs as inclusions in optical continuity in later sillimanite porphyroblasts. There are thus two generations of sillimanite -

(1) fine grained replacing S_2 biotite.

(2) coarse grained porphyroblasts which crystallized in the static post D_{2a} period, and which include plagioclase remnants. (Two generations of sillimanite are quite common in Kimberley metapelites of the Upper Sillimanite Zone, and sometimes there are three generations in the Transitional Granulite Zone).

Biotite is commonly corroded and replaced by plagioclase. This texture has long been recognised and was described by Tozer in 1955. Carmichael (1969) suggests the following reaction -

$$\text{Bio} + \text{Na}^+ + 6\text{H}^+ \rightarrow \text{Ab} + \text{K}^+ + 3(\text{Mg,Fe})^{2+} + 4\text{H}_2\text{O} \qquad (7)$$

The reaction -

$$\text{Bio} + 5\text{Al}^{3+} + 3\text{H}_2\text{O} \rightarrow 3\text{Sill} + \text{K}^+ + 3(\text{Mg,Fe})^{2+} + 8\text{H}^+ \qquad (8)$$

has been written by Carmichael (op cit) to describe the replacement of biotite by sillimanite. Assuming that biotite is being corroded by both reactions simultaneously (and the texture certainly allows of this interpretation), the nett reaction is -

$$2\text{Bio} + 5\text{Al}^{3+} + \text{Na}^+ \rightarrow 3\text{Sill} + \text{Ab} + 2\text{K}^+ + 6(\text{Mg,Fe})^{2+} + 2\text{H}^+ + \text{H}_2\text{O}$$

The breakdown of albite to sillimanite may be represented by the following equation -

$$2\text{Ab} + 2\text{H}^+ \rightarrow \text{Sill} + 5\text{SiO}_2 + 2\text{Na}^+ + \text{H}_2\text{O} \qquad (10)$$

(The plagioclase is more calcic than this being in the oligoclase-andesine range, but has been represented as albite for simplicity). This composite texture has been described by Allen (1977) in Kanmantoo rocks, the aluminosilicate in this case being andalusite. The reverse reaction to the above, ie. And -> Fels, has also been documented by Allen (op cit) and recognised by Chinner (pers comm).

Metamorphic reactions involving ionic species are inherently attractive. The relatively high mobility of many ions eg. Mg, Fe, and Al as well as the alkalis at upper amphibolite grade is probably generally accepted, and may better represent the path metamorphic reactions actually take, than reactions involving molecular species only. While all major components are accounted for in the proposed scheme, the reactions may not take precisely the above form (equations 6,7,8,and 9) or that exact path. For example, Chinner (1961) writes an equation for the replacement of biotite by fibrolite using a more aluminous biotite composition, thus :-

$$(OH)_8K_4Fe_5Al_8Si_{10}O_{40} \rightarrow 4Al_2SiO_5+10SiO_2+(H_8K_4Mg_4Fe_5O_8) \quad (11)$$

"Carmichael - type" multistage ionic reactons are of dubious merit if textural evidence of intermediate stages is lacking. The major objection to equations (8),(9), and (10) is that they are oxidation/reduction reactions. While there are certainly carbonaceous schists in the immediate vicinity, oxygen is a highly immobile element in metamorphism, and it is doubted that the rock has been subjected to fluctuating conditions of oxygen fugacity as the reactions imply. However, Vernon (1979) has proposed regional hydrogen metasomatism in the Cooma area.

4.5.1.3 Pseudomorphic Replacement of Andalusite.

Fig 4.19 illustrates the polymorphic inversion of andalusite to sillimanite. This specimen is a mineralised carbonaceous schist from the Eileen Bore Prospect, east of Alice Downs Station (Fig 1.1), and south of Fig 2.2. This is an area of extensive alluvium characterised by a strong geophysical anomaly. Two generations of basic intrusives have been identified (Allen, 1980), the latter carrying sub-economic nickel mineralization. The specimen figured shows euhedral M_1 andalusite pseudomorphed by sillimanite of M_2 generation, which is corroded around the edges, and sometimes completely replaced by M_{2b} muscovite. Chromiferous chlorite chrystallized during M_{2c}.

In regional metamorphic terranes, sillimanite rarely forms by direct phase transformation of andalusite (Miyashiro, 1973). In the Kimberley, this prograde texture has been found in this one specimen only, although there are many pseudomorphs in three thin sections cut perpendicular to each other. Although also rare in the Adelaide Fold Belt, South Australia, a similar polymorphic replacement of andalusite by sillimanite has been described and figured from Kanmantoo metapelites (Mills,1968; and Mancktelow, 1979).

4.5.1.4 Late Stage Grain Boundary Nucleation.

Fig 4.20 illustrates the crystallization of late stage fibrolitic sillimanite. Vernon and Flood (1977) using micro-structural criteria, distinguished two fibrolite associations -

(1) "harmonious", the fibrolite being in metamorphic compatibility with other minerals (Vernon,1975), and

(2) "disharmonious", the fibrolite displaying grain boundary disequilibrium. This is interpreted as nucleation of fibrolite after final grain boundary positioning (Vernon, 1979).

In Kimberley metapelites, all fibrolite previously discussed (4.5.1.1 - 3) belongs to the first category. The fibrolite nucleating on grain boundaries illustrated in Fig 4.20 represents the second category. In this thesis, no distinction is made between fibrolite and coarse grained sillimanite. The two morphological forms have been shown to be mineralogically identical (Cameron and Ashworth,1972). Also, Allen (1977) could find in Kanmantoo metasediments in the

Adelaide Fold Belt no specific association between sillimanite morphology and bulk rock chemistry or mineralogy, temperature or pressure conditions, or tectonically induced strain environment during crystallization. Thus, the two terms are used to refer to 'end member' morphological types only, and carry no grade or genetic connotation. For instance, the Lower Sillimanite Zone is defined by the occurrence of retrograde D_{2c} minerals, and not by sillimanite morphology. Coarse grained sillimanite occurs in this zone, as well as fibrolite, although finer grain size is generally more common at lower grades¶.

Grain boundary fibrolitic sillimanite is widespread throughout the mapped areas, and Thornett (pers.comm.) reports that it is common in the granulite facies area around the Sally Malay Prospect. It clearly postdates the M_{2c} assemblages in the Lower Sillimanite Zone (eg. it nucleates on M_{2c} staurolite), and the M_4 assemblages in the Transitional Granulite Zone. It is considered to have crystallized during waning temperatures after complete grain boundary equilibration. In granulite and upper amphibolite facies rocks, this could still be at higher temperatures than the sillimanite/andalusite univariant curve. However, in rocks where the M_{2c} assemblages are andalusite - staurolite, the fibrolite is considered to have nucleated metastably outside the sillimanite stability field. The alternative is a late stage rise in temperature, taking the rocks once again into the sillimanite stability field, but there is neither field nor laboratory evidence to support such an hypothesis. Vernon (1979) also suggests metastable nucleation of fibrolite in the andalusite stabiity field, and considers that this is related to the kinetics of nucleation of the respective polymorphs.

Vernon (op. cit.) suggests that late stage fibrolite in the Cooma region formed by regional hydrogen metasomatism, with breakdown of cordierite as the source of hydrogen ions. He proposes base leaching reactions, analogous to argillic hydrothermal alteration, as the mechanism of fibrolite formation, with Al_2SiO_5 components introduced from elsewhere. In the Kimberley, the fibrolite is considered to be locally derived by exsolution from aluminium rich minerals out of equilibrium with a fluid phase, at temperatures of around 400°C in the Lower Sillimanite Zone, although in the Granulite Zone crystallization temperatures could be considerably higher. The proposed fluid containing Al^{3+} ions and SiO_2 as a volatile species (either $Si(OH)_4$ or $SiO_2.nH_2O$) migrates along grain boundaries, and precipitates fibrolite on high energy nucleation sites as the kinetically favourable Al_2SiO_5 polymorph.

The various lines of evidence on which the above conclusion is based are presented hereunder :-

(1) The late stage fibrolite is not homogeneously distibuted between rock types, being most common in metapelites, and non-existent in immediately adjacent marbles and amphibolites.

(2) The needles of fibrolite nucleate preferentially on felspar grain boundaries in rocks of semi-pelitic composition.

(3) In aluminous metapelites, grain boundary fibrolite is very abundant, and nucleates on any and all grain boundaries including felspar, quartz, garnet, staurolite, muscovite, and biotite.

(4) The individual fibrolite fibres are very fine and short, and are not perceived as occupying, in toto, any great volume. This last observation makes it unnecessary to postulate introduction of components, and the association with particular minerals in specific lithologies suggests a local source.

Thus, although the phenomenon of late stage grain boundary sillimanite as described from the Cooma area (Vernon, 1979) occurs also in the Kimberley, the source of ions, and the mechanism of formation, are perceived as fundamentally different.
Also, while much of the cordierite in Kanmantoo metasediments of the Adelaide Fold Belt is pinitized, grain boundary fibrolite was not seen

by the author or reported by others, in this area. This association of pinitised cordierite and grain boundary fibrolite in the Cooma area does not seem to apply in the Kimberley, nor in the Kanmantoo.

4.5.1.5 Muscovite breakdown

The classical "muscovite-out" reaction is schematically shown by the equation -

$$\text{Musc} + \text{Qtz} \rightarrow \text{K-spar} + \text{Sill} + H_2O \qquad (11)$$

In the mapped areas there is no textural evidence of this reaction. In some rocks (from the southern, low grade area) muscovite interleaved with biotite defines S_2 in bi-mica schists. In areas affected by D_{2b} shearing, muscovite is common and generally easily recognised as M_{2b} generation. In higher grade areas muscovite is generally absent. K-spar occurs sporadically as ovoid porphyroblasts elongate along the schistosity. Micro-textural relationships indicate that it is of M_{2a} generation, partly wrapped by and partly including the biotite which forms the S_2 schistosity. Sillimanite is frequently included. In the Corkwood area (north of Sally Malay bore - Fig 1.1) Neville (1974) has described 'streaky felsic lenses' in microcline gneiss. The lenses consist of transposed rootless folds which parallel the regional schistosity. Both the gneiss and the lenses contain microcline which is described as elongate, anhedral and defining a weak schistosity. It is thus also interpreted here as M_{2a}. Muscovite is not included in any mineral assemblages in his zone C (granulite), which includes the above lithologies. The lack of muscovite and abundant sillimanite in most K-spar bearing peraluminous schists and gneisses at high metamorphic grade is considered to be generically related, and Equation 11 applies.

In some rocks, K-spar coexists with garnet (Fig 4.21) and it is possible that, although plentiful biotite and sillimanite remains, the following reaction was operative in these rocks --

$$\text{Bio} + \text{Sill} \rightarrow \text{Gt} + \text{Microcline} + \text{V} \qquad (12)$$

In some specimens, fine grained biotite and sillimanite occur as inclusions in very coarse grained perthite (as do small garnets). However, there is no definite textural indication of the reactants involved in the formation of K-spar.

The sill-K-spar isograd had been mapped variously at the amphibolite-granulite facies boundary (Thompson and Norton, 1968) and within the amphibolite facies (Mills 1964, Ono 1969). As Miyashiro (op. cit) points out, the equation --

$$\text{Musc} + \text{Qtz} \rightarrow \text{K-spar} + \text{Sill} + H_2O \qquad (13)$$

if Na content of muscovite and K-spar is taken into account, is more closely akin to --

$$\text{Musc} + \text{Qtz} + \text{Plag} \rightarrow \text{K-spar} + \text{Sill} + \text{more calcic Plag} + H_2O \ (14)$$

This continuous reaction probably occurs over a range of temperatures. Also, Powell (1983) has indicated that "internal buffering during incipient partial melting may lead to substantial lowering of a_{H2O} before ....a melting step." This variation in a_{H2O} could be partly responsible for the sporadic distribution of rocks showing evidence of melting (cord-gt-sill gneisses, and migmatitic, myrmikitic, and microcline perthite bearing gneisses), and the above-mentioned variations in the position of the K-spar - sill isograd in the field. In the Kimberley, incipient melting conditions have been inferred (Section 4.5.1.2 B, and Equation 5) in the north of the mapped areas, and the K-spar - sill isograd is most appropriately positioned coincident with the Upper Sillimanite - Transitional Granulite Zone boundary (Fig 4.1).

4.5.1.6 The Sillimanite Isograd

In the Halls Creek Mobile Zone sillimanite forms by a number of different reactions as documented above. There is no a priori reason to suppose that these reactions all take place at the same temperature. In fact, there is reason to believe they occur over a range of temperatures, at least 100°C and probably >150°C. Thus 'sillimanite in' doesn't represent an isograd in the sense that it parallels an isotherm. Considering the reaction —

$$\text{Staur} + \text{Qtz} \rightarrow \text{Alm} + \text{Sill} + H_2O \qquad (2)$$

M_1 staurolite has variable proportions of Zn. The temperature of this reaction increases with increasing Zn content and it seems probable that the reaction does not take place at all except under quite unusual conditions of bulk rock chemistry. Considering the reaction —

$$\text{Bio} \rightarrow \text{Sill} + \text{Ilm} + K^+ + H_2O \qquad (4)$$

this is the most common method of sillimanite formation in the Kimberleys, also in the Kanmantoo, (South Australia) and perhaps in general. This reaction produces fine grained fibrolite to coarse sillimanite spanning the temperature range from the Lower Sillimanite Zone to the Upper Sillimanite Zone (550 - 650°C. Fig 4.6). The reaction by which biotite is broken down to sillimanite with plagioclase as an intermediate stage (Eq^n 6) has been documented in Kanmantoo rocks, with andalusite rather than sillimanite as the product (Allen, 1977). Given the low entropies involved, polymorphic inversion from andalusite to sillimanite is generally considered to occur sluggishly, involving temperature overstepping of the equilibrium boundary. The formation of late stage grain boundary sillimanite is, to an extent, independent of temperature and more closely related to the composition of the intergranular fluid. Thus, within the range of metapelite composition, some sillimanite producing reactions take place in rocks of varying chemistry at fairly specific temperatures. Others occur only in rocks of very restricted chemistry within a small range of temperatures. Others again, take place over a relatively wide range of temperatures, in rocks of a wide range of chemistry. The practice of mapping a sillimanite isograd with spotty fibrolite occurrences downgrade, and a sill-K-spar isograd at higher grade acknowledges that a range of temperatures is involved in sillimanite formation reactions.

4.5.2 Sillimanite Breakdown Reactions

A possible sillimanite breakdown reaction has been discussed in relation to the formation of K-spar at high metamorphic grade (section 4.5.1.5) where incipient melting is inferred just below the Granulite Zone. The textures do not permit of high levels of confidence in this interpretation of sillimanite breakdown, and more extensive mapping and sampling needs to be done north of the mapped areas. Sillimanite abundance certainly decreases upgrade in the Granulite Zone, but there may well be, and probably are, other reactions which are also involved in its disappearance.

Down grade in the Lower Sillimanite Zone, as has been mentioned, in areas which show evidence of D_{2b} shearing, M_{2a} sillimanite is frequently replaced by muscovite. This is best explained as an increase of f_{H2O} and a_{K+} (Eugster, 1970) consequent on the ingress of water and other volatiles along the faults and shear planes. This interpretation is supported by the frequent synchronous crystallisation of tourmaline. D_{2b} occurred after peak metamorphic temperatures were reached, and prior to the formation of the lower grade M_{2c} assemblages (Fig 4.4), thus the temperature was already falling at the time of this event. However, metamorphic grade is seen as one determinant in the formation of M_{2b} muscovite, the others being the chemical parameters mentioned above. Fig 4.22 illustrates sillimanite breakdown during D_{2b}.

M_{2c} assemblages, while retrograde with respect to M_{2a}, could be viewed as prograde with respect to M_{2b} hydrous assemblages, specifically muscovite. (However, as indicated, temperature is only one of the controlling variables during D_{2b}). Parageneses attributable to this event are widespread in the Lower Sillimanite Zone (Fig 4.23). M_{2c} minerals are characteristically randomly oriented, inclusion free, and develop euhedral outlines, indicating slow growth in a static environment. The higher temperature alumino-silicate polymorph became unstable as temperatures dropped below the sillimanite stability field. Fine grained andalusite overgrows M_{2a} sillimanite. Staurolite, which is consumed during M_{2a}, is produced during M_{2c}. Tiny euhedral staurolites nucleate generally on M_{2a} biotite, also on M_{2a} garnet, or in a matrix of fine grained intergrown muscovite of M_{2b} generation. M_{2c} staurolite has also been observed nucleating in felspar grain boundaries, and along micro-fractures in coarse grained sillimanite. The source of Fe for staurolite formation is assumed to be corroded biotite, where it is not directly attributable to its ferromagnesian host. Most frequently these abundant M_{2c} staurolites overgrow sillimanite in peraluminous metapelites. Thus aluminium is readily available. No staurolite has been observed as overgrowths on earlier staurolite at temperatures higher than the 'sillimanite in' isograd. This texture is common at lower grades in the Kanmantoo, South Australia, and has been observed by the author in specimens from lower grade areas in both the East and West Kimberley. Most of the remnant

M_1 staurolite is totally included in product grains at higher grade. Thus, in the Lower Sillimanite Zone, M_{2c} is clearly a retrograde event. Not only is there inversion to the lower temperature aluminosilicate polymorph, but parageneses are consistently lower grade than in M_{2a}.

The foregoing discussions of the relationship between deformation and metamorphism, the tectono-thermal history, and the petrogenesis of the metamorphic rocks, have been confined mainly to rocks of pelitic composition. These provide more revealing fabric studies at amphibolite grade than rocks of other chemical composition. Prograde metamorphic minerals occuring in metabasic and calcareous rocks, in the mapped metamorphic zones are tabulated in Fig 4.24. As can be seen, these are appropriate to the metamorphic grade. The only unusual mineral occurence is wollastonite, which is found not only throughout the Upper Sillimanite Zone and the Transitional Granulite Zone, but also in the Granulite Zone. The significance of this is discussed in section 4.6.

4.6 Geothermal Gradients and Pressure/Temperature/Time Paths.

The Halls Creek Mobile Zone is a high temperature / low pressure terrain. The mineralogical evidence is constrained by geothermometry, and less well by geobarometry. Kyanite has been reported in the East Kimberley from only one small area with anomalous metamorphic grade (sillimanite overgrown by kyanite in the Lower Sillimanite Zone). The lack of kyanite, coupled with the occurrence of wollastonite in marbles in granulite facies rocks, east and west of the Mabel Downs Granodiorite (Neville 1974, and Thornett 1983) is indicative of a low pressure regime (Fig 4.25). The maximum recorded temperature of 800°C and only 5.5 kb. indicates that the Halls Creek Mobile Zone developed an abnormally high geothermal gradient during orogenesis.

Sources of information on PTt paths (England and Richardson, 1977) in the East Kimberley come from the different types of metamorphic reaction described above, the direction of the temperature change recorded, and the relative chronology.

(1) Discontinuous reaction indicated by remnant inclusions of one phase in a product mineral: eg.

(i) staur to gt and sill

M_1 M_2 with increasing temperature.

Upper and Lower Sillimanite Zones.

(ii) cord to gt and sill

M_2 M_3 with increasing temperature.

and cord to qtz/sill and mag

M_3 M_4 with decreasing temperature.

Transitional Granulite Zone.

(2) Continuous reaction indicated by zonation in garnet.

pyrope rich cores and almandine rich rims.

M_3 M_4 with decreasing temperature.

Upper Sillimanite and Transitional Granulite Zones.

(3) Reactions related to introduction of a fluid and formation of a hydrous phase (eg. musc) which is not itself indicative of grade, but preserves pre-existing and later phases.

sill to musc to andal and staur

M_{2a} M_{2c} with decreasing temperature.

Lower Sillimanite Zone.

Thus PTt paths have been derived (Fig 4.25), which are partly schematic due to paucity of geobarometric information except in the Granulite and Transitional Granulite Zones. However, the clockwise trajectory is believed to be an accurate representation of the situation, and the geothermal gradients are believed to be approximately the correct shape, allowing geologically reasonable error bars of about 50°C and 2kb.

IGNEOUS ROCKS.

5.1 Introduction.

Igneous rocks both extrusive and intrusive crop out extensively in the Halls Creek Mobile Zone (Figs 2.1, 2.2, and 5.1). Much of the stratigraphic sequence (Fig 2.4) consists of extrusive rocks, the four formations of the Halls Creek Group being aptly described as 'alternately volcanic and sedimentary' (Thom, 1975). As described in Chapter 2, thick sequences of pillow basalts occur in the Ding Dong Downs Volcanics, and in the Biscay Formation in all four units, being particularly widespread in Units 1 and 2, where they are interbedded with acid volcanics of the 'Wills Creek Suite'. Ignimbritic rocks of the 'Corkwood East Suite' in Units 1 and 2, and the 'Alkaline Suite' in Unit 3 of the Biscay Formation, are in places tens of metres thick, while the voluminous Whitewater Volcanics have an estimated thickness of "up to 3,500 metres" (Plumb, 1985). It is presumed that there is a high volcaniclastic component in some of the metasediments, the unconsolidated acid volcanic debris probably contributing source material.

Intrusive rocks obliterate much of the stratigraphy especially at high grades (Figs 4.21 and 5.1). This is Dow and Gemuts's Lamboo Complex (Fig 1.2). Magmatic material intrudes as extensive sills of pre-tectonic Woodward Dolerite (Chapter 2), differentiated basic and ultrabasic lopoliths up to 30 km. in diameter (see frontispiece where two of these, the Toby Sill and the smaller McIntosh Sill are clearly discernable), variably foliated irregular gabbroids and gabbro/granite breccias, or as late, mineralised, basic bodies (eg. in the Sally Malay Prospect area). 'Granitic' bodies range from small stocks to the elongate foliated Mabel Downs Granodiorite (Figs 2.1 and 5.1), and extensive sheets of late Bow River Granite (seen in the frontis piece with characteristic jointed outcrop pattern). Thus the Halls Creek province is essentially a volcano-plutonic terrain.

The Lamboo Complex is defined as "the igneous and high grade metamorphic rocks of the Halls Creek Mobile Zone" (Dow and Gemuts, 1969). Fig 5.1 illustrates the extensive areal outcrop of intrusive rocks, and as indicated above, and illustrated in Fig 5.2, these plutonic rocks were intruded throughout the tectonic history of the area. Metamorphic grade changes in the Halls Creek Mobile Zone represent a diachronous continuum (Chapter 4). Because of these difficulties in demarcating the Lamboo Complex in time, temperature, or space, within either the Halls Creek Mobile Zone, or the King Leopold Mobile Zone, and difficulties in correlation between the mobile zones (Chapter 6), the term 'Lamboo Complex' is discarded. While this concept was helpful in describing the broad picture in this little known fold belt, more detailed work renders its continued use unnecessary and confusing. Igneous rocks are referred to by their mineralogical, textural, and chemical affinities.

In this chapter, two of the fundamental problems mentioned in Chapter 1 are addressed, namely 'the time of formation and emplacement of igneous bodies relative to structural events and metamorphic grades in the vicinity', and 'the chemistry and petrogenesis of extrusive rocks as they relate to tectonic processes'.

5.2 Intrusive Rocks.

The tectonothermal history of intrusive bodies is examined here to assess their tectonic significance and their contribution to the total heat budget. With the exception of a hitherto un-recognised leucogranite, only a few selected granite samples have been analysed. Detailed geochemistry of suites of samples, and examination of crystallization controls has not been attempted.

5.2.1 Acid Intrusive Rocks.

Dow and Gemuts (1969) mapped five 'granites' in the Halls Creek

Mobile Zone.

(1) Mabel Downs Granodiorite

(2) Sophie Downs Granite

(3) Bow River Granite

(4) Violet Valley Tonalite

(5) Mc.Hales Granodiorite

The two late acid intrusives (4 and 5) were not examined by the author, nor by Ogasawara nor Hancock, and hence are referred to very briefly for completeness only. The contact relationships of the Sophie Downs Granite are mapped and described by Hancock (in prep.). The geochemistry and petrogenesis of the Sophie Downs Granite, and a pluton south of the Ord River, ('Sally Downs Tonalite' - see below) will be presented elsewhere (Ogasawara, in prep.), along with preliminary petrology and geochemistry of the Bow River Granite, and some West Kimberley 'granites'.

5.2.1.1 Mabel Downs Granodiorite

The main body of Mabel Downs Granodiorite crops out as an elongate pluton west of the Halls Creek Fault and north of the Ord River (Figs 2.1 and 5.1). It is mapped on Fig 4.1 as 'Syn-tectonic Acid Intrusives' and shows the regional NNE trend of the fold belt. This batholith and the granitoids in its vicinity consist of a number of discrete 'granite' types. They are all foliated with a quite well developed S_2 schistosity, and were intruded over a range of time either pre-dating or syn-tectonic with D_2. Their distribution and contact relationships (as well as the mineralogy and texture by which they are differentiated) are illustrated in Figs. 5.1, 5.3, 5.4, and 5.5, and briefly described under the following informal names -

(a) the type Mabel Downs Granodiorite.

(b) 'Black Rock Tonalite'

(c) 'Sally Downs Tonalite'

(d) 'Melon Patch Granite'

(e) 'White Rock Leucogranite'

(a) Mabel Downs Granodiorite

The main phase of the Mabel Downs Granodiorite, in its type area north of the Ord River, is a medium to coarse grained, foliated, porphyritic, hornblende-rich tonalite. The foliation parallels the strong regional schistosity, S_2. Contacts with the country rock are variably conformable, migmatitic, faulted or intrusive. It is rich in xenoliths, particularly around the southern edges of the main pluton. The great majority of xenoliths are Woodward Dolerite, which largely replaces the base of the Olympio Formation in this location (Chapter 2). The Mabel Downs Granodiorite intrudes the 'Melon Patch Granite' and the 'White Rock Leucogranite'. It cross cuts D_{2a} folds, is folded by D_3 and refolded by D_4 (with, in places, its swarms of mafic schleiren). Xenoliths of uralitised gabbro are in places so profuse as to form a granite-gabbro breccia. East of the main pluton, this granitoid includes a xenolith of basic intrusive, with quartz-feldspar veins folded by D_{2a} and garnets wrapped by S_2. However in one place an apophesis is folded by D_{2a}. In the north and east this granitoid is charnockitic (Dow and Gemuts, 1969 and Neville, 1974). The orthopyroxene probably replaced hornblende during M_3. A mineralogically distinct phase of the Mabel Downs Granodiorite is a K-spar megacrystic granite. It is similar in appearance to the major phase of the Bow River Granite, however it is foliated, the megacrysts are elongate along the fabric, and contacts with the hornblende-bearing phase are gradational. The Mabel Downs Granodiorite appears to have crystallised and been emplaced in the waning stages of D_2 . The fabric is partly superimposed and partly an emplacement fabric.

(b) 'Black Rock Tonalite'.

This is a very coarse grained porphyritic biotite hornblende tonalite. It has a very limited distribution, being restricted to the Black Rock Anticline and its immediate western environs. In the Black Rock Anticline it crops out as elongate concordant bodies along the western margin, and also in the core of the major fold just south of the Ord River (Figs 2.2 and 5.1). It has an S_2 schistosity, and a well developed L_2 elongation lineation defined by biotite and amphibole respectively. It is considered by both Allen and Hancock to be an early 'granite' clearly pre-dating D_{2a} (Fig 5.2). At the time of intrusion the Black Rock Anticline is considered to have been nearly 100 kilo-metres south of its present location (Chapters 3 and 4), and the 'Black Rock Tonalite' may be completely unrelated to the Mabel Downs Granodiorite. This distinction tends to be supported by the very limited geochemistry (Appendix 5).

(c) 'Sally Downs Tonalite'

The small triangular stock south of the Ord River is a foliated porphyritic biotite hornblende tonalite. It is less coarse grained, and the foliation less well developed than the 'Black Rock Tonalite'. The fabric is concordant with that in the country rock, of which large rafts are enclosed (eg. a thick marble horizon from Unit 1 of the Olympio Formation - Chapter 2). Also included are xenoliths of uralitised gabbro. The 'Sally Downs Tonalite' has been mapped and analysed in great detail by Ogasawara (in prep.), who considers that the fabric is an emplacement fabric, and contends that it is a post-tectonic granitoid. However, recent work on the geochronology (Chapter 6) indicates that the isotopic age obtained by Ogasawara could now be interpreted as syn tectonic. The similarity of mineralogy and texture, and the close spatial relationship to the Mabel Downs Granodiorite suggest this small stock is part of the larger pluton. Mabel Downs Granodiorite crops out widely along strike to the southwest (Fig 5.1) in the Melon Patch Bore area. The fabric, also, is strikingly similar.

Aerial photographs clearly show the schistosity, concordant with the regional S_2, folded by D_3 and refolded by D_4 (Fig 3.16). The northern tip of the pluton is truncated by a vertical, E-W, dextral fault of D_3 generation.

(d) 'Melon Patch Granite'

This granitoid crops out in the Melon Patch Bore area where it was first recognised. It is a fine to medium even grained, biotite-rich granite. It is strongly foliated and rich in xenoliths (mostly mafic, however a xenolith of 'White Rock Leucogranite' has been observed) which are generally elongate along the schistosity. The S_2 fabric is continuous with the fabric in the xenoliths, and is considered to have been superimposed on both. South of the main pluton of Mabel Downs Granodiorite, veins of 'Melon Patch Granite' have been isoclinally folded by D_{2a} with the development of axial plane S_2 schistosity. The folded veins have been cross cut by Mabel Downs Granodiorite. According to Dow and Gemuts (1969) the Mabel Downs Granodiorite "grades from a central zone of foliated coarsely porphyritic hornblende rich tonalite and granodiorite ... to a marginal zone of saccharoidal, medium grained gneissic granodiorite or granite containing biotite rich schleiren." This latter is the 'Melon Patch Granite' described above, however contacts are not gradational but intrusive.

(e) 'White Rock Leucogranite'

The SE portion of the main body of Mabel Downs Granodiorite (Figs 2.1 and 5.1) consists of leucogranite here termed 'White Rock Leucogranite', from the White Rock Bore area where it was first recognised. The main pluton of Mabel Downs Granodiorite is faulted against it (Fig 2.1) and includes the leucogranite as rare xenoliths. A small body of this leucogranite crops out to the SSW with the Ord

River swinging north around it (Fig 2.2). The rock is white, or buff, massive, and xenolith poor. It is very quartz and feldspar (plagioclase and microcline) rich (approx 90%), with grains and aggregates of quartz standing out in relief on the weathered surface. It is locally garnetiferous, with few subhedral almandine garnets up to 6mm diameter. There are two slightly more mafic variants. Both are biotite bearing (up to 10%) one with thin films of fine biotite indicating complex refolding, and the other with scattered clots of biotite, up to 20 mm diameter, flattened in the S_2 schistosity. All variants are muscovite bearing, and small amounts of magnetite are ubiquitous. The well defined S_2 in the small pluton south of the Ord River can be clearly seen on aerial photographs to be folded by D_3 and refolded by D_4. There is textural evidence of extensive deformation and re-crystallisation. Although they have somewhat different field expression, the geochemistry is very similar, and in particular the trace element abundances are virtually indistinguishable (Fig 5.6). The 'White Rock Leucogranite' is perceived as the result of an M_{2a} fractional melt episode, leaving gt-cord-sill gneiss restites in the Transitional Granulite Zone (Chapter 4).

Thus, the Mabel Downs Granodiorite consists of a number of mineralogically and chemically distinct species. The 'Black Rock Tonalite' may be completely unrelated to the 'granites' which comprise the major pluton. Metamorphic and geochemical indications suggest that one species at least, the 'White Rock Leucogranite', is of anatectic origin. The other three phases, the type Mabel Downs Granodiorite, 'Sally Downs Tonalite', and the 'Melon Patch Granite' have similarities eg. abundance of xenoliths, which suggest that they may be regarded as a composite batholith. They were intruded as a series of magmatic pulses over a small time interval syntectonic with D_{2a}.

5.2.1.2 Sophie Downs Granite

This granite is texturally distinctly different from any of the other granites in the Halls Creek Mobile Zone. It has been described as granophyric, with grains of microperthite and quartz commonly forming graphic intergrowths (Dow and Gemuts, 1969). A small pluton west of the Saunders Creek Dome (Figs 1.1 and 5.1), with the western margin sheared by the Halls Creek Fault, forms the total outcrop of this granite. Outcrops in the Mc.Clintock Range and Cummins Range areas mapped as Sophie Downs Granite are thought by Ogasawara (on petrological and geochemical grounds) to be unrelated to the Sophie Downs Granite, and to be a variant of the late Bow River Granite. This view is supported by the presence of metamorphic aureoles surrounding these plutons (see below - Section 5.2.1.3).

There is some uncertainty about the time of intrusion of the Sophie Downs Granite. Ogasawara considers it a late, probably post tectonic, granite (pers. comm.). Hancock (1985) considers it a "post D_2 granitoid dome...whose geometry reflects a rigid substrate prior to D_2", and suggests a "pre-D_2 granitoid core". His detailed structural mapping, supported by a re-examination of the pluton and contact relationships in the field, suggest to the present author that the Sophie Downs Granite is in fact the rigid body which pre-dates D_2 folding. Gemuts (1971) describes the Biscay formation country rocks as having a crenulated cleavage with spongy andalusite and garnet with "inclusion trails which are not crenulated", and post crenulation chlorite. The pre D_2 intrusion age proposed above (Fig 5.2) is appropriate to this sequence of metamorphic parageneses. Peak metamorphism in this area is M_{2a} (Chapter 4). The retrograde chlorite overgrowing the crenulated schistosity suggests that the intrusion cannot be later than D_2.

5.2.1.3 Bow River Granite

The Bow River Granite is a linear batholith 400 km. long and 32 km. wide, along the west of the Halls Creek Mobile Zone. (Fig 4.1, where it is mapped with (4) and (5) as 'Post-tectonic Acid Intrusives', and Fig 5.1). The Bow River Granite embraces a number of intrusions, as described by Dow and Gemuts (1969), and Gemuts (1971). These range from granites to granodiorites, from leuco-cratic to melanocratic, and texturally from coarse grained porphyritic, to fine grained even textured. Plumb (1985) considers that "detailed mapping...could almost certainly differentiate the Bow River Batholith into a complex of separate intrusions". The dominant and characteristic phase, homogeneous over large areas, is a porphyritic granite which consists of tabular to ovoid K-fels megacrysts, up to 5 cm. in diameter in a fine grained groundmass of quartz, plagioclase, and biotite. Aplite is sporadically developed around the margins, and swarms of tourmaline rich pegmatite dykes extend into the country rock.

At the margins of the granite, the megacrysts commonly outline a primary flow foliation. Three different types of contact relationship have been observed ; faulted, stoped and migmatitic. The Bow River Granite is a late or post-tectonic intrusion, generally massive, but foliated and sometimes mylonitized in shear zones. Contact metamorphic effects have been mapped in the south of the Halls Creek Mobile Zone by Gemuts (1971). The Bow River Granite is considered to shallowly underlie a considerable area to the east of its mapped extent in the Cummins Range and Mc.Clintock Range areas in the south of the fold belt. Scattered outcrops in these areas, mapped as Sophie Downs Granite, are considered to be more probably Bow River Granite, for the following reasons:-

(1) Randomly oriented, euhedral, andalusite was observed by the author overgrowing the schistosity in the Cummins Range area,

associated with these granite outcrops. It is considered to be contact metamorphic in origin, analogous to that described by Gemuts in Olympio Formation rocks abutting the Bow River Granite to the west.

(2) The tourmaline rich pegmatite dykes (tin/tantalite or tin/columbite bearing in these areas) are analogous to the tourmaline pegmatite dykes associated with Bow River Granite near Mabel Downs Homestead and north of Palm Creek. No tourmaline pegmatites are associated with the Sophie Downs Granite in its type area. Scattered andalusite overgrows the schistosity in biotite schists adjacent to the pegmatites in the Cummins Range and Mc.Clintock Range area.

(3) Ogasawara (pers. comm.) considers the petrology and geochemistry to be more closely related to the Bow River Granite than to the Sophie Downs Granite.

5.2.1.4 Violet Valley Tonalite

The Violet Valley Tonalite intrudes Mabel Downs Granodiorite and Bow River Granite 10 km. northwest of Mabel Downs Homestead. It also intrudes an inlier of Olympio Fm. meta-sediments southwest of the Bow River Granite (Fig 5.1). It is massive and non-foliated. It is considered to be a post tectonic intrusion (Dow and Gemuts, 1969).

5.2.1.5 Mc.Hale Granodiorite

The Mc.Hale Granodiorite intrudes metasediments in the Osmond Range area, east of the Halls Creek Fault and 16 km. further north along the fault. It has been suggested that this granodiorite is contemporaneous with the Violet Valley Tonalite (Dow and Gemuts, 1969).

5.2.2 Basic and Ultrabasic Intrusive Rocks.

Differentiated basic sills, with or without ultrabasic segregations comprise one of the most voluminous rock types in the

Halls Creek sub-province, constituting about a quarter of the outcrop. The basic intrusives have been subdivided by Dow and Gemuts into three categories :-

(1) Woodward Dolerite,

(2) Alice Downs Ultrabasics (of which the Panton Sill is the major body), and

(3) McIntosh gabbro.

The geochemistry of the Woodward Dolerite is examined with the basalts in this study (Section 5.3). The chemistry and petrology of the McIntosh Sill have been reported by Hamlyn in 1977, and of the Panton Sill by the same author in greater detail in 1977, 1979, and 1980. The intrusive rocks in the Sally Malay Prospect are described by Thornett (1981, and in prep.), and similar rocks of equivalent age in the Corkwood Prospect by Neville (1974).

The petrology, field distribution, intrusive and age relationships, and thermal history, of rocks mapped under the umbrella of the three categories above, are described, further delineated and compared. The purpose is to establish their tectonic significance, and their influence on the thermal regime, and the northward migrating metamorphic peak. Detailed mapping and geochemistry with the aim of unravelling the complexities in the basic intrusive rocks throughout the fold belt is beyond the scope of this work.

5.2.2.1 Woodward Dolerite.

The Woodward Dolerite comprises basic sills and dykes up to 20 km. long, and 600 metres thick. They are generally intruded as sills, but in places cross cutting contacts are noted, and considerable thicknesses of the stratigraphy are obliterated. Chilled margins, while generally not well developed, have been observed up to 7 metres wide (Dow and Gemuts, 1979). The texture ranges from fine grained and massive to vesicular, coarse grained and porphyritic. The coarsest grained variety has feldspars up to 40mm long. They are tholeiitic (as are the basalts - Section 5.3) and variably fractionated to feldspar accumulative dolerites and gabbroids.

Woodward Dolerite was previously considered to be restricted to the low grade areas, and in general, to the top of the Biscay Formation (Gemuts, 1971). It can now be shown to intrude all units of the Biscay Formation (Figs 2.1 and 2.2), and the lower two units of the Olympio Formation, as described in Chapter 2. It is recognisable in rocks of all metamorphic grade from greenschist to granulite facies (Allen, 1981). However, as noted in Chapter 2, the Woodward Dolerite is not uniformly distributed at all stratigraphic levels. While it is widespread throughout the Biscay Formation, it has its major development at the base of Unit 1 of the Olympio Formation, and there are further thick sills at the base of Unit 2. The tectonic significance of the stratigraphic control on distribution of the Woodward Dolerite is discussed in Chapter 6.

The Woodward Dolerite has long been known as a pre-tectonic intrusion. Dow and Gemuts (1969) state that it "was intruded before the formation of the Tickalara Metamorphics." Their "complexly folded" dykes in the Lamboo area (one of which has a restored amplitude of some 15 kilometres), are here interpreted as D_1 folds refolded by D_2. The dolerite has undergone all the phases of deformation and metamorphism which affect the country rock. It is frequently completely reconstituted, but the least altered rocks have a relict ophitic texture. Hancock and Rutland (1984) proposed syndepositional emplacement close to the sediment water interface.

5.2.2.2 Alice Downs Ultrabasics.

The Panton Sill is a layered intrusion with a lower ultra-mafic cumulate zone, originally of harzburgite, dunite, and chromitite

(Hamlyn, 1977), separated from an overlying gabbroic zone by a sheared contact. The basal contact is strongly sheared; the contact with the overlying metasediments is exposed in the core. The sill is a 1 kilometre thick lensoid body, which has been folded into a southerly plunging syncline (Dow and Gemuts, 1969). Hamlyn's map of the Panton Sill shows an hypophysis on the western margin which has been folded and refolded (probably by D_{2a} and D_4). It has been truncated by NW - SE trending left lateral faults. While this sense of movement on this azimuth is appropriate to either the earlier or the later stress fields (Chapter 3), these faults do not affect the later crystallizing Mc.Intosh Sill a few kilometres east (see below), and are presumed to have been active during D_1.

The primary igneous mineralogy has been extensively serpentised and uralitized during metamorphism. Hamlyn (1977) has estimated primary magmatic equilibration at a depth of 25-30 kilometres, at 800-1100°C and 8-9 kb. After emplacement at higher crustal levels, the rocks were re-equilibrated (along with the enclosing metasediments) at 550°C and 4-6 kb, in the Lower Sillimanite Zone (Chapter 4). Metamorphic peak in this area is M_{2a}. The structural and metamorphic evidence presented above suggests an emplacement time of pre D_2. It is suggested that strike slip movement on the Woodward and Halls Creek Faults after D_1 (Chapter 3) facilitated the vertical emplacement of this body, as in the "lemon-pip" model of Lensen (1958).

This emplacement of the Panton Sill into higher crustal levels, and subsequent re-equilibration at lower pressures during metamorphism, forms one of the fundamental pieces of evidence on which Hancock and Rutland (1984) erect their hypothesis of over thrusting from the northwest. However an alternative hypothesis is proposed of strike slip and vertical tectonics, which seems to fit the available data better than a stack of low angle imbricate thrust sheets.

5.2.2.3 Mc.Intosh Gabbro.

Bodies mapped under the umbrella of the Mc.Intosh Gabbro include the large (30 km. across and 1.5 km. thick) layered Toby Sill, the smaller layered Mc.Intosh Sill, the composite Armanda Sill, the mafic and ultramafic complexes in the Sally Malay Prospect and Corkwood Prospect areas, and various other irregular bodies which intrude the metasediments, or occur commonly as roof pendants in the Bow River Granite. These bodies were intruded over a wide interval of time, as evidenced by their different states of preservation of igneous mineralogy and texture.

The Mc.Intosh and Toby sills are rhythmically layered, preserve primary igneous mineralogy and texture throughout most of their thickness, but are uralitized at their faulted contacts. The Mc.Intosh Sill has been folded into a basin by D_4 (Allen, 1985a), but apart from the sheared margins, it has a weak metamorphic overprint, which could be equated with M_{2c}. It postdates the strong peak metamorphic event (M_{2a}) in this Lower Sillimanite Zone (Chapter 4). It is suggested that it was emplaced syn-tectonically with the D_{2b} movement on the Halls Creek Mobile Zone, adjoining its eastern margin (Figs 5.1 and 5.2). This stike slip displacement is illustrated in Chapter 3.

The Armanda Sill is a composite intrusion with coarse grained uralitized gabbros in the core, surrounded by altered dolerites, and intruded by quartz felspar porphyry. The porphyry is in turn intruded, along with the gabbro, by medium to coarse grained granite and granodiorite. Gemuts (1971) has mapped a core region folded into a shallow basin, with steep dips radiating away from the core on the margin of the intrusion. The contacts are sheared, and the northern margin is truncated by dextral ENE trending faults, which also affect the granite.The altered dolerite is interpreted as the thick Woodward Dolerite at the base of the Olympio Formation. The porphyry and the granite are of unknown affinity. The evidence of extensive alteration and deformation suggest that this is an early intrusion, possibly syntectonic with the Panton Sill, and with a similar mode of emplacement.

The Sally Malay composite intrusion (Thornett, 1981) consists of a post D_3 mineralized layered intrusion, enclosed within granulite facies paramigmatites and mafic granulites (here interpreted as Woodward Dolerite - Chapter 2), intruded by a younger norite suite. Similar, smaller, sub-economic, Cu-Ni occurrences are recognised in gabbroic rocks of the Mc.Intosh Gabbro eg. the Corkwood Prospect (Neville, 1974), the Eileen Bore Prospect (Chapter 4), and various other small prospects described in unpublished company reports.

Granite/gabbro breccias outcrop over quite extensive areas in the East Kimberley. The largest areas relate to intrusion of gabbroic material of unknown affinity by Bow River Granite. However, the Mabel Downs Granodiorite also includes uralitised gabbroic xenoliths, particularly around the southern margin, which can attain proportions approximately equal to the granite. This basic material has been interpreted (Section 5.2.1.1) as Woodward Dolerite, on the grounds that the granite intrudes close to the base of Unit 1 of the Olympio Formation. This regional unconformity is heavily invaded by Woodward Dolerite.

5.3. Extrusive Rocks.

The chemistry of the extrusive rocks, both acidic and basic, in the stratigraphic sequence is examined in this section. The purpose is to present the geochemistry of the bi-modal volcanic rocks of the Biscay Formation from high grade areas in the East Kimberley, described in Chapter 2 (the 'Wills Creek Suite' and the 'Corkwood East Suite' of Units 1 and 2, and metabasalts from Units 3 and 4), and to examine their relationship to volcanic rocks in low grade areas. These latter include not only other volcanic rocks of the Biscay

Formation, but also samples of the Ding Dong Downs Volcanics and the Whitewater Volcanics. These data are compared and contrasted with the geochemistry of modern volcanic suites, and other Proterozoic suites, to provide constraints on a tectonic model. The discussion on crystallization controls is not intended to be exhaustive.

5.3.1 Treatment of Geochemical Data-Significance and Limitations.

The Halls Creek Mobile Zone is a Proterozoic tectonothermal province. All samples have suffered some degree of alteration. All, except the post-orogenic Whitewater Volcanics, have been subjected to multiple deformation, and metamorphosed to lesser or greater extent, (but see Chapter 6 for deformation of the Whitewater Volcanics in the King Leopold Mobile Zone). The proposed I.U.G.S. Classification of Volcanic Rocks has been adopted in this study. It is stressed (Le Maitre, 1984) that the classification is designed for "fresh volcanic rocks" and that it "should not be used with analyses of rocks that have been weathered, altered, metasomatised, metamorphosed or have undergone crystal accumulation." The author accepts the onus of justification for use of data obtained from altered and metamorphosed rocks. This justification applies not only to the use of this classification, but more importantly, to the use of the geochemical data to make comparisons and draw genetic conclusions. The issue is important in view of the widespread belief that ionic mobility during any of the alteration processes mentioned above renders use of such analyses highly questionable, if not completely spurious. It is here maintained that even in an area of highly deformed and metamorphosed rocks, meaningful data can be obtained and valid genetic conclusions drawn.

In the Kimberleys, original lithology can generally be identified with a high degree of confidence. Good stratigraphic control enables the geochemistry of different suites of volcanics

(Chapter 2) to be compared both across strike and for tens of kilometres along strike. Thus there is good control on which geochemical characteristics are primary (a fundamental property of the parent magma), and which secondary (alteration due to weathering, diagenesis, or subsequent metamorphism). It appears from studies in this area, and is perhaps generally applicable, that provided major chemical alteration has not occured at low temperatures, the rocks retain their primary chemical characteristics at least to granulite facies, and metamorphism is generally isochemical.

Biscay basalts were collected from the lower greenschist facies (chlorite grade) to the upper amphibolite facies (sillimanite grade). As can be seen in a later section, they group tightly together as an easily identifiable population. Even for the highly mobile elements, reasonable patterns of element migration can be inferred, although the immobile element plots carry greater conviction. On the other hand, the Ding Dong Downs Volcanics have suffered low temperature alteration and are highly spilitised (Fig 5.6), with increased levels of total alkalis. The effect of alteration and metamorphism has been gauged (in addition to the check for internal consistency described above) by comparison with the field of Cainozoic volcanics. This Cainozoic field (delimited by Giles, 1980) contains representatives from a range of tectonic settings (see supplementary reference list). Where significant differences exist between fields or trends of Cainozoic felsic volcanics from different tectonic settings, the bulk sample is separated and augmented with recent data. Significant departures from the Cainozoic field have been checked, for the felsic volcanics, against little altered post-orogenic Proterozoic volcanics from other provinces in Australia, and for the basalts, with Palaeozoic basalts from the same area, and Proterozoic basalts from other provinces both in Australia and elsewhere. Basalt geochemistry has also been plotted on various discriminant diagrams using data from a range of recognised tectonic settings. This procedure isolates variation specific to a particular province or time and assists in placing constraints on different tectonic models.

5.3.2 Bulk Rock Chemistry

As indicated above, and in Chapter 2, large volumes of acid and basic magmas were extruded throughout the depositional and thermal history of the Halls Creek Mobile zone. However, there is a striking paucity of samples with intermediate SiO_2 levels (Fig 5.7). The great majority of the samples fall either within the basalt field (the spilitized basalts of the Ding Dong Downs Volcanics are not plotted on this diagram), or within the rhyolite or dacite fields, six only registering as andesites. Of these, five samples come from the post orogenic Whitewater Volcanics. Andesites have not been reported from this area by other workers, and their virtual absence is not considered to be an artifact of the sampling process. Thus the Halls Creek Mobile Zone has a bimodal chemical signature which is indicative of an extensional regime, and which characterises many Proterozoic terrains both in Australia and elsewhere (Chapter 6).

Differentiation trends are also distinctly different for the two rock suites (basic and acidic). The felsic volcanics display calc alkaline affinities, while the basalts follow iron enrichment trends which are characteristically tholeiitic. This is the classic calc-alkaline-tholeiite association of Condie (1982). The Peacock index indicates that these rocks belong to the calc-alkaline series. SiO_2 content at the intersection of the alkali and lime differentiation trends is 58%-59% (Fig 5.6) On an AFM diagram, Kimberley felsic volcanics plot, in general, within the calc-alkaline field, with little of the iron enrichment which characterises the tholeiite series (above solid line, Fig 5.8). The rocks do, however, show higher total iron contents than the Cascade lavas (dotted line). The iron rich nature of the Kimberley province has been commented on in Chapter 2 with respect to the development of B.I.F., and in Chapter 4 with respect to the abundance of iron rich phases in metamorphic rocks (also see Allen, 1982). It is also apparent in geochemistry of acid and basic volcanic rocks.

The more immobile trace element plot (Figs 5.8, and 5.9) provides support for the AFM plot. There is little TiO_2 enrichment which characterises a tholeiite series in the felsic volcanics. The basalts, however, follow a typical tholeiite trend. Therefore, the felsic volcanic rocks and basic volcanic rocks are considered separately below.

5.3.3 Felsic Volcanic Rock Suites.

Eruption of felsic volcanic rocks (ie. rocks with felspar as a major component) spans the time interval from the deposition of the oldest rocks outcropping in the area (the Ding Dong Downs Volcanics) to eruption of the late and post tectonic Whitewater Volcanics. Photographs and photomicrographs of rocks from the five different volcanic suites appear in Chapter 2, with the general description of the field relationships and petrography. Brief thin section descriptions of the analysed rocks are presented in Appendix 1. Geochemical data appear in Appendix 5.

Ding Dong Downs Volcanics

Felsic tuffs of the Ding Dong Downs Volcanics were collected from the Saunders Creek Dome. The samples were weathered, (six only being considered fresh enough to be analysed) deformed, and metamorphosed to greenschist facies. They were sampled from the top two of the three felsic tuff units interbedded with basalts which together comprise the known Ding Dong Downs Volcanics.

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Biscay Formation

The lower two units of the Biscay Formation contain felsic volcanics of the 'Wills Creek Suite' and the 'Corkwood East Suite'. These units were sampled in the Upper and Lower Sillimanite Zone (Fig 4.1) of the Halls Creek Mobile Zones. Unit 3 contains the rhyolites and associated tuffs of the 'Alkaline Suite'. These appear to be restricted to the low grade 'hot spot' area.

Olympio Formation

Felsic volcanics were not seen in the course of this study, nor have they been reported elsewhere, from the Olympio Formation in the Halls Creek Mobile Zone. In the East Kimberley, as mentioned in Chapter 2, Unit 2 of the Olympio Formation appears to lack the local volcanogenic component of this unit in the West Kimberley, and the tuffaceous Unit 3 is not exposed. Two specimens from the upper unit of the Olympio Formation in the West Kimberley have been analysed (WK 10 and WK 11 - Appendix 2,).

MgO, MnO, CaO, TiO_2 and P_2O_5 decrease with increasing silica content, while alkalis increase (Fig 5.8).

Al_2O_3

These Kimberley volcanics show the typical calc-alkaline spread in Al_2O_3 contents of the less evolved (more basic) rocks (Fig 5.8 A). Values in general lie within the calc-alkaline field, with the Whitewater Volcanics registering values on the low side of the range throughout all silica levels.

FeO^t

Total iron correlates negatively with SiO_2 (Fig 5.8 B). The high values already commented upon are particularly marked for the Whitewater Volcanics and the Ding Dong Downs Volcanics. Thus there is no apparent correlation between higher iron values and time of eruption within the Kimberley province for the felsic volcanic rocks, in contrast to the situation with the basalts (see later). This trend towards high iron values at all silica levels (as opposed to iron enrichment) is typical of Proterozoic acid volcanics. Fig 5.6 C shows iron contents of acid volcanics from various Australian Proterozoic post-orogenic terrains, with higher concentrations of total iron at all silica levels than their Cainozoic counterparts.

MgO

MgO correlates negatively with SiO_2 as does FeO , however there is significant variation in absolute and relative abundances. In general, MgO values lie within the Cainozoic field (Fig 5.8 C). A large spread in values is evident in the Whitewater Volcanics in the andesites and dacites with some relatively high values in dacites.

MnO

MnO shows well defined linear inverse correlation with SiO_2 with values comparable to the Cainozoic field over the entire range of SiO_2.

CaO

CaO decreases with increasing silica content (Fig 5.8 E). Values are in general comparable with Cainozoic values, with the exception of the "Corkwood East Suite" from unit 2 of the Biscay Formation (Chapter 2). These samples register very low CaO values. They also have very low Na_2O contents.

Na_2O and K_2O

There is such a large spread of values in these two very mobile elements, that when plotted individually trends are hidden by the scatter. However, the values vary sympathetically with each other such that the sum of the alkalis forms a meaningful trend (Fig 5.8 F). Total alkalis correlate positively with SiO_2, and in general there is good agreement with Cainozoic values. Low levels in some of the rhyolitic rocks can be explained by low Na_2O values in the "Corkwood East Suite", and also by K-spar fractionation. This latter is supported by the petrography and by corresponding Ba trends.

TiO_2

There is an inverse correlation between TiO_2 and SiO_2 with values falling generally within the Cainozoic field (Fig 5.8 G). Relatively high values of TiO_2 in andesites of the Whitewater Volcanics, and some rhyolites which lie outside the Cainozoic field, and their correspondance with FeO values, suggest crystallisation and accumulation of magnetite (see later).

P_2O_5

P_2O_5 varies inversely with SiO_2 (Fig 5.8 H). Gill (1981) states 'within tholeiitic suites P_2O_5 contents correlate positively with silica, increasing from about 0.1% to 0.2%; P_2O_5 contents within calc alkaline suites usually remain constant or decrease within the same or an even greater P_2O_5 range'. Thus for Kimberley felsic volcanic rocks, P_2O_5 values and trends are characteristically calcalkaline.

5.3.3.2 Trace Element Systematics.

Trace elements in the Kimberley felsic volcanic rocks define trends which support the conclusions already drawn from major element trends.

Rb

There is a large amount of scatter in this plot (Fig 5.9 A). The Whitewater Volcanics have relatively high Rb contents and many plot outside the Cainozoic field. The "Corkwood East Suite" is characterised by high Rb as well as K, and anomolously low CaO, Na_2O and Sr. These appear to be primary features. Generation of this pattern by secondary alteration seems ruled out by the similar behaviour of the relatively little altered Whitewater Volcanics. Other aspects of behaviour of the high field strength elements (see later) suggest that the anomalous chemistry of this suite of volcanics is of primary origin.

Sr

The negative correlation between Sr and SiO_2 (Fig 5.9 B) parallels the trend for CaO and Al_2O_3. The Whitewater Volcanics can again be seen to define their own separate trend, parallel to, but lower than, the Cainozoic field. The very low values for samples from the 'Corkwood East Suite' mirrors their very low calcium content. Some high values are apparent in the dacite and rhyo-dacite range. These are the rocks, described earlier, from units 1 and 2 of the Biscay Fm. the "Wills Creek Suite" which are intercalated with pillow basalts. The felsic volcanics are enriched in Na and Sr (Fig 5.10 B, filled circles). The associated pillow basalts show no evidence of Na_2O enrichment. This exchange of elements was possibly syn-depositional in a heated sea water environment, the normal "spilitic" processes affecting the felsic volcanics rather than the basalt.

Ba

There is a positive correlation between Ba and silica, with values corresponding to Cainozoic values throughout the range (Fig 5.9 C). Low values in the rhyolite range mirror the same situation in total alkalis (Fig 5.10 C) suggesting K-spar fractionation.

Sc and V

These compatible elements concentrate more in ferromagnesian minerals than in coexisting melt, and consequently correlate negatively with silica (Fig 5.9 G and H). The Whitewater Volcanics define a separate trend for Sc, being displaced parallel to the general trend towards higher values. The same situation obtains for the Gawler Range Volcanics.

Y, Zr and Nb

These high field strength elements are not incorporated appreciably into common minerals, and thus they correlate positively with differentiation indices (Fig 5.9, D,E,F) and with each other (Fig 5.10, G,H,I).It is widely assumed that these elements are alteration resistant (Cann 1970, Pearce and Cann 1973, Winchester and Floyd 1976, Lambert and Holland 1977, and many others). Thus they prove very valuable in discriminating between different suites of igneous rocks on the basis of primary magma characteristics (absolute and relative abundances, and differentiation paths). Overall abundances of all three elements correspond well with Cainozoic values for Biscay and Whitewater Volcanics. This contrasts with the values for the Gawler Range Volcanics which are significantly higher. The Ding Dong Downs felsic volcanics have high values of Y, Zr and Nb, plotting either entirely outside the range of Cainozoic values (Zr) or outside, but with some values just inside the Cainozoic field (Y and Nb). Differences in slope from Cainozoic trends support the inference from major element chemistry of variations in differentiation paths between different suites.

5.3.3.3 Discussion.

The spread in Al_2O_3 values in the least evolved of the felsic volcanic rocks may be attributed to varying degrees of plagioclase crystallisation from highly aluminous liquids. Least squares modelling for Biscay Formation samples supports this inference (see below). Parallel trends for Al_2O_3, CaO, and Sr suggest crystallization of plagioclase and clino-pyroxene. In the dacite and andesite range, pyroxene, as well as magnetite, probably exerted the controlling influence. Comparison between the MgO and TiO_2 plots indicates that in the rhyolitic rocks, magnetite crystallization probably exerted the major influence. This is supported by the petrology. Magnetite occurs as a phenocryst phase in rocks spanning the entire compositional range. Gill (1981) states (The) 'dissimilarity between tholeiitic and calcalkaline andesites was attributed to crystallisetion of magnetite throughout the calcalkaline series by Kuno (1968) and Anderson and Gottfried (1971)'. This is supported by the petrology. Rhyolites have feldspar and magnetite phenocrysts only, whereas some of the andesitic rocks from the Whitewater Volcanics contain remnant pyroxene. (Chapter 2). It has been suggested that pyroxene and magnetite exert major control on FeO and MgO, and therefore they are implicated as controls on Sc and V. The linear correlation between TiO_2, and V with FeO (Fig

5.10, D, E and F) suggests that the effect of magnetite was probably important throughout the compositional range.

Although the chemistry and differentiation trends of these four suites of felsic volcanics in the Halls Creek Mobile Zone are similar in some respects, there are important inter-suite variations and distinctions, and the fifth suite of volcanics is markedly different.

Whitewater Volcanics.

The large spread in MgO values in the andesites and dacites is most probably a reflection of the crystallisation, and relative enrichment or depletion of orthopyroxene. Microprobe analyses indicate that the OP_x present in Fig 2.9 G and H is ferrrohypersthene (FeO /MgO = 1.1).

Y values follow a very flat trend for the andesites and dacites with concentrations of 15-25ppm, followed by a jump to higher values 35-50ppm in the rhyolites. This pattern could be generated by the crystallisation of apatite and its removal from early differentiates. The very flat differentiation paths for Zr suggests continuous crystallisation of zircon.

Ding Dong Downs Volcanics

High Y values suggest incorporation of accumulative apatite, and high Zr incorporation of accumulative zircon. (Heavy mineral bands in the unconformably overlying Saunders Creek Fm. are zircon rich - Chapter 2) Parallel trends for these pre and post tectonic suites of volcanics are seen in the Nb vs. Y, Zr/Nb vs. Y, and Ce vs Y plots (Fig 5.10 G,H,I), although inter-suite values are displaced towards higher or lower levels. In Fig 5.10 G the Kimberley volcanics plot within the field defined by the Gawler Range Volcanics (dotted lines) but closer to the origin due to the lower Y values.

Biscay Volcanics.

Three suites of Biscay felsic volcanics can be defined on chemical grounds.

(i) The Corkwood East Suite registers very low CaO and Na_2O contents. Trends for the two elements (Fig 5.8) suggest that this ignimbrite is chemically relatively uniform, the range in composition being accounted for by accumulation or depletion of andesite feldspar and small amounts of magnetite (both of which occur as phenocryst phases). Least squares modelling supports this hypothesis (Fig 5.11). The "Corkwood East Suite" is closely constrained chemically. As with the Ding Dong Downs Volcanics and the Whitewater Volcanics, Y, Zr and Nb values follow very flat trajectories (Fig 5.9 and 5.12) with values intermediate betweeen these earlier and later suites.

(ii) The "Wills Creek Suite", on the other hand, varies widely chemically (as it does lithologically (Fig 5.12). It has been suggested that some of this variation may be due to secondary alteration.

(iii) The peralkaline volcanics referred to earlier occupy an horizon within Unit 3 of the Biscay Fm. This is the suite with extreme enrichments in incompatible elements, from which the inference of hot spot activity is drawn. Buckovic (pers. comm.) has quoted values of 5000 - 8000 ppm Nb, and similar values for Zr, and 1000 - 1800 ppm Y. Hancock (pers. comm.) quotes similar values of up to 2% for these three elements. An equivalent suite of rhyolite domes with associated volcanics highly enriched in incompatible elements occurs in the Mt. Painter inlier.

Also plotted on these graphs (SiO vs. high field strength elements - Fig 5.9) are samples of the "White Rock Leucogranite" with very low values of Zr, Nb, and Y, which is discussed in the section on intrusive rocks.

5.3.3.4 Conclusion

The Kimberley felsic volcanic rocks have been identified as members of the calcalkaline series using criteria generally considered diagnostic. Comparison has been made with Cainozoic calcalkaline rocks to ensure that the effect of alteration is recognised, and that any doubts cast on the validity of a geochemical approach to altered rocks can be allayed. Where alteration has produced scatter in the differentiation trends, this has been identified. Good field control has proved essential in recognising the probable nature of the alteration. Thus the following within-suite and between-suite comparisons are made, with a high degree of confidance.

1. The Kimberley calcalkaline volcanic rocks are essentially very similar to their Cainozoic counterparts.
2. The major dissimilarity is in the high FeO and Sc contents of the Kimberley rocks.
3. Proterozoic felsic volcanic rocks from a number of other provinces all show higher values for these two elements.
4. The Gawler Range Volcanics have significantly higher Y, Zr, and Nb levels than the Kimberley felsic volcanics. However, if the suite of peralkaline volcanics with very high values of these high field strength elements are included in the population, average values for the Halls Creek Province are increased.
5. Within the Kimberley rocks, the Whitewater Volcanics generally appear to define a separate population. While trends for some elements follow the general trend but are displaced parallel to it eg. FeO , TiO_2, P_2O_5, Sr and Sc, for other elements a trend with a different slope is apparent eg. Zr and Nb. This is considered particularly significant for these latter two incompatible and immobile elements.
6. The Ding Dong Downs Volcanics also appear to define a separate population, but for the felsic volcanics this conclusion is more

tentative due to small sample numbers.

7. Within the Biscay Formation, the peralkaline suite and the "Corkwood East Suite" form well defined populations. The "Wills Creek Suite" is quite variable, some of which may be due to syn-depositional alteration.

8. Different lines of liquid descent are postulated from probable non-consanguineous parent magmas.

The Ding Dong Downs Volcanics appear to have crystallised plag, mag, K spar, apatite and zircon.

The Whitewater Volcanics have crystallised OPx, plag, mag, apatite and zircon.

The "Corkwood East Suite" has crystallised plag, mag (+ apatite and zircon ?).

5.3.4 Basic Volcanic Rock Suites.

As noted in Chapter 2, basalts occupy a considerable portion of the stratigraphic sequence in the Halls Creek Group (Fig 2.4), from the oldest rocks outcropping in the area, the Ding Dong Downs Volcanics, to locally thick pillow basalts at the top of the Biscay Formation. There is no record in the Olympio Formation of basaltic flows, which do not reappear in the stratigraphic column until the Carpentarian Kimberley Basin Succession. Basic sills mapped as Woodward Dolerite intrude the Biscay Formation (where thick sequences are sometimes obliterated) and the base of Units 1 and 2 of the Olympio Formation (Chapter 2). It is often very difficult to distinguish metabasalts from metadolerite sills in the field. The latter are generally coarser grained (sometimes containing feldspar phenocrysts up to 5 cm long), and they occasionally have chilled margins. Deformed pillows and cross cutting relationships are other identifying criteria for basalts and dolerites respectively, which are sometimes present.

Ding Dong Downs Volcanics.

Amygdaloidal basalts were sampled from both basalt horizons in the Saunders Creek Dome. Photographs and photomicrographs of this material appear in Chapter 2, with the general description of field relationships and petrology. Brief thin section descriptions of the analysed rocks are presented in Appendix 1. Geochemical data appear in Appendix 5. As indicated in the petrography, the Ding Dong Downs basalts are highly amygdaloidal, vesicles having been infilled with epidote, quartz and chlorite. Element migration is inferred by this later crystallisation, possibly partly from the basaltic material, and partly introduced into the system. Thus problems of sample contamination and representation are posed. All samples are spilitised and there is a relatively large scatter of values on most plots. Evidence suggests that this variation is not grade related. A series of basalt flows from Unit 1 of the Biscay Formation immediately overlying the Saunders Creek Formation flanking the Saunders Creek Dome has been sampled and analysed. The chemistry of these basalts is virtually indistinguishable from the chemistry of basalts from the same unit in the Upper Sillimanite Zone. The pervasive "weathered" appearance of the Ding Dong Downs basalt possibly relates to the early period of emergence during sub-aerial deposition of the unconformably overlying Saunders Creek Formation.

Biscay Formation.

Pillow basalts were sampled from the bimodal volcanic sequences in Units 1 and 2 of the Biscay Formation, and from the volcanic sequence coeval with the thick carbonate comprising Unit 4, which marks the top of the Biscay Formation, from locations in the greenschist facies to the Upper Sillimanite Zone (Fig 4.1). Field relationships and petrology of Biscay basalts are discussed in Chapter 2, and photographs and photo-micrographs appear in Fig 2. Geochemical data are presented in Appendix 5. The Biscay basalts are geochemically homogeneous. Values of samples from all three horizons, and from a wide range of metamorphic zones form a tight cluster on all plots. There is no evidence of spilitization (Fig 5.6). This coherent population is given greater weight than the other basaltic rocks.

Woodward Dolerites.

Woodward Dolerite, at low metamorphic grades in the south of the Halls Creek Mobile Zone, is folded by D_1 (Chapter 3). It could be envisaged as high level intrusives probably co-magmatic with the basalts. Thus, these samples have been analysed and plotted with the basalts. However, there is a major problem at high metamorphic grades. No D_1 folds have been identified in the northern areas, and the regional fabric is S_2. Thus sills and dykes with a strong D_2 fabric could pre or post date D_1. If the term Woodward Dolerite is applied strictly to pre tectonic basic intrusives, it is inapplicable in the high grade northern areas. It is, however, retained in this work. (No late basic dykes with a well preserved igneous texture have been analysed, although these certainly occur). The dolerites exhibit considerable geochemical variation. This could, relate to the possibility of their injection over a wide time range (possibly of the order of some tens of millions of years). Source inhomogeneities, either mantle or reservoir, with different degrees of crystal settling and/or magma replenishment in magma chamber(s) could be implicated.

5.3.4.1 Major Element Systematics.

Al_2O_3

Al_2O_3 values define a very flat trend with decreasing MgO. (Fig

5.13) indicating fractionation dominated by plagioclase - the observed liquidus phase.

MgO

All the analysed basalts are highly evolved, the least evolved having a magnesium number of 45.

FeO^t

On an AFM diagram (Fig 5.6), the Kimberley basalts show a trend of marked iron enrichment typical of the tholeiite series.

TiO_2

A titanium enrichment trend is apparent in basaltic rocks in Fig 5.6. Also in Fig 5.13, TiO_2 increases with decreasing MgO. This is a characteristic tholeiitic pattern. Enrichment in FeO^t and TiO_2 in East Kimberley basalts indicates differentiation controlled by ferromagnesian phases rather than oxide phases.

MnO

MnO decreases slightly with decreasing MgO (Fig 5.11C). Early fractionation of olivine, and clinopyroxene particularly, preferentially remove MnO from the magma.

Na_2O and K_2O

The abundance of alkalis varies with the alteration. The spilitised Ding Dong Downs basalts show higher Na_2O and K_2O than the non spilitised Biscay basalts (the alteration taking them out of the basalt field, and thus they are not plotted on Fig 5.7), and relatively lower CaO and Sr contents (Fig 5.13). Biscay basalts have low K_2O contents, generally <0.5 wt%. In the dolerites, K_2O values are low but variable.

P_2O_5

P_2O_5 values increase with increasing fractionation (Fig 5.13). This is a tholeiite trend (Gill, 1981) and may be contrasted with the P_2O_5 fractionation trend shown by the felsic volcanics, which is typically calc alkaline.

5.3.4.2 Trace Element Systematics.

V, Cr, Ni

Low transition metal abundances in these evolved plagiophyric basaltic rocks are consistent with extensive fractionation of olivine and clinopyroxene. Values are typical of transition metal abundances in low-K tholeiites (Jakes and Gill, 1970). Cr values are generally low, (Fig 5.14) but are highly depleted in the Ding Dong Downs basalts. All samples are depleted in Ni (Fig 5.14). This is consistent with extensive fractionation of olivine and orthopyroxene. Increase in V values with advancing fractionation supports a tholeiitic rather than calc alkaline association for the East Kimberley metabasites (Miyashiro and Shido, 1975). Ti/V values are approx 20. The tectonic significance of this is discussed in Chapter 6.

Y, Zr, Nb.

As indicated in the section on felsic volcanics, these high field strength elements partition strongly into the melt, and thus they correlate positively with differentiation indices (Fig 5.15) and with each other. These alteration resistant elements discriminate clearly between the three suites of basic rocks in the Halls Creek Mobile Zone. The Biscay basalts have low overall abundances, average values for the Ding Dong Downs basalts are somewhat higher, and the Woodward Dolerite occupies a field intermediate between the two basalt suites.

5.3.4.3 Discussion.

Major and trace element abundances and differentiation trends indicate that basaltic rocks from the Halls Creek Mobile Zone are highly evolved tholeiites which have crystallised olivine, orthopyroxene, clinopyroxene, and plagioclase. Osborn (1959) concluded that fractionation of olivine at low fO_2 is responsible for tholeiitic trends, whereas magnetite fractionation at high or constant fO_2 generates calc alkaline trends. The Ding Dong Downs Volcanics are strongly depleted in Cr. This suggests some spinelcrystallisation. The unconformably overlying Saunders Creek Formation is characterised in the fluvial facies by heavy mineral bands, rich in magnetite.

Similar tholeiite trends are defined for basaltic rocks from various other Proterozoic terrains in Australia and elsewhere, (although basalts with calc-alkaline affinities are recognisedin Proterozoicfold belts from the North American continent - Chapter 6). The Cambrian Antrim Plateau Basalts from the East Kimberleys are also tholeiitic although with moderate Fe-enrichment (Fig 5.16).

5.3.2.2 Conclusions

1. Basaltic rocks from the Halls Creek Mobile Zone are all highly evolved tholeiites.
2. Major and trace element data suggest that they have crystallized olivine, orthopyroxene, clinopyroxene, and plagioclase.
3. While the Biscay basic rocks are strongly tholeiitic with Fe and Ti enrichment and Ni depletion, the Ding Dong Downs basalts show strong Cr depletion generally associated with calc alkaline trends.
4. For most elements there is a compositional hiatus between the two basalt populations which is bridged by the dolerites.
5. Y, Zr and Nb abundances, ratios and trends indicate that basic rocks of the Biscay Formation and the Ding Dong Downs Volcanics show affinities with interbedded felsic volcanics of the same formations.

TECTONIC SETTING AND PROCESSES

6.1 Introduction.

The world wide database compiled for the sub-division of Precambrian time (Plumb and James, 1985) illustrates a cyclicity in major orogenic events (cf. Sutton, 1963), with periods characterised by different orogenic patterns. This tends to suggest an evolution of tectonic style as indicated by Kroner, 1977 and 1981, and Windley, 1977. The tectonic setting of Proterozoic mobile zones has been the focus of much recent attention. One or other of two general models are proposed (and combinations and variations on these) which fit available evidence in different areas more or less well. Some investigators see parallels with modern plate tectonic environments. Others stress secular variation, and propose non subduction related ensialic rifting. It seems likely, as Condie has suggested for the Archaean (1979), and for the Proterozoic of North America (1985), that both systems existed in the Australian Proterozoic.

Proterozoic rocks outcrop sporadically over the whole of Australia west of the Tasman line (Fig 6.1), which marks the junction between the Precambrian craton and the Phanerozoic fold belt (Harrington, 1974; Scheibner, 1974). The east of Australia thus demarcated was added to cratonic Australia by lateral accretion at a somewhat later stage (Veevers 1982, and many others). Proterozoic terrains surrounding the Archaean cratons in West Australia register a more or less continuous history into the Lower Proterozoic, eg. the Mt Bruce Supergroup of the Hammersley Basin (2750-2300 Ma). Rocks dated at older than 1880 Ma are rare in the other Proterozoic provinces , and direct evidence of Archaean and lowermost Proterozoic crust east of the West Australian border is very sporadic. (The Pine Creek Geosyncline provides one exception - Section 6.3 below). Carpentarian and Adelaidean basinal sediments, and Cainozoic surficial sediments (locally hundreds of metres thick) mantle much of the area.

However, this gap in the record may well represent a real hiatus.

Of prime importance in unravelling tectonic processes is the nature of the underlying crust. Low initial $^{87}Sr/^{86}Sr$ ratios of some post tectonic Australian Proterozoic granites, imply that the age of the source for these melts was little older than their emplacement age (Wyborn and Page, 1981). These authors infer a mantle differentiation event around 2,000 Ma., accreting large volumes of material to the base of the crust. A proposal of Archaean continental crust with "massive underplating" of mafic material underlying the Proterozoic provinces of north, central and south Australia is one of the fundamental arguments for proposing an extensive ensialic type of orogeny, specific to the Proterozoic, which "differs significantly from the time transgressive, lateral accretion model of modern orogeny" (Etheridge et al., 1985). Sun (1985) reports secular chemical and isotopic variations for mafic volcanics from northern Australia, and indicates that the Nd isotope data supports the hypothesis of "unexpected" Archaean crust in Proterozoic mobile belts "if subduction models are not considered applicable to the geological development of Early-Middle Proterozoic crust in Australia." One difficulty some workers (eg. Ellis and Wyborn, 1984; Etheridge et al., 1985) see in adopting subduction related processes is the absence of crust of modern oceanic character. However, Plumb (1985) considers "Lack of preserved oceanic crust and abundance of sialic basement is not a problem." He notes that in the Himalayas "most exposed rocks are ensialic. Relicts of oceanic separation and convergence - ophiolites, flysch, melange, and high-P metamorphics - are only preserved in a discontinuous narrow belt of imbricated nappes and thrusts, unlikely to survive future converegence and erosion."

Other parameters which assist in developing a tectonic model are the lithofacies, the structural style, the thermal history, and the geochemical signature of igneous rocks. A tectonic model is developed for the Halls Creek Mobile Zone and associated domains, using a combination of all these parameters, which were examined in previous chapters. This area is compared and contrasted with other Early to Middle Proterozoic domains within Australia (Fig 6.2). The model is tested against existing models for the Australian Proterozoic provinces, and those of similar age elsewhere.

6.2 Local Tectonic Setting: The East Kimberley.

The Halls Creek Mobile Zone is interpreted as an Early Proterozoic back arc basin, with a continental arc and a subduction zone postulated to the east. A provenance area to the west has been established (Chapter 2). The voluminous and persistent bimodal volcanism, the presence of deep water turbidites, interpreted as an accretionary wedge, overlying shallow water sediments, the style of deformation, and the thermal history and geochemistry are all appropriate to this model. This area does not appear to differ unexpectedly in any particular (except the high geothermal gradient) from modern areas subject to these same orogenic processes. The anomalously high temperatures are attributed to regional metamorphism superimposed on a high basal heat supply due to hot spot activity. It is proposed that this heat budget is supplemented by shear heating, and augmented by a process of 'geospeedometry'. Some of the arguments in favour of ensialic orogeny which has been proposed for the entire North Australian Proterozoic Province (Etheridge et al., 1985), are very strong. The merits of the persuasively argued tectonic model for the Kimberleys (Hancock and Rutland, 1984) involving limited A-subduction of an ensialic rift, are also compelling. Nevertheless, new data, unavailable to previous authors, suggest that a subduction associated model may perhaps be more applicable to this area.

6.2.1 Tectonostratigraphic History.

The sequence of lithologies in the stratigraphic column, illustrated in Fig 2.4 and described in Chapter 2, indicates a range of sedimentary environments evolving through time (Fig 6.3). The sedimentary cycle is divided into six sequences of differing tectonostratigraphic character.

(1) A basal, shallow marine to sub-aerial, bimodal volcanic sequence - the Ding Dong Downs Volcanics - which suggests a volcanic archipelagic setting.

(2) An unconformably overlying, clastic, quartz rich, dominantly fluviatile, sequence - the Saunders Creek Formation. This probably represents thermal updoming and the initial phase of crustal extension.

(3) Bimodal volcanics dominate the lower half of a succession increasingly replaced by a fine grained terrigenous facies, commonly carbonaceous, and with abundant carbonates and sporadic B.I.F development - the Biscay Formation. Marine transgression from the southeast, probably represents thermal subsidence.

(4) The abrupt appearance of deep water turbidites - Unit 1 of the Olympio Formation - heralded by voluminous basic magma injected as dolerite sills - the Woodward Dolerite - is interpreted as the initiation of rifting. This flysch facies is perceived as an accretionary wedge.

(5) The equally abrupt return to shallow water conditions, similarly marked by high level dolerite sills, may indicate the final stage of the extensional phase, and the onset of deformation. An upward coarsening clastic sequence, which includes carbonates and sub-aerial supermature quartzites - Unit 2 of the Olympio Formation - represents marine regression. A regime of crustal shortening is considered to have been initiated shortly after this stage. This is interpreted as convergence between the proposed Archaean craton to the

west and the island arc to the east.

6) The top of the sequence is marked by huge volumes of unconformably overlying, generally sub-aerial, post-orogenic felsic volcanics, the Whitewater Volcanics.

Condie (1982) has classified Proterozoic supracrustal rocks into three lithologic assemblages which he considers reflect depositional environments in different tectonic settings.

(i) quartzite-carbonate-shale sequence - stable continental margin or cratonic basin.

(ii) bimodal volcanic-quartzite-arkose - modern continental rift.

(iii) continuous (tholeiitic and calc-alkaline) volcanics-greywacke - modern marginal basin and island arc succession.

A combination of these lithofacies is present in the East Kimberley. The sequence is probably best described as Association (iii), followed by Association (i), (Fig 6.2).

6.2.2. Chronotectonic Framework.

Recent isotopic age determinations (zircon U-Pb) on acid volcanics of the 'alkali suite' in the Biscay Formation (Page, pers.comm.) produced a discordia indicating an igneous crystallization age of between 1850 and 1880 Ma. The post tectonic Bow River Granite produced a minimum age from regional isochrons of 1834 +/- 32 Ma (Bofinger, 1967). A whole rock Rb-Sr age somewhat older than this was obtained on the syn-tectonic Sally Downs Tonalite (Ogasawara, in prep), while an age of 1910 +/- 109 Ma, was obtained for the post orogenic Whitewater Volcanics (data of Bofinger, 1967, reassessed by Page 1976). A whole rock Rb-Sr age determination from regional isochrons of 1920 +/- 30 Ma was obtained for the syntectonic Mabel Downs Granodiorite, and high grade metasediments (Bofinger, 1967). However, the rocks analysed to produce this isochron cover a wide range of relative ages, and this figure is probably meaningless. It has been superceded by the younger zircon U - Pb depositional age quoted above. The estimated age of the post orogenic acid volcanics is very imprecise and inconsistent with the other estimates. The unconformably overlying Kimberley Basin has a minimum age constrained by the age of the Hart Dolerite which intrudes it (1760 +/- 25 Ma., Bofinger, 1967).

More refined single crystal zircon work on the 'alkali suite' of the Biscay Formation is in progress, and the Whitewater Volcanics have been re-sampled. High grade metamorphic rocks (granulite facies) have also been sampled, to obtain a revised M_2 metamorphic age using more recent techniques than were available in 1967. Zircon U-Pb age determinations on these rocks during the current dating programme at the Bureau of Mineral Resources is expected to provide considerable improvement in precision, and tightening of the age constraints for deposition, metamorphism, and 'transitional acid volcanism' in the Halls Creek Mobile Zone. Unfortunately, no specimens of the badly altered Ding Dong Downs Volcanics, fresh enough for isotopic analysis, were found in the limited time available for re-sampling. Thus, the age of the oldest rocks out-cropping in the area, pre-dating the orogenic event described in previous chapters will remain unknown for the time being.

6.2.3. Deformational Style.

The two early periods of recumbent folding, F_1 and F_{2a}, documented in Chapter 3, are associated with extensional tectonics. Deformation was probably initiated subsequent to rifting, concomitant with the early stages of deposition of sequence (5) above, at the earliest. The base of Unit 2 of the Olympio Formation (and associated Woodward Dolerite sills) is folded by F_1. Inversion of stratigraphy is rare and of limited extent. This lack of evidence of overturned limbs of early recumbent folds poses a problem. While overturned folds are documented (eg. the Black Rock Anticline and the Garden Creek Anticline), they are regionally unimportant. Steepening of axial planes by rotation associated with movement on the Halls Creek Fault, has been suggested in Chapter 3, but this would have a trivial effect on large scale downward facing areas. Gravitionally induced decoupling at the basement/cover contact, as suggested in Chapter 3, offers a mechanism for generation of recumbent folds without the extensive downward facing zones which characterise nappe tectonics.

The initiation of the Halls Creek Fault system as a transform fault during the extensional phase is documented in Chapter 3. The suggestion that it acted as a trans-tensional margin is supported by the emplacement at higher crustal levels of layered basic and ultrabasic sills. The Panton, Mc.Intosh, and Armanda Sills, and the fault bounded area south of the Panton River with M_{2c} kyanite developed in metapelites, are all generically related to the area of complicated faulting and small block movements, near the junction of the Woodward and Halls Creek Faults. This is the area from which the 'horse', now recognised as the Black Rock Anticline, began its northward race along these two faults. The emplacement of the Panton and Armanda Sills may be associated with post D_1 movement on the Woodward Fault. The intrusion of the Mc.Intosh Sill, and the foundering of the small graben into deeper crustal levels to emerge later as the small block with anomalous late kyanite, probably relate to the D_{2b} period of movement on the Halls Creek Fault. This suggestion of vertical emplacement of the Panton Sill (with a possible component of lateral movement from further south) is at variance with the model of Hancock and Rutland (1984), who suggest emplacement by overthrusting from the northwest. Their model of stacked thrust sheets also does not easily accommodate the observation that the only mapped stratigraphic duplication is restricted to small slivers and 'horses' adjacent to major faults.

Lateral movement appears to have taken place on discrete small lengths or splays of the major strike-slip faults. These then became locked, and further movement occurred on different segments, migrating northward with time (Chapter 3). Thus, the presently exposed system of anastemosing major faults evolved over a very long time, from the Early Proterozoic syn-orogenic movements in the south, to the Late Proterozoic and Early Phanerozoic movements in the north of the Halls Creek Mobile Zone. These faults (and their continuations into the West Kimberley) tap deep crustal levels, and have served as channel ways for the eruption of kimberlitic magmas from Palaeozoic (Permian) to Cainozoic (Miocene) times (Jaques, 1983). All mappable offsets register a sinistral nett sense of movement, thus elongating the original basin shape. The suggested sinistral D_1 block movement, linking the Little Gold Fault with the Osmond Fault, would mean that the section of basin now exposed originally had a more N.E. than N.N.E. orientation. It would also provide a closer link between the Pine Creek and the Granites-Tanami Inliers (Fig 6.1).

The two periods of upright folding follow (as described in Chapter 3) a change in orientation of the stress field, with concomitant initiation of a crustal shortening regime. The entire fold history, encompassing the early extensional and the later compressional deformation phases, occupied the period between deposition of sequences 5 and 6 above. Hancock and Rutland (1984) suggest that the extension factor B (McKenzie, 1978) could be as high as 4, and this is appropriate to the massive outpourings of basic magma (Woodward Dolerite) associated with rifting in sequence 4 above. As these authors note, the compressional phase did not produce great crustal thickening, with extensive molasse deposits. Basement remobilization and reworking has not been documented, and there is no convincing evidence of nappe tectonics, with extensive downward facing zones and low angle thrusts (Fig 6.2).

6.2.4. History of Magmatic Intrusion.

As indicated in Chapter 5, basic and acidic magmas were generated and emplaced in the crust throughout the thermal history of the Halls Creek Mobile Zone. This activity commenced with high level intrusion of rhyolite domal structures and associated volcanics of the 'alkali suite' in the Biscay Formation, accompanying thermal subsidence (sequence 3 above). Very high values of high field strength elements (eg. Nb, Zr, Y,) in these igneous rocks are considered to indicate melting of normally refractory minerals eg. zircon, apatite, sphene, at high temperatures associated with hot spot activity under thinned lithosphere. Large volumes of Woodward Dolerite were intruded and/or extruded, possibly near the sediment/water interface, at the base of sequence 4 and sequence 5 prior to deformation.

A few, small volume, early tectonic, granitic plutons were intruded in the south of the fold belt in the proposed "hot spot area", where the rocks of the 'alkali suite' crop out. These are the Sophie Downs Granite, and the 'Black Rock Tonalite', the latter intruded prior to dislocation of the Black Rock Anticline. As mentioned, layered basic and ultrabasic bodies were tectonically emplaced during, and at the termination of the extensional phase, associated with transform faulting. The syn-tectonic heterogeneous batholith (the Mabel Downs Granodiorite and variants) was intruded into thick Woodward Dolerite at the base of the Olympio Formation towards the end of the extensional phase (or even, perhaps, a little later during the change from extensional to compressional tectonics. It postdates D_1 sinistral movement on the Little Gold - Osmond Fault system, but the southern tip of the pluton is truncated by the D_3 dextral movement on this same fault). The base of the Olympio Formation (Sequence 4 above) is designated in Chapter 2 as a regional unconformity. Thus the linear form of this batholith is interpreted as unconformity controlled. The large volume, Bow River Granite was intruded in the waning stages of the compressional phase, and obliterates most of Units 2 and 3 of the Olympio Formation in the East Kimberley. Its linear form is probably fault controlled (Hancock and Rutland, 1984) and unconformity related. Late porphyritic granites, co-magmatic with the Whitewater Volcanics, have their major expression in the north of the Halls Creek Mobile Zone.

Thus a very high proportion of basic magma intrusion is associated with extension, and most of the acid magma was intruded under a compressional regime. Small volume early 'granites' are associated with hot spots, and there are also relatively small basic and ultrabasic late intrusions in the northern high grade areas. The generalization may be made that intrusion migrated northwards with time.

One, atleast, of the component 'granites' of the Mabel Downs batholith is a tonalite, one of the early granites is tonalitic, and there is a post tectonic tonalite, thus providing a suggestion of the two stage melting characteristic of modern arc systems. Limited geochemical data from the extensive K spar megacrystic Bow River Granite indicates that it is similar to large I-type post tectonic granite batholiths in other Proterozoic terrains eg. Mt.Isa. It is from chemical and isotopic data from these Mt.Isa granites that the inference is drawn for the mantle differentiation event about 2000 Ma, accreting large volumes of material to the base of the crust (Wyborn and Page, 1983).

6.2.5. Metamorphism.

In the Halls Creek Mobile Zone, the high temperature low pressure metamorphic regime (Fig 6.2) reached a peak of 800°C and 5.5 kb. as indicated in Chapter 4. High metamorphic temperatures (granulite facies) following substantial tectonism may result from a number of different tectonic processes (Ernst, 1973, 1975; Le Fort, 1975; Stocklin, 1980; Bouchez and Pecher, 1981). These include :-

(1) hot spot activity

(2) crustal thickening, eg. by overthrusting or obduction.

(3) A-subduction or B-subduction, or both, with variable proportions of heat input from shear heating, delamination, and magmatic intrusion.

High geothermal gradients are considered to have been initiated during early lithospheric extension. As indicated above, hot spot activity is associated with sequence 3. A component of shear heating may be inferred from the proliferation of strike slip faults active during the high heat flow regime, and the association of greater numbers of faults with higher grade areas. Graham and England (1976) pointed out the importance of shear strain as an energy source. Hot spot activity and shear heating are also considered to be important causative agents of the similarly high geothermal gradient in the Mt. Painter Inlier (Teale, pers.comm.). Peralkaline domal structures with associated volcanics greatly enriched in incompatible elements, and long straight syn-tectonic shear zones tapping deep crustal levels are recognised in this latter area also (Figs 6.1 and 6.2). Theinternal heat source is high in the Halls Creek Mobile Zone. Unpublished company reports indicate thorogummite in the Saunders Creek Formation, and relatively high levels of uranium in the Olympio Formation. This factor has a marked influence in the Mt. Painter area where granites and sediments are highly enriched in uranium and thorium.

A strong causative association may be inferred between high metamorphic grade and magmatic intrusion, since intensity peaks of both increase and migrate northwards with time. The geothermal gradients during different metamorphic events (Fig 4.25) are convex towards the temperature axis, which supports this inference. (Richardson, 1970; Miyashiro, 1973).

It is also considered that a considerable input to the total heat budget, and a contributing cause of the very high geothermal gradients in the Halls Creek Mobile Zone relates to 'geospeedometry'. England and Thompson (1984) consider that areas that are "compressed within 60 Myr of their extension will have thermal profiles hotter than can be supported in steady state by their internal and basal heat supplies, and would achieve higher temperature metamorphism". The basal heat supply ie. the heat flux from the convecting upper mantle was abnormally high during the extension phase as already indicated, and considerably less than 60 Ma, and possibly less than 20 Ma, elapsed between extension and compression.

The segments of P/T/t paths plotted from sequential metamorphic reactions in rocks from the Halls Creek Mobile Zone are clockwise trajectories (Fig 4.25).This is to be expected from the uplift and erosion which took place immediately after the compressional phase. The area was still hot at the time of intrusion of the Bow River Granite (1834 +/- 32 Ma), and was rapidly exhumed and denuded prior to eruption of the Whitewater Volcanics. Thus, rocks from lower crustal levels were being uplifted while heating was still in progress - another form of 'metamorphic jet lag' (J.Dixon, quoted as pers. comm. by England and Thompson, 1984). Sullivan (1985) also documents near isothermal uplift in the Harts Range area of the Arunta inlier, giving rise to clockwise P/T/t paths, as does Teale (in prep.) in the Mt Painter inlier - interesting exceptions to the isobaric cooling postulated for the early to middle Proterozoic (Etheridge, Rutland, and Wyborn, 1985).

There is no evidence of the paired blueschist metamorphic belt which would be expected in a modern subduction setting. Ellis and Wyborn (1984) quote the absence of blueschist terrain at Mt.Isa as one reason for rejecting a subduction related environment. The lack of blueschist metamorphism is also noted by Etheridge et al.(1985) as an assential component of their ensialic rift model. Belts of blueschist metamorphism have never been reported in Lower Proterozoic terrains. de Roever (1956) and Ernst (1972) noted the scarcity of blueschist suites in the Precambrian record. It has long been recognised that these areas are uplifted by mountain building processes associated with isostatic adjustments, and rapidly denuded. Zwart (1967) and England and Richardson (1977) point out that both thermal relaxation and erosion increase temperature within blueschist terrains. This produces progradation to higher entropy assemblages, characteristic of greenschist or amphibolite facies terrains (Bloxam and Allen, 1959; Miller, 1974; Frey et al., 1974; Carpenter and Civetta, 1976). England and Richardson (1977) showed that for normal erosion rates, the probability of blueschist preservation for more than a few hundred million years is very low.

6.2.6. Geochemistry of Volcanic Rocks.

As noted in Chapter 5, the Halls Creek Mobile Zone is in essence a volcano-plutonic terrain. Hancock and Rutland, 1984, note that there was "persistent volcanic activity, especially siliceous volcanism, in the source area which therefore may have had some characteristics of a volcanic arc." The chemistry of the volcanic rocks is distinctly bimodal, witha hiatus in SiO_2 composition between 56% and 63% (Fig 5.7). The basalts are tholeiites, and the felsic volcanics have calc-alkaline affinities. This classic association is characteristic of all the Lower and Middle Proterozoic terrains in Australia, and is widespread in fold belts of this age elsewhere. It is considered to be a product of extensional tectonics (Christianson and Lipman, 1972; Martin and Piwinski, 1972). Ellis and Wyborn, 1984, suggest that bimodality indicates "rifting rather than a subduction related environment such as an island arc or continental margin", and this is one of their reasons for proposing an intracontinental rift setting for the Mt.Isa Inlier. However, back arc basins are also subject to extensional tectonics, and continental margins sometimes have transtensional faulting (Veevers, 1982),and thus bimodal vulcanism is appropriate to these settings also.

The intimate association of calc-alkaline and tholeiitic rocks suggests a common origin. Condie (1982) proposes that "This can be accomplished by fractional cystallization of a tholeiitic parent magma at varying depths. Olivine, pyroxenes, and plagioclase are removed at shallow depths (less than 35 km) and produce the tholeiitic series; clinopyroxene and garnet and/or amphibole (35-80 km) are removed at greater depths producing the calc-alkaline series." Major and trace element geochemistry, plotted as differentiation trends in Chapter 5, indicate that the tholeiitic basalts crystallized olivine, pyroxenes, and plagioclase, as suggested above, and clinopyroxene is an observed phenocryst phase in the calc-alkaline felsic volcanics. Thus, the fractional crystallization paths suggested for the calc-alkaline and tholeiitic volcanic rocks of the East Kimberley supports the hypothesis of a common origin for the bimodal volcanics. Further, thereis a striking singularity in abundances and ratios of high field strength elements in felsic and basic volcanics from the different bimodal suites (Zr/Nb v/s Y - Fig 5.15) which is strongly supportive of a common origin.

Comparison with samples from known tectonic settings indicates that the tholeiites from the Halls Creek Mobile Zone are similar to modern ocean floor basalts. The Biscay basalts are the least altered and most coherent population, and therefore the most reliable indicators. On discriminant diagrams using a range of major and trace elements (Fig 6.4), the following affinities are observed:-

(a) Most analysed samples plot within the field of Oceanic Tholeiitic Basalt.

(b) The spilitized Ding Dong Downs Volcanics plot generally in the Non-Oceanic field due to their high K_2O content. However most samples (and nearly all the Biscay basalts) plot in the Oceanic field.

(c) Nearly all samples (and all the Biscay basalts) plot as Ocean Floor Basalts.

(d) Most samples (and all but one of the Biscay basalts) plot as MORB, with some samples plotting in the area of overlap with Island Arc Basalts.

(e) Most samples (and all of the Biscay basalts) plot in the field of Island Arc Tholeiites.

Few of the samples (and none of the Biscay basalts) plot as Within Plate Basalts. (Holm, 1982) objects that samples of continental tholeiites are not well defined on these discriminant diagrams but spread widely across all fields. However, as noted, basaltic rocks from the East Kimberley form a well defined population, and this is particularly marked for the Biscay basalts.

On the Ti/V plot of Shervais,1982, (Fig 6.5) all samples lie in the Back Arc Basin field. Jaques and Green (1983) indicate that dredging and recent drilling has shown that back arc basins behind active island arcs are floored by olivine tholeiite basalts of very similar composition to MORB, and originate by similar mantle processes.

Thus, there seems little doubt that the closest parallel with basalts from modern tectonic settings is with back arc basin basalts. The geochemistry of the tholeiites from the Halls Creek Mobile Zone appears tobe completely unrelated to the chemistry of basalts from modern continental rift environments. Hancock, 1985, also indicates that the East Kimberley basalts are oceanic tholeiites, and characterises them as 'MORB - type'. Basalt geochemistry is one of the criteria on which the Island Arc model proposed for the Kimberleys is erected.

6.3 Regional Tectonic Setting.

The Proterozoic North Australian Province (Rutland, 1981) comprises various orogenic domains, the Halls Creek and King Leopold Mobile Zones (which, together with the Kimberley Basin form the Kimberley sub-province), the Pine Creek Geosyncline, and the Granites-Tanami, the Arunta, and the Tennant Creek Inliers (Fig 6.1). Plumb, in Plumb, Allen, and Hancock (1985) includes various other orogenic provinces further to the east - the Arnhem, Murphy and Davenport Inliers, and the Kalkadoon-Leichhardt Block of the Mt. Isa Inlier. However, the Rum Jungle, Litchfield and Nanambu Complexes in the Pine Creek Geosyncline have been assigned to the West Australian Orogenic Province. All these zones, and the Gawler, Willyama and Mt. Painter Blocks, share common elements within a partly comparable chronotectonic framework (they are all Proterozoic fold belts). However, there are differences in tectonostratigraphy, deformational style, and thermal history, metamorphic gradient, geochemistry, and numbers and length of tectonic episodes. Too loose a grouping and too heavy an emphasis on any one aspect, may mask important variation, either gradations or quantum jumps.

The Halls Creek and King Leopold Mobile Zones were and are physically connected and have a common depositional history, although correlation of deformational and thermal events is not simple. The Pine Creek Geosyncline and the Granites-Tanami Block were probably coeval and contiguous with the Halls Creek Mobile Zone for part of their sedimentary and tectonic history. This correlation has been made by Traves (1955), Blake (1978), and Hancock and Rutland (1984). The probability that the Halls Creek Mobile Zone and the Pine Creek Geosyncline were physically connected is enhanced by reconstruction along major faults in the Halls Creek Mobile Zone (Fig 3.23). Elements of the structural and thermal histories of these areas are also broadly comparable, and they are considered together below.

6.3.1. The Northwest Australian Sub-province

6.3.1.1 The Kimberley Block.

The margins of the associated, intersecting, Halls Creek and King Leopold Mobile Zones are onlapped and obscured by Carpentarian, and younger cover sequences. The two lower formations of the Halls Creek Group do not crop out in the West Kimberley. They, and most of the Biscay formation in the south of the King Leopold Mobile Zone, are presumed to underlie the Palaeozoic rocks of the Lennard Shelf and the Fitzroy Trough. Thus correlation of the two mobile zones is difficult. However, evidence has been presented in Chapter 2 which suggests widespread deposition of strictly equivalent formations (the Biscay and the Olympio) with probably coeval facies changes, extending from the West to the East Kimberley. Hancock and Rutland (1984) state "The similarities of lithology, sedimentary environment and directions of transport strongly suggest that the Olympio Formation once formed a single lithostratigraphic unit", and they also suggest "continuity of sedimentation of the Biscay Formation" across the two mobile zones.

Elements of the later orogenic deformational history described for the Halls Creek Mobile Zone can be correlated with deformations in the King Leopold Mobile Zone, with a reasonable degree of confidence. Earlier structural correlations are tentative, due to the as yet reconnaissance nature of the work in the West Kimberley. There may be fundamental differences in style in the early fold episodes, eg. "thick slices of the succession" are reported by Hancock and Rutland (1984) to be downward facing in the Sandy Creek and Little Gold inliers. As noted above, stratigraphic inversions are rare and of small consequence in the Halls Creek Mobile Zone.

Regional isochrons indicate overprinting events at about 1650 Ma, and 1400-1550 Ma in both the East and West Kimberley (Bofinger,1967, and Bennett and Gellatly, 1970). However whole rock, and more particularly mineral data show wide scatter, and these early estimates may well be revised by later work. A younger overthrusting event in the King Leopold Mobile Zone at about 600 Ma (Bennett and Gellatly, 1970) has no stratigraphic, structural, or isotopic correlative in the East Kimberley.

The later thermal history also appears to be closely related in the two mobile zones. Here again metamorphic correlation is confounded in large part by the obfuscation of the high grade metamorphics of the Biscay Formation in the south of the King Leopold Mobile Zone. One poorly known area only of Biscay Formation outcrops. Good petrological correlation, supported by geochronology, can be made for late metamorphic granitic rocks (Fig 5.2). Late acid volcanism appears to be diachronous, commencing earlier in the King Leopold Mobile Zone where it is syn-tectonic and syn-metamorphic, than in the Halls Creek Mobile Zone where it is post orogenic.

6.3.1.2 The Pine Creek Geosyncline.

14 km. of Early Proterozoic metasediments and metavolcanics overlie Archaean basement. A cyclic history has been established for the Pine Creek Geosyncline, of 'stretch-sag-rift-orogeny-uplift' with a periodicity of 10 - 20 Ma. (Fig 6.6). The Halls Creek Mobile Zone has a comparatively simple history with one cycle exposed, and the Ding Dong Downs Volcanics representing remnants of an earlier cycle. Hancock and Rutland (1984) correlated the Biscay Formation with the South Alligator Group, and the Olympio Formation with the Burrell Formation. The recent dating of the Biscay Formation at 1850 - 1880 Ma suggests the correlation may be with a later cycle. The Halls Creek Group could be the equivalent of the El Sherana Group, with the regional metamorphism in the Kimberleys equivalent to the Maud Creek Event, and the underlying Ding Downs Volcanics partly equivalent to the South Alligator Group. This 'geospeedometry' may be confined to the Northwest Australian Sub-province. However similar fine tuning of

the tectonostratigraphy and the geochronology may reveal this pattern to be more widespread. In some areas eg. the Arunta Block, it is difficult to imagine that such detailed correlation is possible.

6.3.1.3 The Granites-Tanami.

The stratigraphic sequence in the Granites-Tanami is similar to the Halls Creek Group and the geochronological evidence suggests time correlation with the Pine Creek Geosyncline. Zircon U - Pb dating of the felsic volcanics in the Granites-Tanami should permit closer correlation.

6.3.2 The Central Australian Orogenic Province.

The Central Australian Orogenic Province of Plumb et al.(1981) consists of the Georgetown Inlier, the Musgrave Block, and parts of the Mt. Isa and Arunta Inliers. Rutland (1981) included the Arunta Inlier in the North Australian Province. This difficulty in assigning its affinities is a function of its very different history from the other Proterozoic terrains (with the exception of the Musgrave Block). Plumb, 1985, suggests that the Arunta and Musgrave Blocks form a single mobile belt, which continues subsurface to the West Australian coast, and "They separate cratons of quite different histories." Cooper et al. (1986) state that "the grade of metamorphism and degree of deformation are such that a stratigraphy has not been unravelled". The complex structural evolution is described by Ding and James (1985) as "four major fold generations and a later discrete shear event in the basement, and two major fold generations and a later series of stacked nappes developing in the cover." Basement and cover were later remobilised by thrusting, with repeated mylonitization and isoclinal folding along the dislocation. High grade granulite facies metamorphism reached 850°C and 8 kb (Windrim and Cameron 1983), and pressures of 7 - 9 kb (Warren 1983). The Musgrave Block is similarly highly deformed and metamorphosed, with four major periods of folding and abundant low angle thrusts and shears, and granulite facies metamorphism estimated at 1,000°C and 10 kb. (Oliver, 1983). The oldest rocks dated in these areas are about 1800 Ma (Iyer et al., 1976; Black et al., 1983), 1762 +/- 2 for the Harts Range area (Cooper et al., 1986), and between 1650 and 1200 Ma for the Musgrave Ranges.

Thus correlations of stratigraphy, structure, metamorphism, geochronology and inferred tectonic setting, between these two terrains and other Australian Lower to Middle Preterozoic areas is not immediately obvious. Ding and James (1985) describe the tectonic setting of the Harts Range Area of the Arunta Block as an intensely reworked basement, with cover deformation closely resembling "continental margin Cordillera type overthrusting and thus thin-skinned tectonics associated with large scale crustal shortening." Plumb, 1985, proposes a collision model (which he compares with Nepal - Tibet Himalaya) and intracontinental convergence which "requires massive plate movements, difficult to conceive without some continental separations."

Isobaric cooling and anticlockwise PTt paths have been described for the Arunta Block. PTt paths refer to the post orogenic cooling history during uplift and erosion. Thus they must be confined within one orogenic cycle. It is not valid to define a PTt path using metamorphic mineals which have nucleated and grown in superimposed orogenic cycles. Thus, such trajectories applied on a broad scale to the Arunta Block (Warren, 1983) are suspect, and to the entire Northern Australian Proterozoic Province (Etheridge et al., 1985), even more questionable.

The Central Australian Orogenic Province is very different from the Halls Creek Mobile Zone. The only features which can be seen to be similar are the bimodal igneous geochemistry (Shaw et al., 1985) and proposed continental margin and inferred plate tectonic association.

6.3.3 The North Australian Proterozoic Province.

The Mt.Isa Inlier is divided into three tectonic units (Day et al., 1983): a central north trending basement belt, deformed and metamorphosed before about 1875 Ma, flanked by stratigraphically equivalent cover sequences in the Eastern and Western Fold Belts. The three cover sequences separated by unconformities (Blake et al., 1985) consist of bimodal volcanics dominating Cover Sequence 1 and the lower half of Cover Sequence 2, increasingly replaced by shallow water sedimentary rocks. The cover rocks were first deformed by thrust and fold nappes (Bell, 1983; B.M.R., 1985; Laing, 1986) followed by upright crustal shortening, and major vertical N-S shear zones. Metamorphism reached upper amphibolite facies 1620 - 1550 Ma. The igneous geochemistry is bimodal (Ellis and Wyborn, 1984). Four suites of felsic volcanics have been recognised, each from a chemically unique source. The basic volcanics appear to volumetrically exceed the felsic volcanics, and are classified as continental tholeiites "although they have lower contents of incompatible elements such as Ti, P, Zr, and Y than are typical for continental tholeiites" (Blake et al., 1985). Also "elements such as K_2O, TiO_2, Ba, Rb, and Sr tend to be low, and K/Rb exceptionally so" Ellis and Wyborn, 1984. The mafic rocks are in general described as "of uniform chemical composition" (Blake et al., 1985), although Glickson et al., 1976, and Glickson and Derrick, 1978, identified the heterogeneous basaltic rocks in the Eastern Fold Belt as ocean floor tholeiites, and suggested a continental margin to the east. Later authors (Blake, 1983; Ellis and Wyborn, 1984; Etheridge et al., 1985, prefer a model of intracratonic rifting of thick, heavily underplated Archaean continental crust.

Characteristics of other inliers referrable to this province (Fig 6.1) are tabulated in Fig 6.2.

6.3.4 The Eastern Australian Proterozoic Province.

Recent correlation of the stratigraphy in the Willyama Block with that in the Eastern Mount Isa and Georgetown Blocks (Laing, 1986), and an indication of sub-surface continuity between these latter two inliers, suggests an Eastern Australian Proterozoic Province. (The 1,200 kilometre gap in outcrop continuity from north to south presents a small problem). In addition to the perceived lithological and structural similarities, the Mount Isa Inlier and the Willyama Block share features distinct from the Northern Australian Proterozoic Province. Nappe style tectonics have been inferred for these areas from extensive zones of inverted stratigraphy. Further fine tuning of the geochronology may reveal that these eastern domains can be related through the Mt. Isa block. However, this data is not currently available, and important differences are noted by Laing (1986) between these three grouped stratotectonic terrains, including their style of stratiform Pb+Zn deposits.

Teale (in prep.) has correlated elements of the Mt. Painter Block with the Willyama Block. The Mt. Painter Block is seen as an ensialic rift. Itis characterised as a bimodal volcanic - arkosic association. Peralkaline volcanics, as noted above, are similar to the 'alkaline suite' in the Halls Creek Mobile Zone, and are similarly construed as originating in mantle diapirism. A number of sedimentary and orogenic cycles are separated by unconformities and disconformities. Correlation has been made with the Willyama Supergroup of the Broken Hill Block, from the lowermost unit to the top of the Mine Sequence. Various units have been correlated in fine detail.

The basement sequences of the Willyama Block have also been correlated with basement sequences of the Gawler Block (Glen et al., 1977), although correlation of absolute chronology is at present lacking. Like the Pine Creek Geosyncline, outcropping basement inliers indicate the Gawler Province is floored by Archaean gneiss.

Thus, while there are basic similarities between the different Australian Proterozoic provinces, there are significant differences which have important tectonic implications for models of crustal evolution during the Proterozoic. On the basis of current data, it would appear that any one model is inadequate to represent all the Australian Proterozoic terrains. One factor of great importance is the geochemical signature of igneous rocks. The designation of basaltic rocks as continental or oceanic lends weight to a model of continental rifting, or an alternative subduction related model. Classification criteria are crucial. In the Mt Isa Inlier the basaltic rocks are identified as continental (thus supporting an ensialic rift model) although no fewer than nine analysed elements are quoted as being atypical of basalts in this category. In the Halls Creek Mobile Zone, Allen, 1985 and this work, and Hancock, 1985, have identified the basalts as oceanic. However, Sun, 1985, states that Lamboo Complex basic rocks (unspecified) are continental. Much work remains to be done on the geochemistry of igneous rocks in Australian Proterozoic terrains, and great care needs to be taken in interpreting these data when tectonic models are inferred therefrom. The unifying factor appears to be a burst of intense thermal and tectonic activity following a major pulse of crust formation after a protracted period of quietus.

6.4 Global Tectonic Setting.

Rutland (1973, 1976, 1981, 1982) divided Australian continental crust into provinces corresponding to evolution during three chelogenic cycles, defined as global thermal cycles, with metamorphism and granite intrusion succeeded by cratonization of large areas of continental crust (Sutton, 1963). The more or less simultaneous onset of active diapirism at around 1880 Ma. over wide areas of the crust of Australia illustrates this episodic evolution. However, Plumb and

James,1985,suggest this cyclicity is diachronous worldwide.

Australian Proterozoic rocks have broadly similar geochemical characteristics. Tholeiite trends are defined for the basalts of the Gawler Ranges (Giles 1980), the Mount Isa Inlier (Ellis and Wyborn, 1984) the Harts Range in the Arunta Block (Sivell and Foden, 1985), and the Mount Painter Block (Teale, pers comm), as well as the Halls Creek Mobile Zone. The Late Proterozoic Keweenawan basalts (Mamainse Point Formation - Ontario) are also strongly tholeiitic (Figs 6.7). However, the early Proterozoic basalts of the Green Mountain Formation (Wyoming) show little iron - enrichment, plotting just inside the tholeiite field. These basalts also show a tholeiitic TiO_2 enrichment trend on Fig 6.7. However, using a wide range of criteria, the Green Mountain Formation basalts are classed as calc alkaline by Condie and Shadel, 1984. These authors state that the basalts 'are similar in composition to other mafic volcanics from Proterozoic volcanic terranes in Colorado and northern New Mexico'. Thus although the basalts from the Proterozoic Northern Australian province show tholeiitic trends, this pattern is not invariant for the Proterozoic.

The Gawler Range basalts have similar Y, Zr, and Nb abundances to the somewhat enriched Ding Dong Downs basalts (Fig 5.10). The dolerites from the Mount Isa inlier define the same trend for Y and Zr, but have a larger range of values than the basaltic rocks from the East Kimberleys. The tholeiitic Keweenawan basalts of the Mamainse Point Formation have similar average values with a rather more restricted range than the Kimberley basic rocks. The calc alkaline Green Mountain Formation basalts are strongly depleted in Y, Zr and Nb. They are also strongly depleted in Cr and Ni (Fig 6.9). Thus, a tholeiitic trend is not invariant for the Proterozoic, some provinces being classed as calc alkaline. Some other Proterozoic provinces are gradational with features characteristic of each series.

The associated felsic volcanics in Australian Proterozoic provinces are characteristically calc-alkaline, not only in the Kimberleys, but also eg. in the Gawler Province and the Mt.Isa inlier. These basalt-calcalkaline sequences are widespread in Proterozoic Terrains in other continents eg. North America, Africa, Sweeden, and constitute a classic association. Calcalkaline felsic volcanics have relatively high Al_2O_3, moderate alkalis and calcium contents, and show no iron enrichment trend in an AFM diagram, as indicated in Chapter 5. However these Proterozoic calcalkaline felsic volcanics appear to have distinctly higher trace element abundances such as Nb, Y, Zr, (cf. Pearce and Norry, 1979), and are also enriched in Fe and Sc compared with younger analogues (Fig 6.10). There are a numberof factors which may account for these relatively high values.

(1) arc maturity. In modern arc settings immature arcs are relatively iron enriched. The proposed volcanic arc(s) in the Northwestern Australian Proterozoic Province may well be seen as immature, having been aborted and re-initiated a number of times.

(2) melting of normally refractory phases eg. zircon, apatite, and sphene as discussed in Chapter 5, and magnetite and ilmenite. This is the process which is considered responsible for the iron rich nature of the whole province, the metasediments (Chapter 4) as well as the felsic volcanics.

These high values appear to be present in many Proterozoic fold belts and may be characteristic. The implied mantle diapirism suggests higher thermal gradients and/or thinner lithospheric plates. Brown, 1980, calculated that in the Archaean, terrestrial heat production was 5.0 - 7.5 times that of present values, and in the Upper Proterozoic between 1.4 and 1.7 times greater. Gass, 1982, suggests that in the Proterozoic "steeper thermal gradients and lower upper mantle viscosities may have produced thinner lithospheric plates, steeper subduction zones, and narrower arc systems."

The steeper subduction zones could possibly be responsible for the process of 'geospeedometry'. An increase in the steep gradient could cause abortion of the subduction zone, and cessation of activity in the immature volcanic arc, with a new subduction zone initiated shortly thereafter. Evolution of the Lower Proterozoic continental crust of Australia is suggested to have commenced with a number of intra-oceanic island arc systems and micro-continents, and to have evolved by episodic sedimentary, metamorphic, and magmatic processes above destructive plate margins, coalescing into a proto-continent.

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