CONFERENCE ON TECTONICS AND GEOCHEMISTRY OF EARLY TO MIDDLE PROTEROZOIC FOLD BELTS

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EXCURSION GUIDE

PROTEROZOIC EVOLUTION OF THE HALLS CREEK PROVINCE, WESTERN AUSTRALIA

by

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1. INTRODUCTION

(Plumb)

The Kimberley Region is situated in the far north of Western Australia. Precambrian rocks are exposed over about 250 000 km^2, bounded to the north and west by the Timor Sea and Indian Ocean, to the south by the Phanerozoic Canning Basin, and to the east by various Palaeozoic basins on the Sturt Block. This excursion will be confined to the East Kimberley, between latitudes 18°30'S and 15°15'S and longitudes 127°30'E and 129°E

The principal industry is cattle raising, by open-range methods on large holdings. Various crops have been grown, with limited success, on the Ord Irrigation Scheme at Kununurra since about 1963. Gold was discovered at Halls Creek in 1884 (the first in Western Australia), but most deposits were small and production waned rapidly before 1900. The East Kimberley has been the focus of several mineral exploration programs since the late-1960's, but the main boost came from the discovery, in 1978, of the Argyle diamond deposit at the southern tip of the Carr Boyd Ranges, acknowledged as the largest deposit of industrial diamonds in the world: production commenced in 1983.

Isolation, climate, and terrain combined to make the Kimberleys one of the last explored areas in Australia. It was not until 1883-85 that the first permanent pastoral holdings were established by the epic treks of the Durack and MacDonald families, following the explorations of Alexander Forrest in 1879; the Kimberley Plateau remained unknown until the explorations by Hann (1896-98) and Brockland and Crossland (1901). Subsequent development was slow, but has accelerated since about 1960 with improved road, air, and radio communications, and the development of the Ord Irrigation Scheme. The population of the East Kimberley is still only about 8000, about half of European descent and half Aborigines, and most live in the three towns of Halls Creek, Kununurra, or Wyndham.

OUTLINE OF EXCURSION

The Kimberley region is noted for its rugged and spectacular scenery and for its wide range of excellently exposed geology. The stratigraphic succession extends throughout the Early, Middle, and Late Proterozoic, and the Palaeozoic, Mesozoic, and Cainozoic. Rock assemblages range from metamorphic and igneous complexes to mildly-deformed or undeformed sedimentary successions.

This excursion is confined to the East Kimberley (Fig. 1), and is designed mainly to illustrate the early Proterozoic sedimentary, structural, metamorphic, and plutonic evolution of the Halls Creek Orogenic Sub-province. Hancock and Rutland (1984) interpret this sub-province as representing a distinctive type of linear Proterozoic ensialic orogeny, not explicitly identified previously and distinct from both the true collision orogenies of the Phanerozoic, involving a Wilson Cycle, and from the areally extensive Proterozoic orogenies to the east, with which it is associated. Some of the overlying platform covers and their structural evolution, in the Kimberley Basin and Carr Boyd Group, will be also examined briefly to complete the emerging North Australian tectonic models.

This guidebook synthesises the regional setting and the Proterozoic geology of the region, and then provides a brief description of the daily program and localities to be visited. The latter is summarised in Table 1 and Figure 1.

TABLE 1. OUTLINE OF EXCURSION

	Route	Geology
Day 1	Kununurra - Biscay Antiform	Regional structures and Kimberley Basin
Day 2	Saunders Creek Dome	Stratigraphy and structure, Halls Creek Group, Zone I
Day 3	Sophie Downs Dome - Halls Creek - Upper Panton River	Stratigraphy and structure, Halls Creek Group; Moola Bulla Formation; Zone I; basic intrusives, Zone II
Day 4	Upper Panton River - Wills Creek - Dougals Bore (Ord River)	Metamorphism and structure, Halls Creek Group; Alice Downs Ultrabasic. Zone II
Day 5	Dougals Bore - White Rock - Corkwood Track - Ord Riv	Metamorphism and structure, Halls Creek Group; syntectonic granites. Zone II
Day 6	Ord River - Dunham River	Granulite facies, Zone II. Zone II - Zone III suture. Post-tectonic granites and volcanics, Zone III - IV
Day 7	Dunham River - Lake Argyle - Kununurra	Halls Creek Group and late to post-tectonic granite and volcanics, Zone IV. Carr Boyd Group, stratigraphy and structures

Excursion terminates

Climate and Vegetation

The Kimberleys have a hot monsoonal climate, characterised by a short rainy season (November - March) when more than 85% of the rain falls, and a virtual drought for the remainder of the year. The excursion will traverse the full range: typical arid continental climate at Halls Creek,, with a mean annual rainfall of only 400 mm, to semi-arid coastal with a rainfall of 1200 mm around Kununurra and Wyndham. Mean annual temperatures are high: 26° at Halls Creek to 29° at Wyndham (the highest in Australia). Mean daily maxima reach 38° at Halls Creek in summer and 27° in July, while mean daily minima at Halls Creek are only 8.5° in July; temperatures are much more uniform throughout the year nearer the coast.

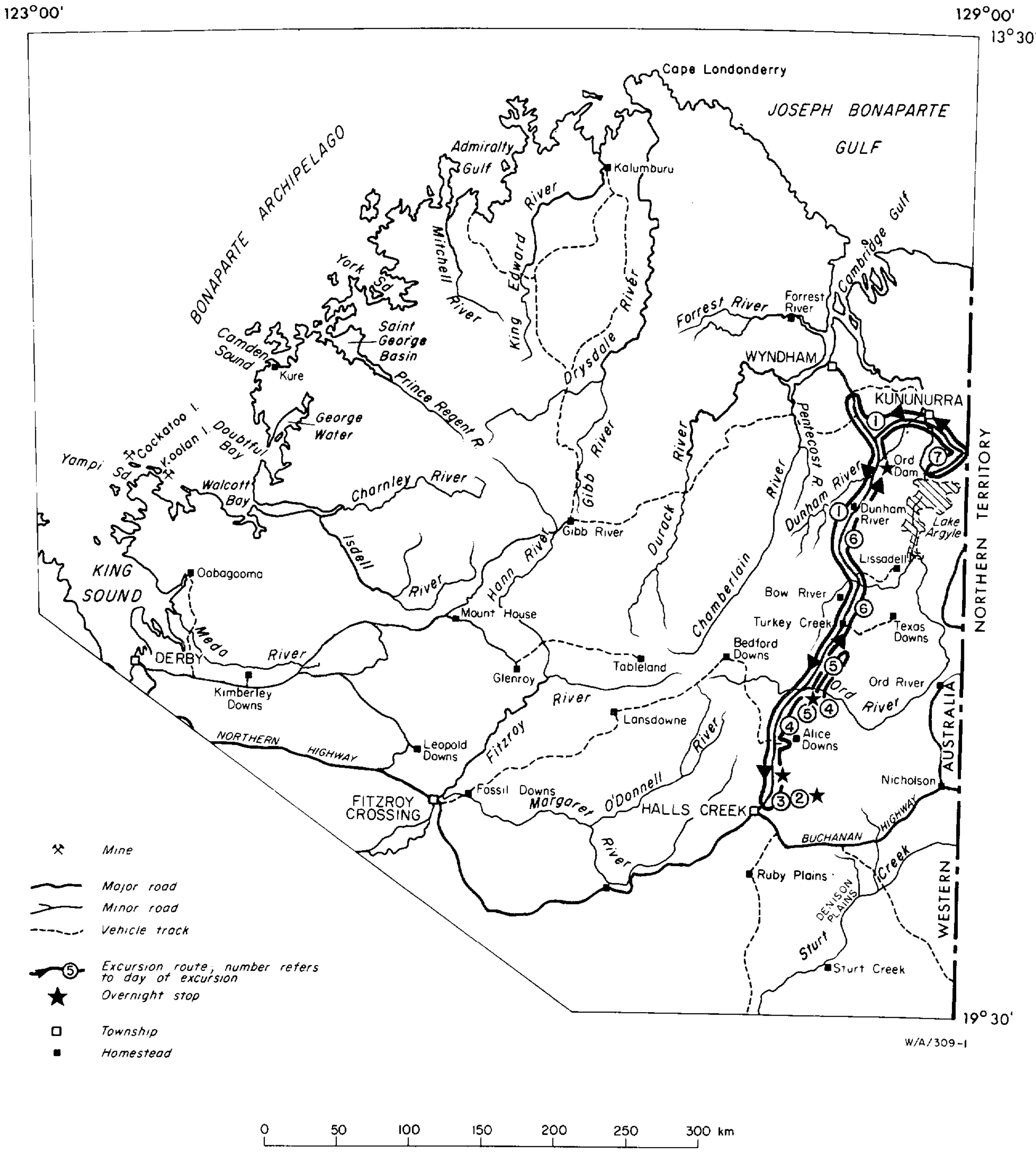

Figure 1. Excursion route

Vegetation is closely related to bedrock, but also varies dramatically through the excursion area with change in rainfall. Rugged rocky terrain is mostly covered by spinifex and sparse low trees throughout the climatic range. Similarly, Mitchell grass plains with sparse tree cover are characteristic of black soil plains; grassy woodlands, alluvial plains; short sparse deciduous trees (e.g. Bauhinia) and spinifex are characteristic of shale and phyllite. The higher rainfall zones (more than 650 mm) have medium to tall open Eucalyptus woodlands with an understorey of various tall grasses. In the lower rainfall zone the tree species change and become progressively shorter and sparser; spinifex on acid rocks, and arid short grass on basic and calcareous soils, become the dominant grasses.

Physiography

Landscape development in the Kimberleys can be traced back to at least the early Mesozoic; even Palaeozoic basins reflect similar topography. The several Mesozoic and Tertiary surfaces of the Northern Territory (Hays, 1968) can be traced into the region. The physiography of the region is dominated by the Kimberley Plateau , to the northwest of the excursion route (Fig. 2). The major drainage is radial about the core of the plateau, in a superimposed consequent pattern related to uplift of the ancient land surfaces, and only locally modified by the structure of the rocks they traverse. A particularly striking example will be seen in Carlton Gorge, where the Ord River cuts right through the Carr Boyd Ranges in a gorge 300 m deep. The base level of present valleys superimposed into the ancient surfaces varies progressively from about 400 m at Halls Creek (just below the old surfaces) to sea level at the coast. Local relief increases towards the coast, to more than 600 m in the Carr Boyd Ranges.

Topographic styles, closely related to the geology of the bedrock, have been used to distinguish a number of physiographic provinces across the region (Fig. 2). The **Kimberley Plateau,** formed on gently dipping rocks of the Kimberley Basin, comprises structural plains and benches, mesas, and shallowly-dipping cuestas, all dissected by deep narrow structurally-controlled gorges. Elevations of the broadly warped plateau surface range from about 550-150 m, with higher plateaux remnants 50-150 above. A laterite profile is preserved over rocks of suitable composition.

The **Kimberley Foreland** comprises a complex pattern of hogbacks and cuestas above folded and faulted sedimentary rocks, at the upturned edge of the Kimberley Basin, and outliers of younger basins such as in the Carr Boyd and Osmond Ranges; concordant ridge summits attest to their origin as a highly dissected remnant of a previously more extensive Kimberley Plateau.

The main province in this excursion, the **Lamboo Hills,** overlie the plutonic rocks of the Lamboo Complex and metasediments of the Halls Creek Group. Dendritic drainage moulding boulder-strewn rounded hills, whalebacks, and bevelled mesas characterise the plutonic rocks; hummocky discontinuous strike ridges and close-textured rectilinear drainage characterise the metasediments. Concordant summits consistently lie 100-200 m below the adjacent high ridge summits of the Kimberley Foreland; local relief ranges from <100 m around Halls Creek to ca. 300m in the north. Laterite remnants cap hills locally.

The **Ord Plains** surround the Ord River where it cuts the Phanerozoic Ord Basin, mostly at elevations of 100-200 m. The **Cambridge Gulf Lowlands,** at elevations of 0-75 m, comprise the coastal plain of the Gulf, and mostly overlie the Phanerozoic Bonaparte Basin. It is covered by sand or black-soil flood plains, and erosional remnants of bedrock rise up to 150 m above the plain.

PRINCIPAL GEOLOGICAL INVESTIGATIONS

Hardman (1885) outlined the major rock divisions of the East and West Kimberley in a remarkably accurate account, considering the reconnaissance nature of his work, and Gibb Maitland (1907) outlined the major features of the Kimberley Plateau. Various investigations were carried out in connection with mineral investigations (e.g. Blatchford, 1922, 1928; Wade, 1924), but Hardman's and Gibb Maitland's reports remained the principal accounts until new major surveys were carried out after the Second World War.

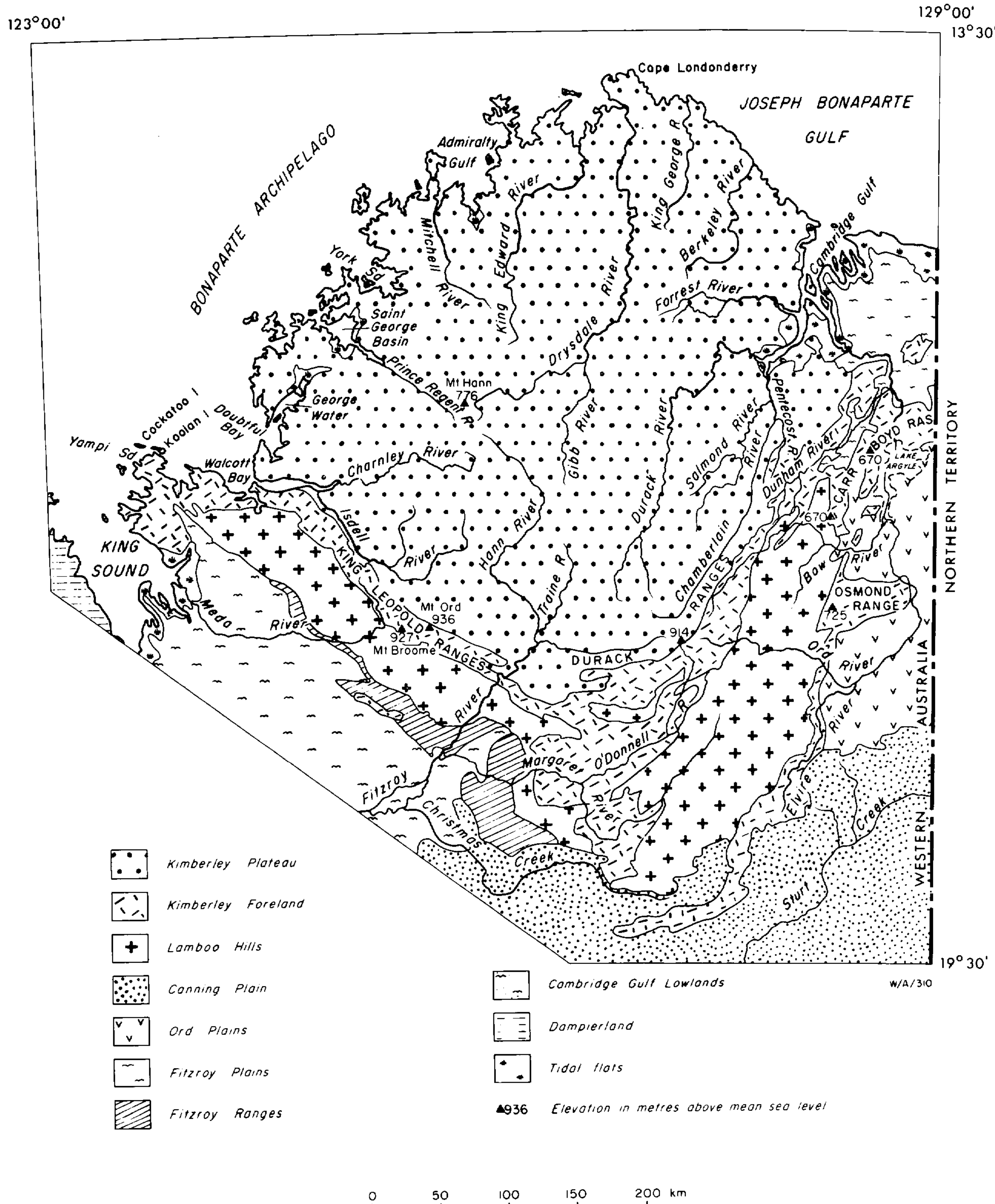

Figure 2. Physiographic sketch map, (after Dow & Gemuts, 1976).

TABLE 2

Summary of Proterozoic evolution and relationships of principal rock units and events, Kimberley region.

TECTONIC STAGE	KIMBERLEY BASIN: KING LEOPOLD MOBILE ZONE	KIMBERLEY BASIN: HALLS CREEK MOBILE ZONE	STURT BLOCK
	NW-trending thrusting and folding ca. 600 Ma		
		GLACIAL ca. 600 - --------------Unconformity-------------- **SUCCESSIONS** 750 Ma --------------UNCONFORMITY--------------	**GLACIAL SUCCESSIONS** ca. 600 - 700 Ma ---------UNCONFORMITY--------
PLATFORM COVERS		**CARR BOYD GROUP** With major syndepositional sinistral strike-slip faulting Ca. 900 - 1200 Ma (or greater)	**VICTORIA RIVER BASIN**
		----------------------------UNCONFORMITY	----------------------------
	Colombo Sandstone		**BIRRINDUDU BASIN** Ca. 1600± Ma
	------------------UNCONFORMITY	------------------	------------------
	Northwest to - - - - - - - - -> northeast-trending folds and thrusts Ca. 1550 - 1650 Ma		
	Hart Dolerite 1760 Ma		
	KIMBERLEY BASIN	Revolver Ck, Moola Bulla Fms	Red Rock Beds
---Ca. 1800 Ma---	---------------**UNCONFORMITY**	---------------	---------------
TRANSITIONAL TECTONISM	(Lennard Gran. etc) **POST - TECTONIC GRANITES** Folding, metamorphism, magmatism E-W to NW trends **Whitewater Volcanics** (acid) and cogenetic intrusives	(Bow River Gran. etc)	
--Ca. 1900 Ma--	---------------**UNCONFORMITY**	---------------	---------------
OROGENESIS	Upright to recumbent folding and thrust stacking	<---------- E-W to NNE trends throughout ----------> High-grade (Tickalara) metamorphism Acid and basic magmatism, Intense recumbent to upright folding and tectonic interleaving	Upright to recumbent folding and thrust stacking
HALLS CREEK GROUP	Turbidites, acid volcan. sediments	Ca 1920 Ma	Turbidites
	--------------------	**Woodward Dolerite**--------------------	--------------------
	Turbidites	Rifting, bimodal volcanism, and (volcanogenic) sedimentation	
--Ca. 2100 Ma +	--------------------	--------------------	--------------------

Matheson and Teichert (1946) were the first to subdivide the stratigraphy of the region, followed by Traves (1955) who reconnoitered and outlined all the regional geology of the East Kimberley and the adjoining Victoria River region of the Northern Territory. Guppy, Lindner, Rattigan, & Casey (1958) subdivided the Kimberley Basin sediments for the first time. Harms (1959) extended these surveys, particularly into the Kimberley Plateau, and synthesised the Precambrian geology of the whole Kimberley region.

These surveys provided the basis for systematic 1:250 000 mapping of the Precambrian rocks by the Bureau of Mineral Resources and the Geological Survey of Western Australia during 1962-67. All 1:250 000 Sheets and Explanatory Notes have long been published. BMR and GSWA Bulletins describe the East Kimberley - the topic of this excursion (Dow & Gemuts,1969; Gemuts, 1971). BMR Reports describe the West Kimberley (Gellatly, Derrick, Halligan, & Sofoulis,1974a; Gellatly, Sofoulis, Derrick, & Morgan 1974b: Gellatly, Derrick, & PLumb, !975). BMR Records describe each of the 1:250 000 Sheet areas in the Kimberley Basin. All of these data have been integrated and synthesised by Plumb and Gemuts (1976) and Plumb et al.(1981a).

More recently, Ph.D. studies in the Halls Creek Orogenic Sub-province have built on these BMR/GSWA studies. These include those by Hamlyn (1977), Allen (in prep), Hancock (in prep.), Ogasawara (in prep.), and Thornett (in prep.). A new model for a distinctive type of linear Proterozoic ensialic orogeny has been developed by Hancock and Rutland (1984). Most of the detailed localities to be studied during this excursion illustrate the work of Allen, Hancock, and Plumb.

2. OUTLINE OF GEOLOGY

(Plumb)

The stratigraphic relations of the major Precambrian rock units and the Precambrian geological history of the Kimberleys are summarised in Table 2. Figure 3 illustrates the regional tectonic setting of the Kimberleys, and the regional structure and distribution of major rock units are illustrated on Figures 4 and 5.

The intensely-deformed Early Proterozoic metasediments and metavolcanics of the Halls Creek Group and the plutonic rocks of the Lamboo Complex - the Halls Creek Orogenic Sub-province - form basement to all the unmetamorphosed sedimentary basins of the Kimberleys. After cratonisation, shallow-marine and fluviatile platform covers were deposited in a series of mildly-deformed, Middle and Late Proterozoic basins.

The Middle and Late Proterozoic structure of the Kimberleys is dominated by the sub-perpendicular Halls Creek and King Leopold Mobile Zones - zones of repeated tectonic activity and alternate elevation or subsidence throughout the Proterozoic and Phanerozoic - which flank the Kimberley and Sturt Blocks and the basins upon them. The Halls Creek Mobile Zone was deformed by left-lateral strike-slip displacements on several anastomosing major faults; the King Leopold Mobile Zone was dominated by reverse faulting and overfolding verging towards the northeast.

The poly-deformed Halls Creek Orogenic Sub-province now crops out in linear zones confined to these mobile zones; it is concluded below that this reflects the original distribution of the sub-province, and that the mobile zones originated from at least this time.

The Halls Creek Sub-province probably lies astride a geosuture between an Archaean nucleus (Kimberley Block) and widespread Early Proterozoic orogens to the east, and the Halls Creek Fault Zone separates the first cratonised Early Proterozoic sub-province (Halls Creek) from widespread slightly younger ones to the east.

Time subdivision: In the absence of a universally agreed scheme of subdivision of the Australian Proterozoic, and the still preliminary nature of the IUGS proposals (Sims, 1980; Plumb & James, in press), an informal subdivision is used here which reflects the major breaks in the local (and indeed regional) history (see Geochronological Framework below).

Early Proterozoic, 2500 - 1800, Ma encompasses the deposition, deformation and metamorphism, and plutonism of the Halls Creek Orogenic Sub-province - the Halls Creek Group and Lamboo Complex. Middle Proterozoic, 1800 - 900 Ma, relates to the subsequent widespread development of platform covers in the Kimberley, Birrindudu, and Victoria River Basins. These two divisions correspond roughly to the "Older" and "Younger Sequences" of the "BMR Model" for Proterozoic tectonic development at this conference. Following major regional break, late Proterozoic, 900 - 600 Ma, includes the glacial successions.

In Plumb's (in press) concept of using chronostratigraphic units only regionally, the Kimberley and Birrindudu Basins can be directly assigned to the Carpentarian of North Australia and, indeed, can be correlated directly to the Haslingden Group and to the Mount Isa/McArthur or Nathan Groups in the type region of the Mount Isa Inlier - McArthur Basin. Similarly, the glacial successions are clearly part of an Australia-wide Adelaidean. The position of the Victoria River Basin in such a scheme remains problematic.

REGIONAL TECTONIC SETTING

(Plumb)

The Kimberley Region lies at the western limit of the North Australian Craton (Plumb, 1979a) or (Orogenic) Province (Rutland,1981): a province of widespread and characteristic ensialic orogeny and plutonism and transitional tectonism over a short time interval about 1850 ± 100 Ma ago. This was followed by similarly widespread Carpentarian platform covers about 1800 - 1400 Ma which, along with younger covers, now conceal most of the basement rocks and the relationships between them. The Carpentarian covers are themselves locally involved in younger orogeny, such as at Mount Isa.

The Halls Creek Orogenic Sub-province has significant differences to the terranes farther east. As noted, the sub-province crops out in, and was probably always confined to, linear belts within the highly-faulted Halls Creek and King Leopold Mobile Zones. Gellatly (1971) inferred that an Archaean nucleus underlies the Kimberley Block (Basin) and, although only Early Proterozoic rocks are directly observed underlying the Basin around its upturned margins, new evidence of sediment sources and tectonic polarity in the Halls Creek Orogenic Sub-province support this model (Hancock & Rutland, 1984). The Halls Creek Sub-province therefore appears to lie astride a geosuture separating an Archaean craton and a province of widespread Early Proterozoic orogeny.

The distinction between the Younger (Palmerston) and older (McClintock - Halls Creek) Sub-provinces (Plumb,1979b; Plumb et al., 1981) is becoming less distinct with recent data. Considerable overlap is emerging between the ages of the sedimentary sequences throughout the North Australian Province, and the younger orogeny is yielding progressively older isotopic ages; the Halls Creek Sub-province appears to have stood at the western edge of a broad belt of Early Proterozoic sedimentation. However, it is equally clear that the principal (Tickalara) metamorphism in the East Kimberley, 1920 ± 27 Ma, is older than much of the preorogenic sediments farther east (e.g. the Gerowie Tuff, 1877 ± 11, 1884 ± 3, at Pine Creek; Page et al., 1984). The Halls Creek Fault Zone marks the boundary to the first <u>cratonised</u> Early Proterozoic orogen.

The precise northward extension of this geosuture is problematic. Metasediments equivalent to the Halls Creek Group can be traced into the Litchfield Complex (Hammond et al., 1984), and the Fitzmaurice Mobile Zone - Litchfield Complex has long been considered to be the extension of the Halls Creek Mobile Zone (e.g. Traves, 1955; Hancock & Rutland, 1984). However, the Litchfield Complex is fundamentally part of the Pine Creek Sub-province. Plumb (1979b) has pointed out the incompatibility between the geometry of movements between the Halls Creek and Fitzmaurice Mobile Zones, and the fact that the distinctive gravity dipole anomaly which characterises the Halls Creek Mobile Zone continues northwards along the Cockatoo and major offshore (Phanerozoic) faults which define the northeast edge of the Bonaparte Basin. He has proposed that it is this structure which marks the critical suture in the north between the Halls Creek Sub-province and younger terranes to the east.

PRINCIPAL TECTONIC UNITS OF THE KIMBERLEY

(Plumb)

The **Halls Creek Orogenic Sub-province** (Rutland, 1981, Hancock & Rutland, 1984; equals Halls Creek Province: Daniels & Horwitz, 1969; Inlier: Plumb, 1979b, Plumb et al., 1981) contains the Early Proterozoic metasediments and

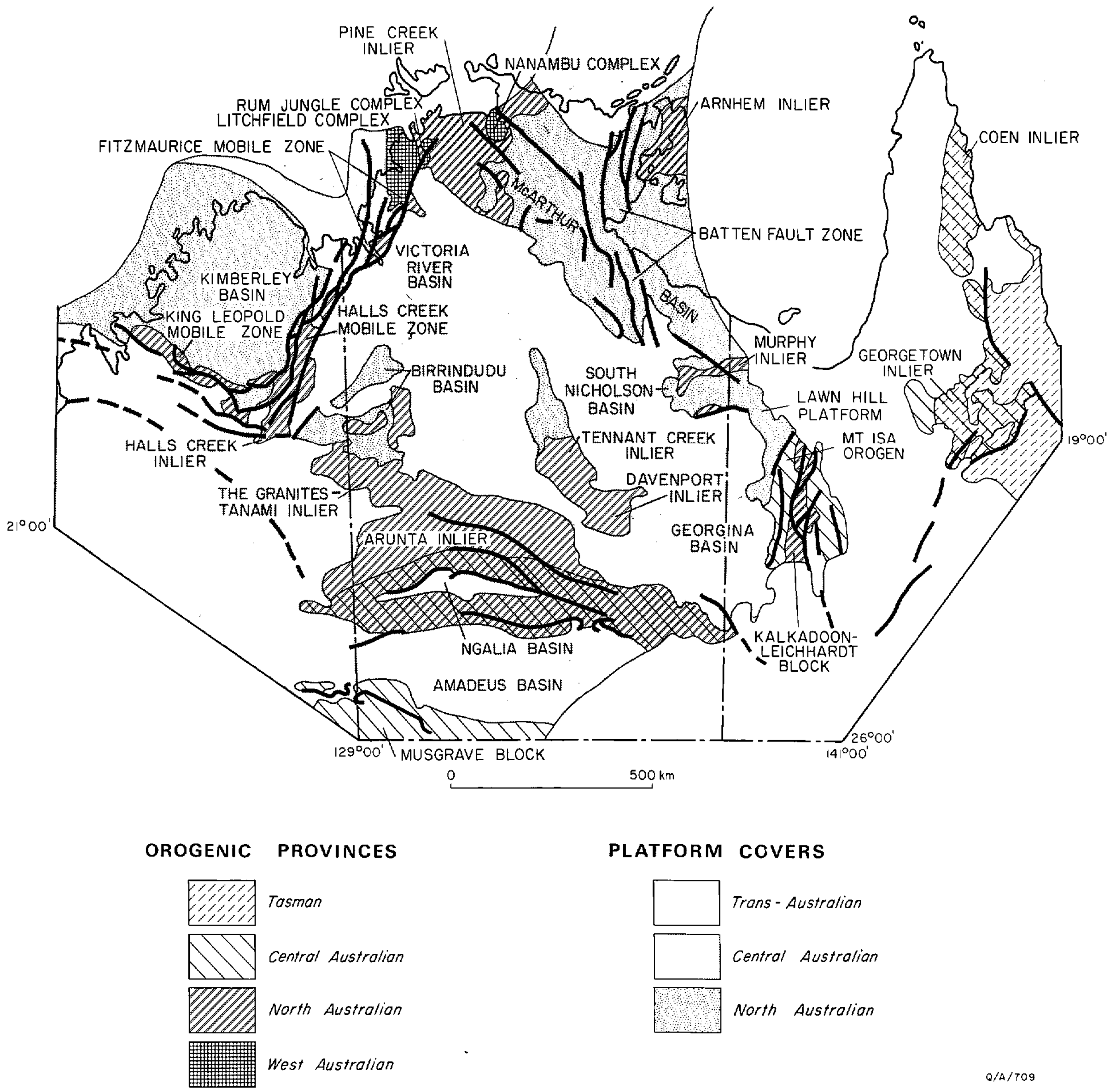

Figure 3. Principal tectonic elements, northern Australia (after Plumb et al., 1981).

metavolcanics of the Halls Creek Group and the plutonic intrusive and metamorphic rocks of the Lamboo Complex. The younger late and post-tectonic (e.g. Bow River) granites and acid (Whitewater) volcanics of the Complex have been assigned to transitional tectonism (GSA, 1971). It is the most westerly domain of the North Australian (Orogenic) Province and, although its sedimentation was probably continuous with at least part of the domains to the east, such as Pine Creek and The Granites-Tanami, its principal metamorphism and cratonisation preceded that of the domains farther east.

The definition of the Lamboo Complex and distinction between the "Early Lamboo Complex" and "Late Lamboo Complex" (Plumb & Gemuts, 1976), are becoming diffused as the evolutionary history becomes more of a diachronous continuum. However, the terms are retained here as useful regional "group" terms.

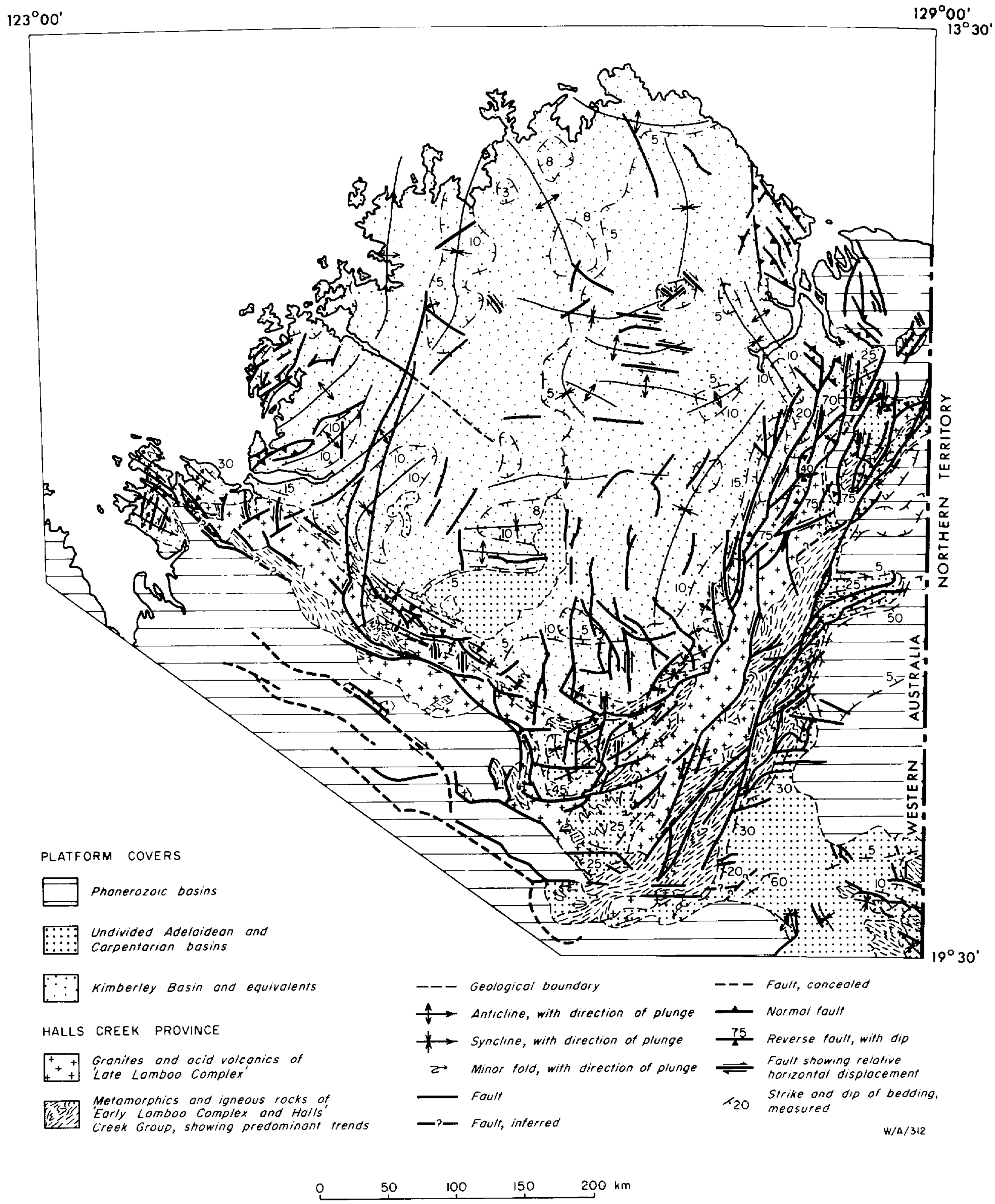

Figure 4. Structural sketch map and distribution of principal rock units, (after Plumb & Gemuts, 1976).

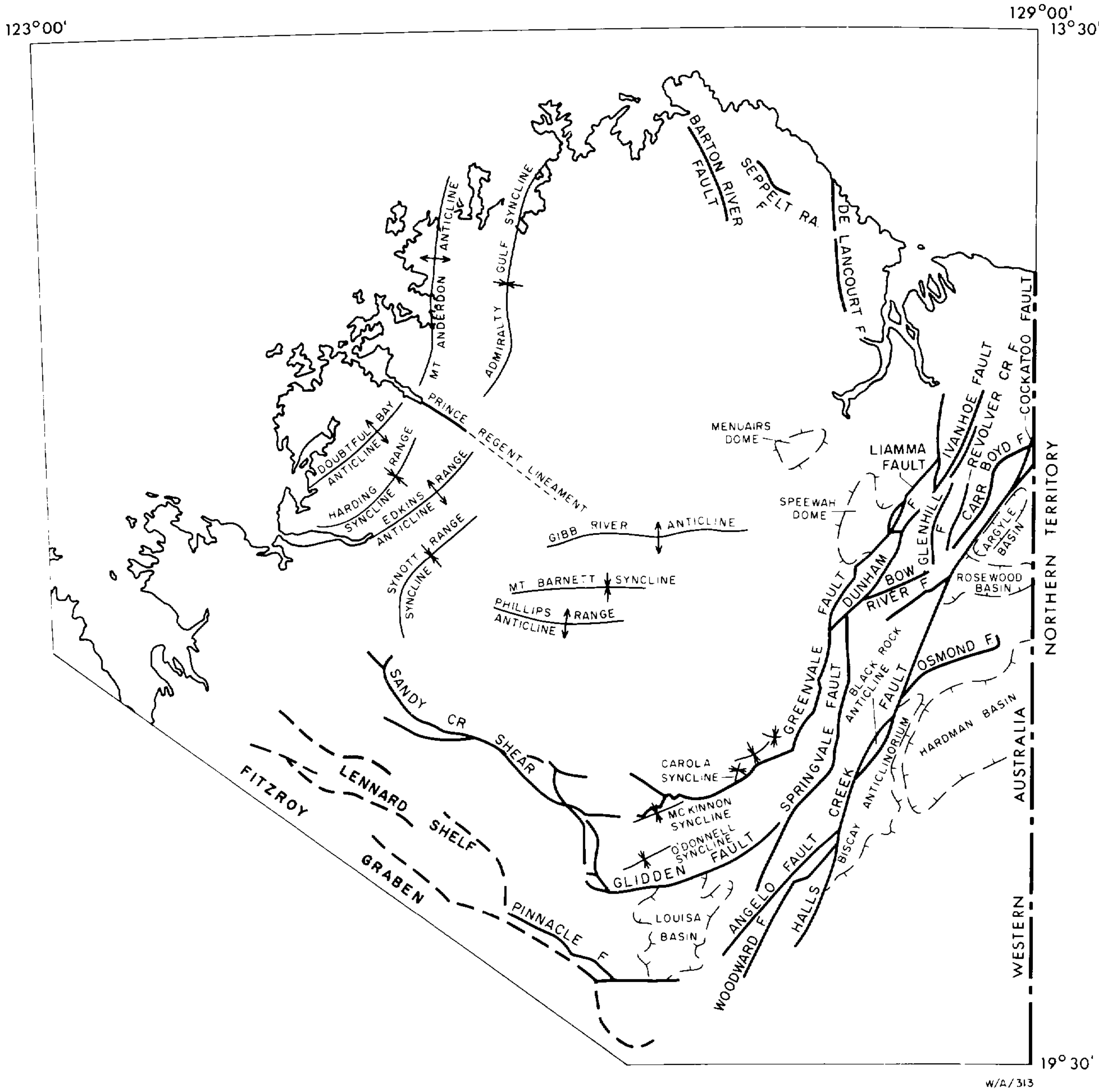

Figure 5. Principal structures (after Plumb & Gemuts, 1976).

The **Halls Creek** and **King Leopold Mobile Zones** (Traves, 1955) are linear zones of repeated localised deformation bounding the stable Kimberley and Sturt Blocks. The **Kimberley Block** underlies the Kimberley Basin, and the **Sturt Block** underlies the Birrindudu, Victoria River, and Phanerozoic basins to the east of the Halls Creek Mobile Zone (Fig. 3). The mobile zones controlled the tectonic development of the region from at least the Early Proterozoic to the Palaeozoic and, although they apparently had their origin in the evolution of the Halls Creek Orogenic Sub-province, they are most obvious from their domination of the development and deformation of all the subsequent platform cover basins of the region. A particularly significant feature of the Halls Creek Mobile Zone is its history of alternate elevation and subsidence during platform cover development; major basin subsidence alternately flanks or occurs within it (Table 2). The Halls Creek Mobile Zone is the East Kimberley Geosuture of Rod (1966).

The **Kimberley Basin** is the the relatively undisturbed basin on the Kimberley Block within which the Middle Proterozoic (Carpentarian) Speewah, Kimberley, Bastion, and Crowhurst Groups are preserved. It is over 160 000 km^2 in area and is flanked by the Halls Creek and King Leopold Mobile Zones. The basin overlies the Halls Creek Orogenic Sub-province with marked unconformity, and is unconformably overlain by the Carr Boyd Group and younger basins around its margins. Only minor and local lateral equivalents of the Kimberley Basin (Red Rock Beds, Moola Bulla Formation, Revolver Creek Formation) occur on or to the east of the Halls Creek Mobile Zone, and they are not assigned to any named basin. The Halls Creek Mobile Zone was largely a positive element during deposition, but the later sequences transgressed the King Leopold Mobile Zone without marked facies change.

Most of the basins of the Sturt Block lie in the Northern Territory, outside the area of this excursion. The **Birrindudu Basin** is the mildly-deformed basin, about 120 000 km^2 in area, in which the Middle Proterozoic (Carpentarian) Birrindudu and Limbunya Groups, and the Mount Parker Sandstone/Bungle Bungle Dolomite of the Kimberley are preserved. The basin unconformably overlies rocks of the Halls Creek and The Granites-Tanami Orogenic Sub-provinces, and Kimberley Basin equivalents, and is unconformably overlain by the Victoria River Basin. The Halls Creek Mobile Zone appears to have been a positive element at this time. The **Victoria River Basin** is the very mildly deformed basin in which the Middle Proterozoic Wattie, Bullita, Tolmer, and Auvergne Groups, the Bullo River Sandstone, and Stubb and Wondoan Hill Formations, and the Helicopter Siltstone and Wade Creek Sandstone of the Kimberley, are preserved. The partly-equivalent Carr Boyd and Fitzmaurice Groups in the adjoining Halls Creek and Fitzmaurice Mobile Zones are very much thicker and more deformed, and are not defined as part of the same basin. These mobile zones were very much zones of major subsidence at this time, and no equivalents are recorded from above the Kimberley Block. The Victoria Basin and its equivalents unconformably overlie the Halls Creek, Pine Creek, and The Granites-Tanami Orogenic Sub-provinces, and the Birrindudu Basin and Kimberley Basin equivalents.

The well-known late Adelaidean **glacial successions** which unconformably overlie the Victoria River Basin and other successions throughout the Kimberleys are not assigned to any formally named basin. The Halls Creek Mobile Zone was again a positive source area during at least the earlier glaciation.

Around the margins of the Kimberleys the Precambrian rocks are unconformably overlain by various Phanerozoic basins: the Ord Basin in the east; the Bonaparte Basin in the northeast; the offshore Browse Basin to the northwest; and the Canning Basin to the southwest.

GEOCHRONOLOGICAL FRAMEWORK

(Plumb)

No geochronological work has been carried out in the East Kimberley since the regional Rb-Sr study of Bofinger (1967). Many of his data lack the precision of later techniques, but selected regional isochrons, recalculated to the 1.42×10^{-11} yr^{-1} decay constant of ^{87}Rb, effectively constrain the principal events (Table 2).

A combined Model 1 whole- rock and mineral Rb-Sr isochron of 1920 ± 27 Ma (I.R. 0.7010) from the Tickalara Metamorphics/Mabel Downs Granodiorite has been assigned to the M_2 metamorphism (Hancock & Rutland, 1984); initial ratios show that the source sediments cannot be older than about 2150 Ma (Page, 1976). The post-tectonic Bow River Granite produced minimum ages from regional isochrons of 1815 ± 14 Ma (0.703) or 1834 ± 32 Ma (0.7013) (Bofinger, 1967), supported by 1840 ± 50 Ma (0.703) for related rocks in the West Kimberley (Bennett & Gellatly, 1970); Bennett & Gellatly also obtained the imprecise but consistent isochron of 1900 ± 100 Ma (0.7065) for the related Whitewater Volcanics.

The minimum age of the unconformably-overlying Kimberley Basin is constrained by the Hart Dolerite which intrudes it; a Model 1 total-rock and mineral Rb-Sr isochron, controlled by granophyre, of 1760 ± 25 Ma (Bofinger, 1967); concordant, but individually imprecise isochrons are given by the Carson Volcanics - ca.1770 Ma, and Wyndham Shale - 1750 ± 58 Ma.

The Birrindudu Basin is generally correlated with the ca. 1680 - 1600 Ma McArthur or Nathan Groups of the McArthur Basin (Plumb, in press), supported by minimum glauconite ages of ca. 1560 Ma (Page, 1976).

The generally preferred age range of the Victoria Basin succession and equivalents has been taken to be somewhere about 1200-900 Ma (Plumb & Gemuts, 1976, Plumb et al, 1981) from stratigraphically-consistent shale whole-rock Rb-Sr isochrons from the Carr Boyd Group by Bofinger (1967): the Golden Gate Siltstone 1158 ± 123 Ma; the Glenhill Formation 1057 ± 80 Ma; and the Pincombe Formation 891 ± 149 Ma; and the correlated Mount John Shale Member at 1104 ± 110 Ma and Glidden Group, 1019 ± 51 Ma. However, they show evidence of open-system behaviour and come from within the Halls Creek Mobile Zone, so the ages can only be regarded as minimums.

The glacial successions are constrained by identical shale total-rock Rb-Sr isochrons of 671 ± 75 Ma (Throssell Shale), 671 ± 72 Ma (Johnny Cake Shale Member), and 671 ± 44 Ma (composite; Throssell Shale/Johnny Cake Shale Member), and consistent isochrons from the Elvire Formation and Timperley Shale. All other isochrons have been updated by 600 Ma metamorphism in the King Leopold Mobile Zone (Plumb,1981).

Other whole-rock, and more particularly mineral data show wide scatter, reflecting overprinting in the Halls Creek Mobile Zone; selected data lie on regional isochrons indicating peaks of movement at about 1650 Ma, 1400 - 1500 Ma, and 1025 Ma (Bofinger, 1967). Bennett and Gellatly (1970) have indicated similar overprints in the King Leopold Mobile Zone of about 1650 Ma and 1550 Ma, and a younger one at about 600 Ma, not represented isotopically or stratigraphically in the East Kimberley.

3. EVOLUTION OF THE HALLS CREEK OROGENIC SUB-PROVINCE

(Plumb)

In spite of general similarities in their evolution, the Halls Creek and King Leopold segments of the Halls Creek Orogenic Sub-province have important differences in stratigraphy, structure, and metamorphism. Thus, they cannot be regarded as closely analogous orogenic belts flanking the Kimberley Block. The combined geological and gravity evidence suggest that any close analogue of the exposed Halls Creek belt, if present in the west, lies south of the exposed King Leopold belt beneath the Palaeozoic Lennard shelf and Fitzroy Trough.

Hancock and Rutland (1984) have divided the sub-province into several zones (Fig. 6) and the tectonic framework which they have derived forms the basis for most of the evolutionary model presented herein. However, Allen does not agree with many aspects of Hancock and Rutland's framework and considers their model to be a working hypothesis only; while some conclusions agree well with available evidence, others are more tenuous and, in some aspects, fundamentally at variance with her own conclusions. In particular, Hancock and Rutland's definition of zones, largely in terms of metamorphic grade and with boundaries marked by major faults, does not agree with the metamorphic isograds mapped during the several consistent petrological studies of Gemuts (1971), Neville (1974), Hamlyn (1977), Allen (in preparation), and Thornett (in preparation) (cf. Figs 6 & 11), and Allen does not perceive any fundamental difference in structural style, orientation, or numbers of deformations between zones I and II. However, both Allen's and Hancock's work will be described in terms of Hancock and Rutland's zones, as a convenient regional breakup for discussion purposes, and Allen's objections will be detailed in association with Hancock's model for the tectonic evolution of the sub-province.

Hancock and Rutland define their zones as follows:

Zone I is the easternmost zone and comprises low-grade rocks of the Halls Creek Group. It is bounded on the west by elements of zones II and III, and to the east is overlain by younger platform covers. The zone lies in the gravity gradient to the east of the main positive gravity anomaly of the East Kimberley.

Zone II is the complex zone of polydeformation, high-grade polymetamorphism, and syntectonic magmatism in the Halls Creek belt. High grade (IIc) and medium grade (IIa) sub-zones have been defined as being separated by faults and by the main occurrences of syn-tectonic felsic intrusives (IIb).

Zone III comprises the linear batholithic complex of the post-tectonic Bow River Granite, to the west of Zone II. It is essentially parallel to, and lies over the gradient zone to the west of, the main positive gravity anomaly of Zone II.

Zone IV - the "western low-grade zone" - lies to the northwest of zone III and throughout the King Leopold belt, where the low-grade metasediments of the Halls Creek Group and overlying acid Whitewater Volcanics are intruded by granitic complexes of similar age and type to the Bow River Granite.

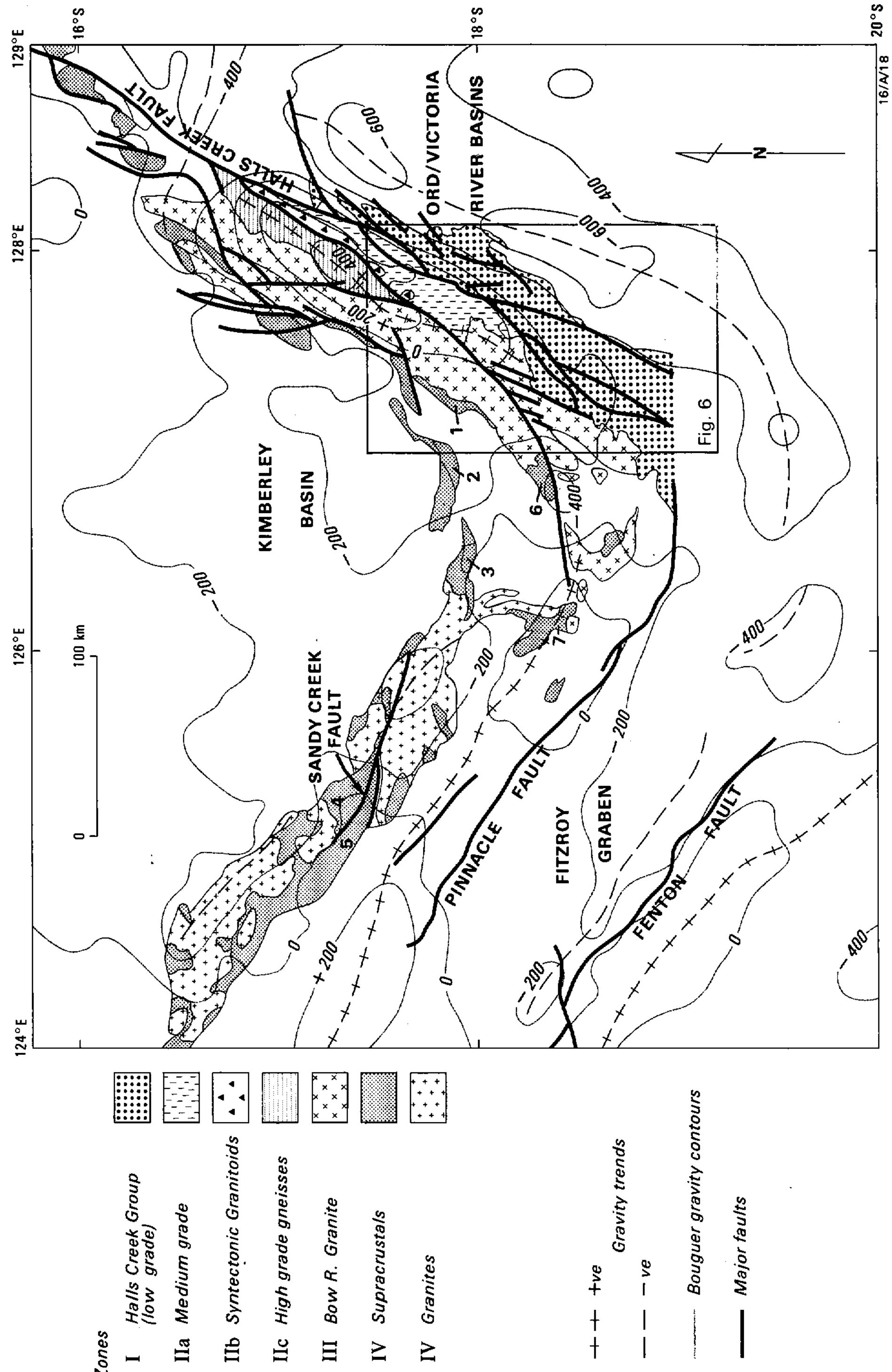

Figure 6. Principal tectonic elements of the Halls Creek Orogenic Sub-Province (after Hancock & Rutland, 1984). Gravity contours are in um/sec^2. Note NW-NE trending belt of inliers which contain low-grade metasediments, Whitewater Volcanics, and post-tectonic granites across the northern part of the Halls Creek domain.
N.B. Inset refers to Figure 8 in this work.

Zone III essentially parallels the main gravity trend and megastructures of the Halls Creek Mobile Zone, but the other zones (I, IIa, IIb, IIc, and IV) run obliquely across this trend. Hancock and Rutland (1984) interpret this as a sinistral system of en-echelon zones, separated by NE-trending (thrust) faults.

STRATIGRAPHY

(Hancock)

Zone 1: Halls Creek Group

The Early Proterozoic, pre-tectonic stratigraphic succession in the Halls Creek Sub-province has been defined as the Halls Creek Group, and comprises four recognised units of Formation status (Fig. 7). Recent work has shown that elements of this succession can be traced through zones I and II (Fig. 6), although sequences in zone II are generally incomplete. Isotopic and structural arguments suggest that zone III also contains rafts of Halls Creek Group although no definitive correlations can be made. Successions in zone IV (Fig. 6) have general lithological similarity to elements of the Halls Creek Group, and sufficient structural and isotopic data are available to indicate that they are probably coeval with the zone I/II sequences, but detailed correlations cannot, at present, be rigorously sustained.

The type areas of the component formations of the Halls Creek Group are located in the low grade, well exposed, <u>relatively</u> little "structured" successions of zone I. Outcrop of the lower two formations is restricted to limited areas around domal culminations in the Biscay Anticlinorium and the Cummins Range, respectively central to and toward the southern margin of zone I outcrop. Relatively similar successions are exposed in these two areas, but too few data are available to assess either the stratigraphic uniformity of these units or the significance of small differences between them. The upper two Formations, Biscay Formation and Olympio Formation, crop out widely in zone I. The Biscay Formation can be subdivided locally into units of member status in the Biscay Anticlinorium and its faulted remnants to the south (Fig. 8), but areas of highly-condensed anomalously-thin units are known, for example, around the Cummins Range Dome. The Olympio Formation has a monotonous sedimentary facies which has, to date, not been subdivided in any detail, but geographic differences are apparent in zone I; for example, conglomeratic units are more prominent in the north-central area than in the south. The pre-tectonic, tholeiitic Woodward Dolerite seems an integral part of the stratigraphic succession in zone I; its typically laterally extensive, closely concordant form and stratigraphic restriction to the richly volcanogenic Biscay Formation and very lowermost Olympio Formation in zone I suggest that it is intimately related to the accumulation of this stratigraphically restricted interval.

The aggregate thickness of incomplete Halls Creek Group successions in zone I is poorly constrained. Estimates given on Figure 7 are derived from thick successions free of obvious late faulting, in the core and peripheral areas of the Biscay Anticlinorium. Earlier repetitions within the Olympio Formation, although not detected in areas examined, may none-the-less be present, and the aggregate stratigraphic thickness of some 8 000 m indicated for the exposed sequence probably represents only an order of magnitude. The following brief notes have been included to augment data presented on Figure 7.

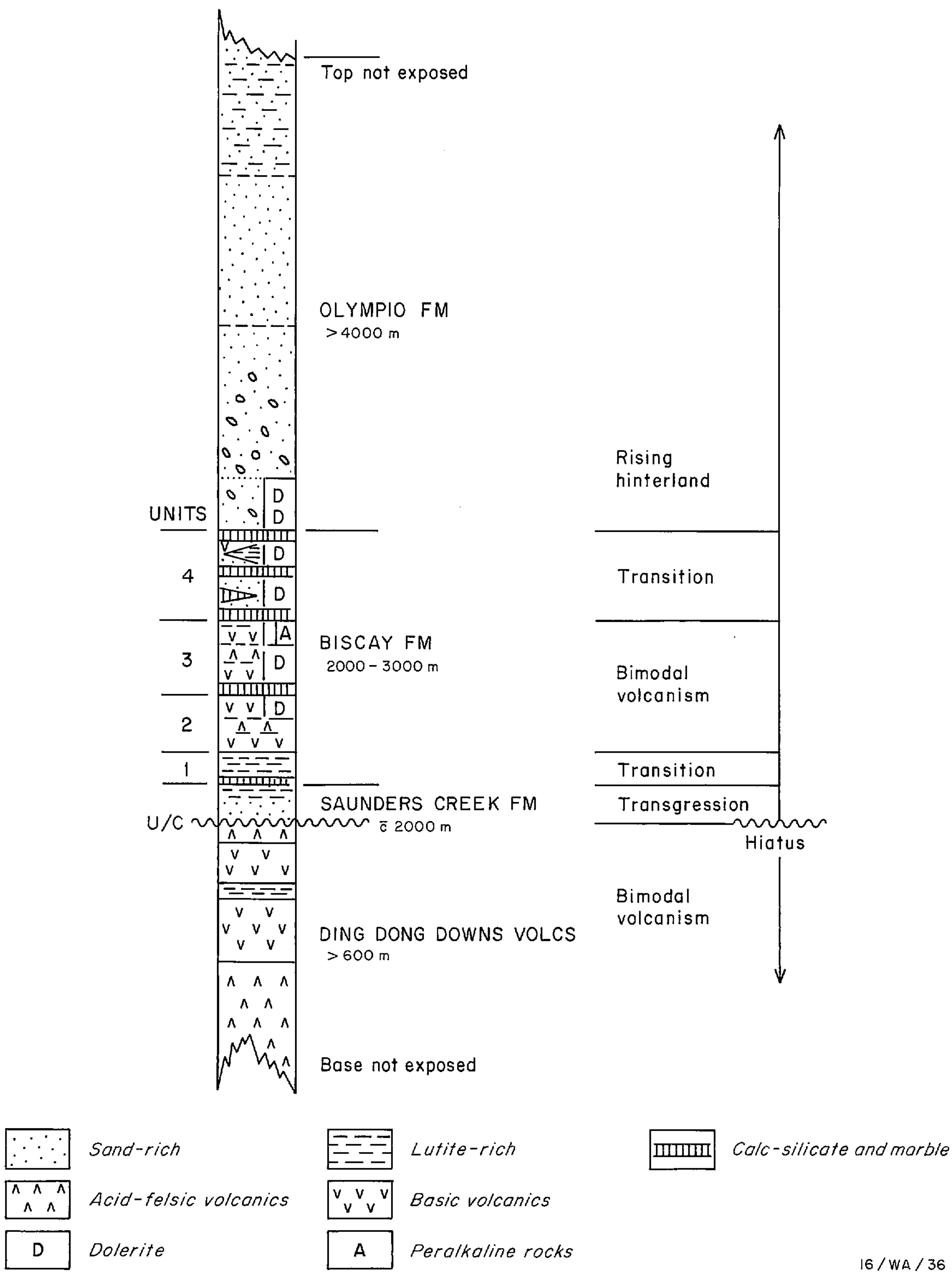

Figure 7. Diagrammatic stratigraphy of the Halls Creek Group, zone I, from data of Hancock (in preparation).

Ding Dong Downs Volcanics: A bimodal volcanic succession comprising up to 1000m of section in the Saunders Creek Dome (Fig. 8) has no mapped base. Basaltic units are amygdaloidal to varied extent; a prominent amygdaloidal metabasalt marker unit is present near the stratigraphic centre of the exposed sequence. Acid units are all rhyolitic to rhyodacitic in phenocryst mineralogy, and include crystal tuffs, crystal-lithic tuffs and chemically immature tuffaceous wacke and phyllite.

The internal stratigraphy of this formation in the Saunders Creek Dome is slightly discordant to the base of the overlying Saunders Creek Formation and minor tilt is indicated in this area prior to Saunders Creek Formation deposition. The stratigraphic similarity between widely separated Ding Dong Downs Volcanics successions in the Biscay Anticlinorium and Cummins Range suggests this is probably not a major unconformity surface.

Saunders Creek Formation: The Saunders Creek Formation is a thin succession (200m) of cross-bedded quartzite, arkosic quartzite and lithic arenite, and interbedded buff phyllite is prominent near the top of the sequence. The lower portion in the south (Biscay Antiform) is an alluvial braided-stream facies, and a beach deposit farther north in the Black Rock Antiform. This facies passes upward, through an interval of undetermined affinity, to shallow-marine successions in the lower Biscay Formation. Heavy mineral bands, chiefly of magnetite and its oxidised products, are conspicuous in the lower portions.

Biscay Formation: As indicated on Figure 7, this is a richly volcanogenic, bimodal sequence, including conspicuous marble, and phyllite derived from fine-grained, variably tuffaceous sediments. It is heavily intruded by Woodward Dolerite. An informal, member- status hierarchy is defined by varied abundance of acid and basic volcanic or subvolcanic units, and by calc-silicate and metasedimentary marker successions. The base of the formation has been set, arbitrarily, at the stratigraphically highest, cross-bedded "Saunders Creek" quartzite, and the top of the unit is defined by a generally poddy, but grossly-continuous calc-silicate band within turbiditic successions otherwise indistinguishable from the Olympio Formation. As such, the sequence is broadly transitional between the subaerial Saunders Creek Formation and deepwater resedimented wacke of the Olympio Formation.

Chemical and petrographic studies of Biscay Formation sequences and the closely allied Woodward Dolerite have defined three suites of igneous rocks (Hancock, in preparation; cf. Allen,this work).

(a) the acid tuffaceous units of Biscay unit 2 and lower unit 3 are rhyolitic to rhyodacitic in phenocryst mineralogy. They are dominated by crystal lithic tuffs and crystal tuffs with associated fine-grained tuffaceous phyllite, including some quartz-albite metasiltstones, and have a chemistry indicative of calc-alkaline rhyolite.

(b) Metabasalt, metadolerite, and metagabbro within the Biscay Formation and Woodward Dolerite include a limited compositional range from ophitic basic units to plagioclase rich accumulates approaching gabbro-anorthosite composition. Their present mineralogy is dominated by amphibole, albite, chlorite, quartz, patchy apatite, leucoxene, and Ti-magnetite. Chemical studies indicate close analogy with N-type MORB units in both major and trace elements and, in general, igneous trends for most elements are little perturbed by metamorphism. Variation across the compositional range seems to have been controlled by cotectic plagioclase-clinopyroxene-olivine fractionation, with spinel fractionation apparently only significant toward the more fractionated

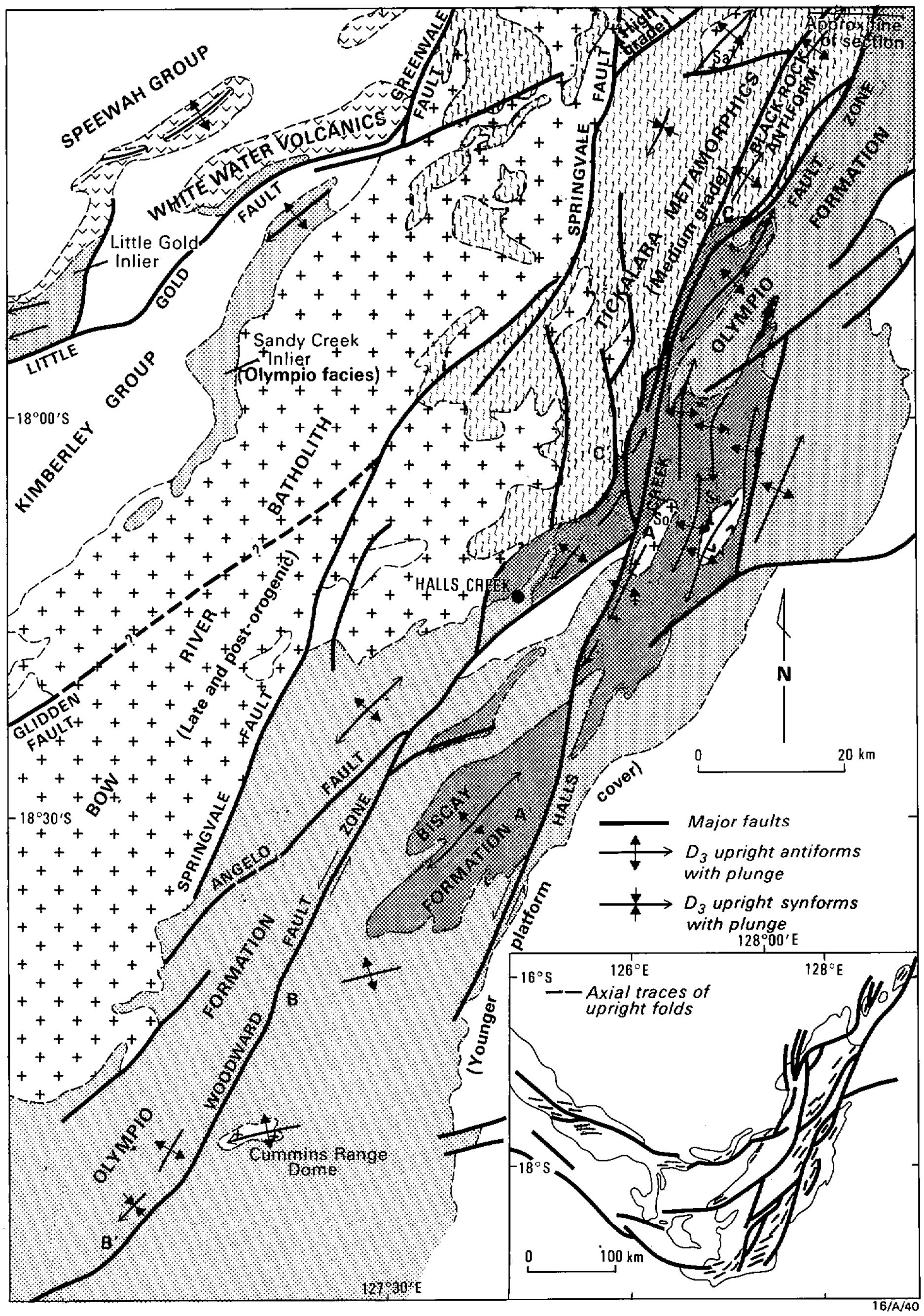

Figure 8. Geology of the Halls Creek area showing trends of upright folds and probable strike-slip movements on the Halls Creek and Woodward faults (after Hancock & Rutland, 1984). Inset shows fold trends for the whole sub-province. N.B. D_3 on this legend is equivalent to D_2 (zone II) in this work.

end of the compositional spectrum.

(c) A distinctive suite of probably subvolcanic spherulitic and trachytic to latitic, highly fractionated acid units and related crystal tuffs, crystal-lithic tuffs and highly tuffaceous sediments, recognised in upper Biscay unit 3 (Fig. 7) in the central parts of zone 1. These have extreme enrichments in incompatible, highly charged trace elements (Zr, Nd, Y, Sn, Cl, Nb) reminiscent of Phanerozoic peralkaline suites, but a texturally intact and apparently little modified composition which is only subalkaline to alkaline in composition. Most units are highly felsic with quartz (0-20%), alkali feldspar, and albitic plagioclase being dominant constituents, and with fine biotite, minor fine spinel, and rare alkali amphibole (Bofinger, 1967) the only mafic minerals present.

They are interpreted as the deformed products of highly fractionated "A-type rhyolite" (Collins et al., 1982) transitional upward to peralkaline rhyolite. The presence of highly felsic latite/trachyte may suggest an origin via extreme fractionation of basaltic magma, but too few data are available to make any firm petrogenetic hypothesis and units intermediate between basalt and latite are not known.

Olympio Formation: This is the uppermost, areally most extensive succession in zone 1. It comprises a thick (>4000m), relatively monotonous succession of coarse to medium-grained quartz-feldspar-lithic wacke of turbidite derivation. They are particularly quartz-rich, and K-spar is the dominant feldspar. The lower and upper-middle parts of the sequence are dominated by medium-grained wacke, transitional to more phyllitic units near the stratigraphic top (Dow and Gemuts, 1969). The lower-middle stratigraphic interval is conspicuously coarser grained and frequently conglomeratic.

Short detailed measured sections through the lower and middle portions of the Olympio Formation indicate accumulation on an extensive submarine fan complex, which was sourced in the west and north. Most facies are reminiscent of sequences of "mid-fan" affinity and include deposits which may have accumulated in broad, open, midfan channels and lobes (for example, Walker, 1978).

An actively rising high-level granitic-acid volcanic-low grade metamorphic provenance is clearly indicated by sample petrography, and the relative coarseness and shape immaturity of most detritus indicates little "across-shelf" transport, prior to accumulation in the submarine fan complex. Palaeocurrents indicate transport from the NW, across rather than along the axis of the basin.

Zone IV Sequences

Halls Creek Group: Sequences in zone IV are dominated by thick (>2000m), greenschist facies meta-turbidite wacke, petrographically similar to the Olympio Formation. Only in the West Kimberley is a more complete section preserved, and this is indicated schematically in Figure 9. Wacke units of Unit 1 are similar in grainsize and facies to the wacke sequences in the eastern portions of zone 1 (Olympio Formation) and their petrography is similarly dominated by detrital quartz, but plagioclase rather than K-feldspar in the limited number of samples studied to date. The overlying Unit 2 sequence has a basal zone of intercalated graphitic and tuffaceous phyllite, which becomes dominated by quartz-muscovite-biotite tuffaceous phyllite up sequence. Intercalated crystal tuffs are more common near the top of the section. Thick tholeiitic sills mapped as Woodward Dolerite occur as variably fractionated gabbroic to feldspar-accumulative anorthositic gabbro bodies, and are strictly concordant to mappable stratigraphy and closely coincident with the Unit 1/Unit 2 boundary over most of the area.

(Plumb)

Whitewater Volcanics: Throughout zone IV, the Halls Creek Group is unconformably overlain by up to 3500 m of porphyritic acid volcanics - the Whitewater Volcanics - and these are in turn unconformably overlain by the Kimberley Basin succession. The volcanics are petrographically and spatially related to the high-level intrusive **Castlereagh Hill Porphyry** of zones III/IV and to the **Bickleys Porphyry and equivalents** in the West Kimberley, and the volcanics as mapped include a considerable amount of undifferentiated

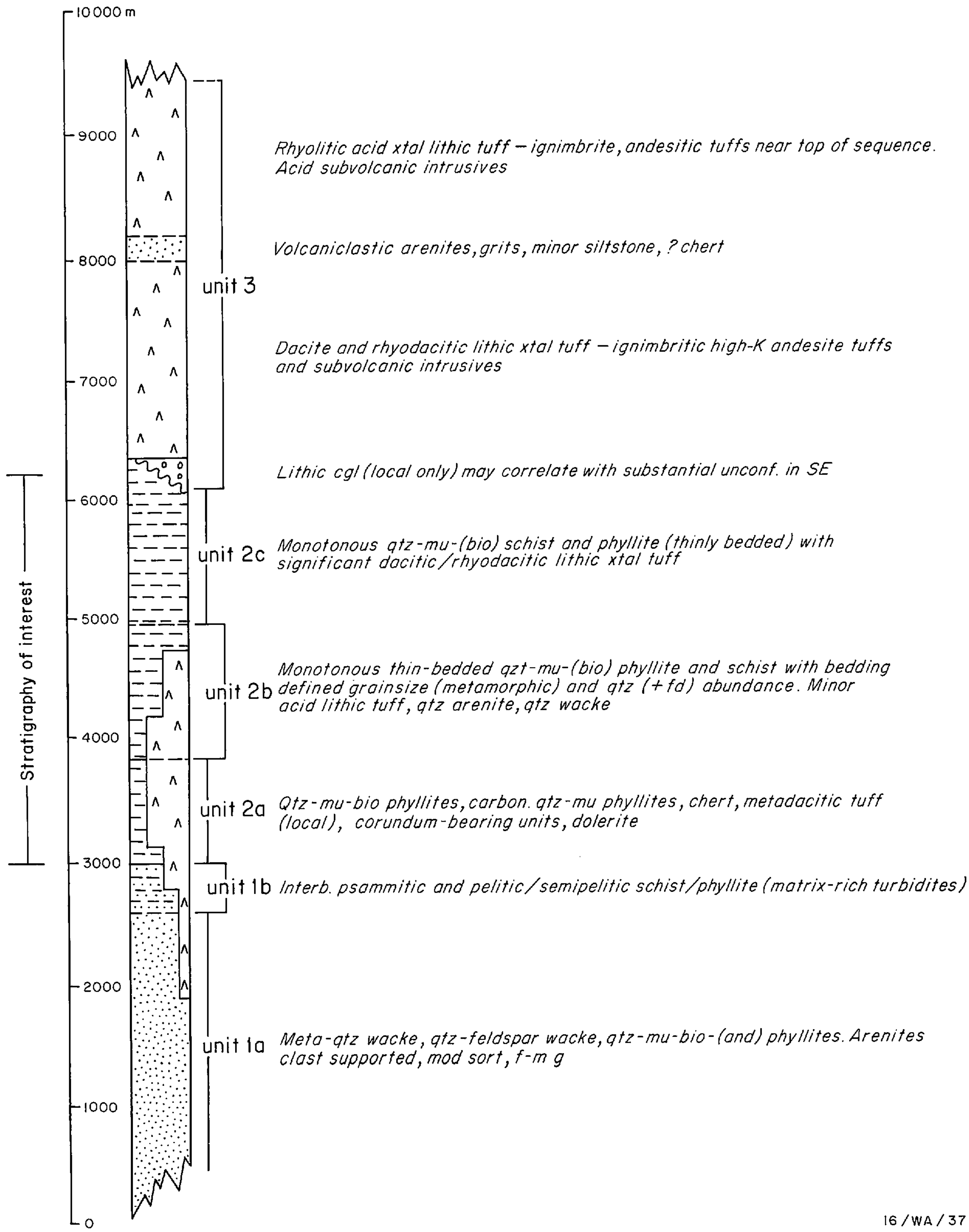

Figure 9. Diagrammatic stratigraphy of the Halls Creek Group, zone IV (west), from data of Hancock (in preparation).

intrusive porphry. Both the volcanics and the porphyries are intruded by the post-tectonic Bow River Granite (zone III) and Lennard Granite and equivalents in the West Kimberley. In the East Kimberley, the volcanics and porphyries are only mildly deformed, display only mild unconformity with the overlying Kimberley Basin, and are spatially associated with the post-tectonic Bow River Granite; these were all grouped and assigned to transitional tectonism (GSA, 1971). In the West Kimberley, however, the volcanics and porphyries have been strongly deformed and metamorphosed by at least two events, D_{2B} and D_3, before the post-tectonic Lennard Granite and associated bodies were emplaced (Tables 2, 7).

Gellatly et al. (1975) have documented a transition in the volcanic succession from basal high-K andesites (feldspar-pyroxene-biotite porphyry) to rhyodacite (quartz-feldspar porphyry) in the higher levels. Texturally, they are ignimbrites or ash-flow tuffs. A basal conglomerate contains pebbles of Halls Creek Group in some places, and volcanic pebbles elsewhere. Similar beds of conglomerate and other volcaniclastic sediments are scattered through the sequence. These rock types pertain throughout the region.

GEOCHEMICAL CHARACTERISTICS OF VOLCANIC ROCKS

(Allen)

Detailed geochemistry on suites of Lower Proterozoic felsic volcanics and basalts has led to the following conclusions:

Felsic volcanics

1. The Lower Proterozoic calc-alkaline volcanic rocks from the Halls Creek Sub-province 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 Ding Dong Downs Volcanics appear to define a distinct population.

5. Within the Biscay Formation, the peralkaline suite and the "Corkwood East Suite" form well-defined populations; the "Wills Creek Suite" needs closer definition.

6. The Whitewater Volcanics define a separate population. Differentiation trends for some elements are displaced parallel to the general trend, and for other elements define a different slope.

7. The Gawler Range Volcanics of South Australia have significantly higher Y, Zr, and Nb levels than the Kimberley felsic volcanics. The exception to this generalisation is the suite of peralkaline volcanics, with very high values of these high field strength elements.

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

   The Ding Dong Downs Volcanics have crystallised - plagioclase, magnetite, K-spar, apatite, and zircon.

   The "Corkwood East Suite" has crystallised - plagioclase, magnetite, (apatite and zircon?)

The Whitewater Volcanics have crystallised - orthopyroxene, plagioclase, magnetite, apatite, and zircon.

Basic volcanics

1. All the analysed basaltic rocks from the Halls Creek Orogenic Sub-province are tholeiites.

2. In addition to the characteristic tholeiitic iron enrichment, these Lower Proterozoic basaltic rocks are consistently more iron rich than the Cambrian tholeiitic Antrim Plateau Volcanics from the same region.

3. All the basalts are evolved, the most primitive having a magnesium number of 45.

4. Plagioclase is a ubiquitous phenocryst phase. No olivine and/or pyroxene basalts have been recorded from the East Kimberley. However, the geochemistry indicates extensive fractionation of olivine, pyroxene, and plagioclase.

5. Trace element geochemistry indicates that the basalts of the Biscay Formation, the basalts of the Ding Dong Downs Formation, and the Woodward Dolerite form three discrete populations.

6. Geochemical plots of basalts from the various formations, using different discrimination techniques of the authors below, show the following comparisons with modern volcanic environments:-

   A (Pearce et al., 1975)
   - (i) Biscay Formation plots generally in the Oceanic Basalt field
   - (ii) Ding Dong Downs Formation plots generally in the Non-Oceanic field.
   - (iii) Woodward Dolerite is widely scattered.

   B (Pearce & Cann, 1973)
   - (i) All the Biscay Formation plots within the Ocean Floor Basalt field.
   - (ii) The Ding Dong Downs Formation straddles the Within-Plate and Calc-Alkali basalt fields.
   - (iii) The Woodward Dolerite plots within the Calc-Alkali Basalt field.

   C (Floyd & Winchester, 1975)
   All samples plot as tholeiites straddling the Oceanic and Continental Tholeiite fields.

   D (Mullen, 1983)
   - (i) The Biscay Formation generally plots within the MORB field.
   - (ii) The Ding Dong Downs Formation plots within the Island Arc Tholeiite field.
   - (iii) The Woodward Dolerite straddles the Island-Arc Tholeiite and the Calc-Alkali Basalt fields.

   E (Shervais, 1982)
   Basaltic rocks from the Kimberleys plot closest to the Back-Arc Basin field, with some overlap into the MORB field.

Thus, the felsic and basic volcanic rocks, while coeval, are not comagmatic.

TECTONIC SETTING

(Plumb)

Although the only known basement to the Kimberley Basin is the Early Proterozoic rocks of the Halls Creek Orogenic Sub-province, exposed around the upturned basin margins (Plumb & Gemuts, 1976), Gellatly (1971) proposed from gravity evidence that an Archaean craton underlies the Kimberley Block. This is supported by Hancock and Rutland (1984) from evidence of sedimentary source areas and tectonic polarity in the Early Proterozoic orogen. In the absence of any evidence for the involvement of oceanic crust and other critical features of a "Wilson-cycle" collision belt, Hancock and Rutland interpret the Halls Creek sub-province as a distinctive type of linear ensialic orogen, lying astride a "suture zone" between an island continent (Kimberley Block) subject to persistent volcanic activity, and a wide zone of attenuated continental crust (North Australian Province) to the east.

(Hancock)

The Halls Creek Group can be subdivided into three sedimentary stages (Fig. 7): Ding Down Downs Volcanics (?rifting stage), volcanolithic pre-flysch stage (lower Biscay Formation), and "flysch" facies successions (upper Biscay and Olympio Formations). We suggest that this succession documents five broad stages of basin evolution:

1. **Tectonically active rifting,** commencing at the base of the exposed sequence, with the emplacement of the subaerial and shallow-subaqueous bimodal suite of the Ding Dong Downs Volcanics.

2. **Separation of fault blocks and further basin segmentation,** probably at a variety of scales, which controlled the subsequent homogeneous basin development. The general character of the unconformity at the base of the Saunders Creek Formation is reminiscent of Phanerozoic "breakup" unconformities (e.g., Falvey, 1974).

3. **Establishment of a MORB-style thermal regime,** beneath the rifted-basin floor, and continued thermally active rifting and associated bimodal volcanism (lower Biscay Formation).

4. **Basin-margin tectonism and active faulting,** accompanying the onset of flysch deposition and associated with the continued attenuation of the basin floor (upper Biscay Formation). The sub-basin lithosphere probably approached levels of attenuation characteristic of near ocean floor crustal thickness by this time (extension factor, B>=4).

5. **Continued subsidence,** probably accelerated by basin-margin tectonic loading associated with the accumulation of a thick turbidite sequence.

A notable attribute of the stratigraphic record is the nexus between basin-margin orogeny and continued emplacement of MORB-type magma into the host basin. This apparently anomalous juxtaposition of criteria, normally associated with crustal compression and extension, respectively, will be discussed below.

STRUCTURAL EVOLUTION - ZONES I AND IV

(Hancock)

The dominant structural elements in the low to moderate grade successions which comprise zones I and IV (Fig. 6) are upright folds and associated cleavage of crenulate to penetrative form. Fold envelopes, from mesoscopic to regional, trend parallel to the long dimension of the basement outcrops, and typically plunge flatly in zones I and the eastern part of zone IV; steeply plunging structures are only known to be regionally developed in the West Kimberley (zone IV, west).

Zone I

A polyphase structural development can be recognised in sporadic areas across the outcrop extent of zone I, and structural elements can be related to three "deformation" events. D_1 structures are of restricted distribution, are generally parallel to bedding, and have a "stratiform" distribution within the lower elements of Halls Creek Group stratigraphy. Veining, tight to isoclinal folds, penetrative cleavage, and sporadic mineral lineations are associated with D_1 zones, but no mappable shear separations have been defined to date.

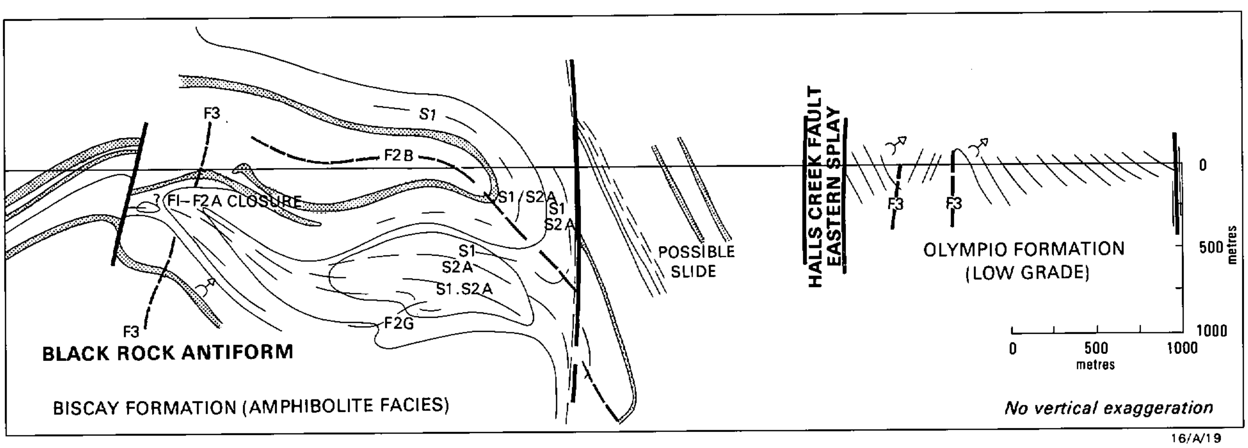

Figure 10. Structure across the eastern splay of the Halls Creek Fault (NE corner, Figure 8), across zone I - zone II boundary (after Hancock & Rutland, 1984). Arrows show facing of sedimentary structures.

The ubiquitous D_2 event is the expression of the grossly NNE-trending, flatly doubly-plunging macroscopic fold envelope which moulds the outcrop form of zone I. Mesoscopic structures associated with this event include common tight flatly-plunging folds, intersection lineations, and an upright greenschist-facies S-surface which varies from crenulate to penetrative in form. Stratigraphic and structural mapping indicate that shortening of 40-50% occurred across the S_2 surface over significant areas of zone 1 during D_2.

An interesting aspect of D_2 geometry is the localisation of post D_2-granitoid domes (Sophie Downs, Cummins Range) in D_2 closures, whose geometry reflects a rigid substrate prior to D_2. The structural history of both areas is marked by the preservation of pre-D_2 structural elements, due probably to strain shadow effects, although some of this structure also relates to their peculiar structural position. Pre-D_2 granitoid cores may be indicated by structural data in both areas and Bofinger (1967) has some isotopic evidence of possibly older (ca. 2100 Ma) material in the Cummins Range, and the sense of structural development around the domes suggests a rotational component of D_2 strain, compatible with a nexus between D_2 folding and left-lateral strike-slip shear.

Superimposed on D_2 structures are a range of other structural elements (D_3) which develop in discrete zones, probably associated with shear movements. Associated S-surfaces are almost always crenulate in form; folds and intersection lineations, where mapped, are typically steeply inclined. Host "shear zones" can be developed on a variety of scales, from metres to a kilometre or so, and preferential trends are NNE and ENE. These structures are considered to be intimately associated with a strong left-lateral shear system, associated with the initiation of the left-lateral Halls Creek fault system.

Fault movements have proved difficult to quantify in detail and the complex history of the Halls Creek Mobile Zone, subsequent to cratonisation of the basement terrane, renders association of mappable displacement with Early Proterozoic evolution almost impossible. Estimates of gross strike-slip displacement across structures of the Halls Creek fault system range from in excess of 200 km (Rod, 1966) to several tens of km (Plumb and Gemuts, 1976). Data relevant to this are shown on Figure 8, and indicate an accumulated post-D_2/D_3 left-lateral, displacement on splays of the Hall Creek Fault in excess of 60 km. Redistribution of strain across the extent of the Halls Creek Mobile Zone could clearly produce net left-lateral strain in excess of 100 km.

Using estimates of D_2 shortening and net strike-slip displacement, a restored zone 1 outcrop would be in excess of 300 km along strike and in excess of 150 km across strike. Clearly a basin of very significant size is indicated, because neither estimate includes likely along-strike correlations or across-strike sequences hidden under younger cover.

Zone IV

Zone IV can be considered best as two areally discrete units: zone IV (east) adjacent to zone III, of NNE to NE/ENE trend parallel to the East Kimberley structural grain ;and zone IV (west) in the West Kimberley (Fig. 6). The zone IV (east) stratigraphic and structural successions are more closely reminiscent of zone I than are those in the West Kimberley.

Reconnaissance-scale structural mapping in zone IV (east) has identified a similar polyphase structural history to zone I. The earliest tectonic S-surface is closely layer-parallel, and associated with recumbent folds developed in significant thicknesses (hundreds of metres) of the quartz wacke association. Sparse data suggest that this event may have had geometric fold axes parallel to overprinting D_2 structures, and the occurrence of breccia zones of wacke in cleaved phyllite, near the base of overturned successions in one area, suggests a high-level thrusting and recumbent folding event.

The dominant mesoscopic and macroscopic structures in zone IV (east) are upright, east or southeast vergent, flatly doubly-plunging, asymmetric, tight folds and a penetrative to rarely crenulate S-surface, of lower greenschist facies. The axial planes of these D_2 structures gently curve from NNE in the north through NE to ENE across the trend of zone IV (east) outcrops, in sympathy with outcrop distribution of the basement province. The gross structure of the D_2 envelope across zone IV (east) is assymmetric and east vergent, and this was probably the result of its imposition upon already west-dipping structural sequences of D_1 age. Outcrop relationships indicate that the Whitewater Volcanics, which unconformably overlie units of the Halls Creek Group over the extent of zone IV, were emplaced late in and during the D_2 event.

As in zone I, a range of spatially discrete structural elements, commonly associated with crenulate S-surfaces and steeply dipping intersection lineations, have been superimposed on the D_2 envelope. Collectively, these are grouped as D_3 structures, where they pre-date Kimberley Basin deposition. Structures of similar trends to those in zone I occur throughout the extent of zone IV (east) in the north, but a distinctive, strong, crenulate structural surface of NW trend has been superimposed on the southern extremity of zone IV (east), near the area of strong reorientation toward the junction of East Kimberley and West Kimberley parts of the basement province.

Structural and stratigraphic mapping in parts of the West Kimberley basement province (zone IV, west) has indicated a polyphase structural history which can be tied only partially to the zone IV (east) structural succession. The earliest macroscopic structure in this area is a tight folding event of regional extent, which varies from upright in the greenschist facies terrane to near recumbent in amphibolite-facies Halls Creek Group. This structure is imposed upon both the Halls Creek Group and the Whitewater Volcanics and, prior to its overprinting by later structures, the upright fold envelope had a grossly east-west orientation and relatively flat plunge. A distinctive generation of greenschist and lower amphibolite facies static metamorphic textures, comprising most elements of the metamorphic zonation of this basement terrane by Gellatly et al. (1974b), was developed late in this event, and association is likely with a prominent episode of emplacement of mafic (Wombarella Quartz Gabbro), intermediate (McSherries Granodiorite), and acid (Kongorow Granite) magma at this time. Structural and chronological considerations suggest this event correlates closely with the D_2 event in zone IV (east) and I.

Superimposed on this D_2 envelope is a strong regional folding event about NW-trending upright axial planes, assigned to D_3. S_3 surfaces are generally crenulate, but macroscopic and mesoscopic D_3 folds are tight and pervasive. These form the most commonly encountered minor folds in zone IV (west). Fold axes plunge steeply, in accord with the imposition of this envelope on upright D_2 structures across the extent of the greenschist facies terrane in zone IV (west), but flat plunges are common in amphibolite facies terranes adjacent to the onlap of Phanerozoic cover at the southwestern margin of the outcrop belt. These structures are strongly developed equivalents of the NW-trending structural suite, prominent at the southern end of zone IV (east).

As in zones I and IV (east), a range of pre-Kimberley Basin structures is confined to relatively discrete zones in the West Kimberley. These structural zones commonly trend near east-west in this subzone, and are associated with localised strong metasomatism, probably broadly coincident with the intrusion of late granitoids (the megacrystic Lennard Granite suite). Major faulting along the NW-trending structural grain of the zone also occurred at this time, but inferred displacements seem to have been relatively minor. The only structure with a quantifiable shear displacement is the Sandy Creek Shear Zone, where opinions vary as to the sense and magnitude of shear. Gellatly et al (1975b) suggest a sinistral displacement of 5 km from correlation of lenses of Woodward Dolerite but our view is that a better reconciliation of sequence is provided by a dextral displacement of approximately 18 km in the Sandy Creek Valley. Later sinistral offset of 10 km can be conclusively demonstrated for post-Kimberley Basin dykes.

IGNEOUS AND METAMORPHIC EVOLUTION - ZONES II AND III

Lamboo Complex

(Plumb)

The Lamboo Complex comprises all of the Lower Proterozoic igneous and high-grade metamorphic rocks of the Kimberley region which postdate the Halls Creek Group, and which are unconformably overlain by the Kimberley Basin succession or its equivalents. However, the term is being progressively abandoned by recent workers as the complexities of the region are unravelled and the evolutionary history emerges as a typical diachronous continuum. In particular, the deformation/metamorphism/intrusive phases of the Complex overlap the deposition of both the "preorogenic" Halls Creek Group and "post-orogenic" Whitewater Volcanics (Hancock & Rutland, 1984), and the stratigraphic units of the Halls Creek Group can now be identified and mapped into the high-grade rocks of the "Tickalara Metamorphics".

(Allen)

Igneous rocks, both intrusive (Lamboo Complex) and extrusive (Halls Creek Group & Whitewater Volcanics), crop out extensively in both belts of the Lower Proterozoic Halls Creek Subprovince (Table 3). Two of the formations of the Halls Creek Group (Ding Dong Downs Volcanics and Biscay Formation) are largely composed of volcanic material, and huge volumes of acid volcanics (Whitewater Volcanics) blanketed the region at the close of the Lower Proterozoic orogenic cycle. Intrusive rocks obliterate much of the stratigraphy. Magmatic material intrudes as extensive sills (Woodward Dolerite), lopoliths of differentiated ultrabasic and basic material up to 30-40 km in diameter (e.g. Toby Sill, McIntosh Sill), or as late mineralised bodies (e.g. Sally Malay ultramafic complex). "Granitic" plutons range from small stocks and veins to the elongate foliated Mabel Downs Granodiorite, and extensive sheets of late-tectonic Bow River Granite and Lennard Granite, and equivalents. This magmatic-volcanic activity spans the entire thermal history of the Halls Creek subprovince, from syn-deposition (ca 2,000 Ma) to post-tectonic (ca 1830 Ma). The Middle Proterozoic platform sequence also contains abundant igneous rocks, and actively continues into the Palaeozoic with outpourings of tholeiitic basalt (Antrim Plateau Volcanics).

The tectonism of the Halls Creek Group and the pre to syn-tectonic intrusive rocks have been accompanied by metamorphism through several stages, to grades ranging from greenschist to granulite facies (Tickalara metamorphism). A younger, post-Whitewater Volcanics metamorphism (not detailed here), up to amphibolite facies, has occurred in the West Kimberley (Gellatly et al., 1974b). Allen (in prep.) has identified more deformation/metamorphic phases in the high-grade rocks of zone II (Table 4) than in zone I, and thus the nomenclature in the following section differs from that immediately preceding.

SYNTECTONIC INTRUSIVE ROCKS

Mafic - ultramafic intrusives

(Plumb)

Mafic and ultramafic rocks, emplaced into the Halls Creek Orogenic Sub-province before (Woodward Dolerite), during (Alice Downs Ultrabasics), and late (Mcintosh Gabbro) in the deformation /metamorphism (Table 3), comprise one of the most voluminous rock-types in the sub-province, particularly in zone II. Recent work has significantly expanded the history of emplacement by Dow and Gemuts (1969), and some relationships remain problematic.

There is a broad spatial relationship between the abundance of basic bodies (McIntosh Gabbro) and increasing grades of metamorphism in zone II and, together, they correlate with and presumably explain the prominent positive gravity anomalies of the East Kimberley. There is possibly a northward migration in times of emplacement with times of peak metamorphism (see discussions below). Together, these relationships perhaps imply a connection between the magmatic and metamorphic (high-temperature) heat sources.

Woodward Dolerite: Tholeiitic sills and dykes, ranging from a couple of metres long and several centimetres thick, to 20 km long and 600 metres thick, intrude the Halls Creek Group in zones II and IV. They have been folded and metamorphosed by all events, and metamorphosed equivalents probably comprise many of the metabasics in zone II.

Alice Downs Ultrabasics: The 1 km-thick layered Panton Sill has been folded into a southerly plunging syncline and disrupted by transverve faults. The basal contact is strongly sheared; a lower ultramafic cumulate zone, originally of harzburgite, dunite, and chromitite, is separated from the overlying zone of banded mela-gabbros, leuco-gabbros, and anorthosites, by a faulted sheared contact; the contact with overlying metasediments is exposed in the core of the syncline. The primary igneous mineralogy has been extensively serpentinised and uralitised during later metamorphism (Hamlyn, 1980).

McIntosh Gabbro: Gabbro, troctolite, norite, and minor anorthosite and ultramafics occur in the large (up to 30 kms across and 1.5 km thick) layered McIntosh and Toby sills, in dismembered sills and irregular bodies, and, very commonly, in roof pendants in Bow River Granite. All were mapped as McIntosh Gabbro by Dow and Gemuts (1969), but may now include bodies of several generations (Table 3).

The large sills are rhythmically layered, preserve primary igneous mineralogy throughout most of their thickness, and are uralitised at their margins. They have been folded into broad synclines or basins and most of the contacts are faulted. Thornett (1981) has described preserved intrusive contacts in the smaller, mineralised, layered mafic-ultramafic Sally Malay sill, but this may be of younger age (Table 3).

Age relationships: From their spatial association with the contact between the Biscay and Olympio Formations in zone I, and between Units 1 and 2 in zone IV, Hancock and Rutland (1984) have proposed syndepositional emplacement for the pre-metamorphic Woodward Dolerite.

Dow and Gemuts (1969) interpreted the layered sills of Alice Downs Ultrabasics as the basal zones of the larger layered sills of McIntosh Gabbro. Hamlyn (1980) showed that the primary igneous mineralogy of the Alice Downs Ultrabasics in the Panton sill equilibrated at a depth of 25-30 km, at 800-1100^{o}C and 8-9 kb. Following emplacement into a higher crustal level, this mineralogy was then reequilibrated at 550^{o}C and 4-6 kb, in the middle amphibolite facies; the metamorphic zone within which it is now found. Hancock and Rutland (1984) therefore interpreted them both as exotic bodies, crystallised at depth before D_2, and then emplaced tectonically into their present position, by thrusting from the northwest across zone IIa during D_2.

However, Hamlyn (1977) has shown from trace element data that the Panton (Alice Downs) and McIntosh sills must come from different magma sources, and also that they have had different metamorphic histories. The Panton Sill was equilibrated in the Lower Sillimanite Zone, and must have been emplaced during or before the peak metamorphic temperatures of this zone, reached during D_{2A}/M_{2A} (see Allen, below). The overall lack of recrystallisation of the McIntosh sill suggests emplacement after D_{2A}; probably during D_{2B} thrusting, under waning metamorphic temperatures, and before D_3/D_4 folding (Fig. 13).

The smaller Salay Malay sill was intruded and later mildly folded after peak metamorphic temperatures were reached in the granulite facies hosts (Thornett, 1981); i.e. after D_3 and probably before D_4 (Table 3; Allen, below; Fig. 13).

Rocks mapped as McIntosh Gabbro therefore include a range of bodies, probably emplaced at various times, and emplacement may have migrated along the belt in sympathy with the migrating peaks of metamorphic temperature.

Mabel Downs Granodiorite

(Allen)

Five syntectonic "granites" have been mapped in the Halls Creek Mobile Zone (Table 3).

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. It is mapped on Fig 11 as "Syntectonic Acid Intrusives" and shows the regional NNE trend of the fold belt. This batholith and the related granitoids in its vicinity consist of a number of "granite" types, which can be distinguished in the field by differences in mineralogy and fabric. Contact relationships indicate that they have been intruded over a range of time either pre-dating or syntectonic with D_2 (Table 3). They are generally foliated with a quite well developed S_2 schistosity. Their distribution, contact relationships, and petrology are briefly described under the following informal names:

TABLE 3

Correlation of igneous events in the Halls Creek Orogenic Sub-province with deformation events in zones II or IV, by Allen. From data of Allen (in prep), Dow and Gemuts (1969), Giles and Manktelow (1979), Hamlyn (1977), Hancock and Rutland (1984), Plumb and Gemuts (1976), and Thornett (1983).

ISOTOPIC AGE	DEFORMATION	ROCK UNIT	DISTRIBUTION E or W Kimberley	ROCK TYPE	STRATIGRAPHIC RELATIONSHIPS
		"Late granitoids"	W	Granodiorite, tonalite, gran.	Intrudes Lennard Granite
		Violet Valley Tonalite	E	Biot. tonalite, granodiorite.	Intrudes Bow River Granite
1840±40 Ma 1834±32 Ma		Lennard Granite etc. Bow River Granite Sophie Downs Granite McHales Granodiorite	W E E E	Granitic batholithic cplx.) Granitic batholithic cplx.) Granophyric granite) Biotite granodiorite)	POST-TECTONIC. Intrude Whitewater Volc, Halls Ck Gp. Intrudes metamorphosed Halls Ck Gp.
	D_{2B} (IV)	Wombarella Quartz Gabbro	W	Opxene qtz gabbro & tonalite	Syn-D_{2B} in zone IV
		McSherries Granodiorite Kongorow Granite	W W	Foliated biot-hblde granodior Fol. gran. batholith cplx	Syn-D_{2B}, zone IV. Intrudes Whitewater V., Halls Ck Gp.
		Bickleys Porphyry etc. Castlereagh Hill Porphyry	W) E)	Quartz-feldspar porphyry & porphyritic microgranite	Cogenetic(?) with Whitewater Volcanics
		Whitewater Volcanics	W & E	Andesitic to rhyodacitic ignimbrite	Unconformably overlies Halls Ck Gp.
	UNCONFORMITY				
	D_4 (II) D_3 (II)	"Sally Malay, Corkwood, & Bow R." mafics & ultramafics. (Ni-Cu bearing)	E	Peridotite, troctolite, norite, gabbro. Ultramaf. granulite. Norite	Multiple intrusions. Mineralised suite post-M_3 Intrudes early u/m; intruded by norite.
	D_{2B} (II)	McIntosh Gabbro - McIntosh, Toby Sill Cplxs	E	Troctolite, olivine gabbro, norite; minor anorthosite. Gabbro.	Circular sills unmetamorph; primary minerals preserved. Gabbros sheared, metamorph. No hornfels or chilled margins
1920±30	D_{2A} (II)	Mabel Downs Granodiorite	E	Foliated hornblende granodiorite.)	Syn-S_2 (II). Folded by D_3 & D_4. Intrudes "Melon Patch Gran." Halls Ck Gp.
		"Dougall's Tonalite"	E	Tonalite)	
		McIntosh Gabbro, foliated	E	Foliated gabbro	Intruded by Mabel Downs Grano.
		Alice Downs Ultrabasics	E	Harzburgite, dunite, peridotite, troctolite. Gabbro.	Metamorphosed by M_{2A} (II). U/m-gabbro contact sheared, intruded by trondhjemite.
		"Melon Patch Granite"	E	Even-gr. biotite granite	Syn-S_2 (II).
		"Black Rock Tonalite"	E	Coarse biot-hblde tonalite.	Syn-S_2. Folded by $D_2/D_3/D_4$ (II)
		"White Rock Leucogranite"	E	Leucogranite. Biot. & garnet variants.	Intruded by Mabel Downs Granodiorite.
		"Unit 2" - Halls Ck Gp, zone IV.	W	Acid-intermed. crystal tuffs. Conglomerate base.	Folded by D_1, D_{2A} (IV).
		Woodward Dolerite	W & E	Altered intrusive dolerite sills & dykes	Regionally stratabound - Biscay-Olympio & Unit 1-2 contact zones. Folded, metamorphosed.
Ca 2 000 Ma		Biscay Formation	E	Bimodal. Basalt & rhyolitic to rhyodacitic tuffs.)	Separated by "breakup" unconformity.
		Ding Dong Downs Volcanics	E	Bimodal. Basalt & rhyolitic to rhyodacitic tuffs.)	

(a) "Black Rock Tonalite"
(b) "White Rock Leucogranite"
(c) "Melon Patch Granite"
(d) "Dougal's Tonalite"

and the type Mabel Downs Granodiorite.

"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. It has an S_2 schistosity and an L_1/L_2 lineation defined by biotite and amphibole.

"White Rock Leucogranite": The southeast portion of the main body of Mabel Downs Granodiorite (Fig. 11) 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, and includes the leucogranite as rare xenoliths. A small body of this leucogranite crops out to the south-southwest, with the Ord River swinging north around it. The rock is white, pink or buff, massive, and xenolith poor. It is very quartz-feldspar rich (plagioclase and microcline; approx. 90%), with grains and aggregates of quartz standing out in relief on the weathered surface. It is locally garnetiferous, with a few subhedral almandine garnets up to 6 mm 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. 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 recrystallisation. All are muscovite-bearing, and small amounts of magnetite are ubiquitous. Although these variants have different field expression, the geochemistry is very similar and, in particular, the trace element abundances are virtually indistinguishable.

"Melon Patch Granite": This granitoid crops out extensively in the Melon Patch Bore area, where it was first recognised. It is a fine-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 xenolith 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 hornblende-bearing 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, through foliated medium-grained biotite-rich granodiorite..."; this latter is the "Melon Patch Granite", described above. However, contacts are not gradational, but intrusive. Contact relationships are quite definitive in the Melon Patch Bore area, where both granitoids crop out extensively.

"Dougal's Tonalite": The small triangular stock south of the Ord River has similar mineralogy and fabric to the hornblende-bearing phase of the Mabel Downs Granodiorite. It is a foliated coarsely-porphyritic biotite-hornblende tonalite. Aerial photographs clearly show a well-developed S_2 schistosity, folded by D_3 and refolded by D_4. The fabric is concordant with that in the country rock, of which large rafts are enclosed (as are xenoliths of uralitised gabbro). The similarity of mineralogy and fabric, and the close spatial relationships to the Mabel Downs Granodiorite, suggest that this small stock is part of the larger pluton. However, Ogasawara (in prep.) considers that the fabric in the Dougal's tonalite is an emplacement fabric and contends that it is a post-tectonic granitoid, and this is supported by an isotopic age similar to that of the Bow River Granite.

Mabel Downs Granodiorite: The main phase of the Mabel Downs Granodiorite, in its type area north of the Ord River, is a medium coarse-grained, foliated, porphyritic, hornblende-rich tonalite. Contacts with the country rock are variably conformable, migmatitic, mylonitic, or intrusive. The foliation parallels the strong regional schistosity, S_2. It 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; Neville, 1974). The orthopyroxene probably replaced hornblende during M_3. Thus, the Mabel Downs Granodiorite appears to have crystallised and been emplaced in the waning stages of D_{2a}. The fabric is partly superimposed and partly an emplacement fabric. 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 always gradational.

METAMORPHISM

(Allen)

The Halls Creek Subprovince is a polymetamorphic terrane. Overprinting criteria indicate a number of regional metamorphic events which can be correlated with different deformations. In both the Halls Creek Mobile Zone and the King Leopold Mobile Zone, contact metamorphism associated with late intrusions is superimposed on the regional metamorphism. Correlation between the two belts is difficult, because most of the high-grade metasediments south of the King Leopold Mobile Zone are obscured by Palaeozoic rocks of the Lennard Shelf and Fitzroy Trough. Peak metamorphism in both belts is associated with E-W upright folding which is apparently continuous across the high grade areas. The E-W macroscopic folds in zone II are refolded about NNE-SSW axes. Although the relationship between metamorphic and fold events in the West Kimberleys still lacks detailed fabric work, a clear picture has emerged in the East Kimberley (zone II).

REGIONAL METAMORPHISM IN THE HALLS CREEK MOBILE ZONE

(Allen)

The Early Proterozoic terranes of the Halls Creek Mobile Zone range in grade from greenschist in the south to granulite in the north (Fig. 11). Dow and Gemuts's (1969) and Gemuts' (1971) isograds are modified and expanded. Dow and Gemuts (1969) recognised two periods of folding with associated metamorphism, and mapped three metamorphic zones. Five metamorphic zones are now mapped, and four periods of deformation and metamorphism recognised. Peak metamorphic temperatures occur progressively later with increasing grade (Fig. 13). The lower amphibolite zone encompasses the upper greenschist facies as well. Almandine, staurolite and andalusite zones are not defined.

The present author (Allen) follows Dow and Gemuts (1969) in interpreting the belt as a cylindrical metamorphic belt, in which higher grade zones

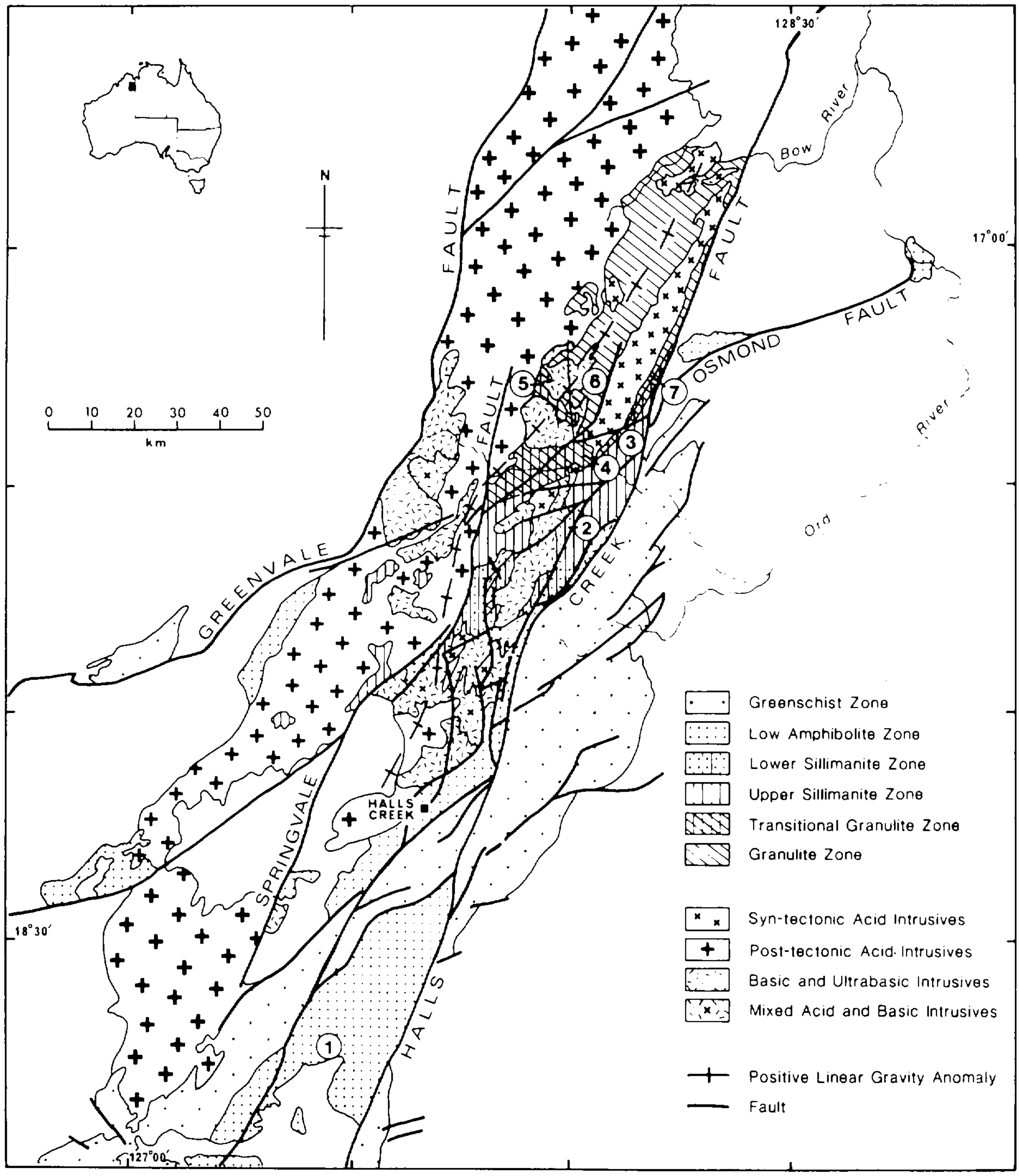

Figure 11. Metamorphic zones in the Halls Creek Group, East Kimberley. Adapted from Gemuts (1971), with data from Neville (1974), Thornett (in preparation) and Allen (in preparation).

plunge southwards beneath low grade zones, and with an axis more or less coincident with the magmatic culmination. This contrasts with Hancock and Rutland (1984), who perceive the metamorphic zones in the Halls Creek Mobile Zone as fault-bounded, and tectonically interleaved during thrusting.

Editorial Note (by Plumb): These concepts need not be wholly incompatible. Hancock and Rutland's postulated tectonic interleaving occurred during (M_1/M_2) and before the peak (M_3) metamorphism, and thus the final metamorphic belt could still have a cylindrical form. Those major faults which now demonstrably separate metamorphic zones had considerable later post-cratonic reactivation, superimposed upon the earlier belt (see later discussion, Cratonic Structure).

RELATIONSHIP BETWEEN DEFORMATION AND METAMORPHISM

(Allen)

Regional metamorphism in the East Kimberleys commenced syntectonically with the first period of folding (Table 4). The paragenetic sequence of mineral nucleation and growth in relation to deformational events is presented hereunder for metapelites in the five mapped zones, and tabulated for the amphibolite facies in Table 5. The metamorphic history of rocks of other compositions is presented in Table 6.

TABLE 4

Correlation of deformation and metamorphic events in zone II, after Allen (in preparation).

DEFORMATION EVENT	ATTITUDE AND ORIENTATION	ASSOCIATED STRUCTURAL ELEMENTS	METAMORPHIC EVENT	METAMORPHIC FABRIC
D_4	Upright, open-tight folds Axes and plunges vary with location and with degree of rotation of pre-existing structures. NNE in north. Refolding D_3, ENE in south.	Crenulation/lineation	M_4 Transitional Granulite & Granulite Zones only	Granoblastic. Corona textures.
D_3	Upright, tight folds. Axes E-W to ENE. Widespread major faulting	Sporadic coarse crenulation	M_3	Migmatization Wrapping pre-existing phases. High-grade mineral nucleation
			M_{2C}	Anisotropic. Randomly oriented, inclusion-free, euhedral new minerals and overgrowths. (Retrograde in Lower (Sillimanite Zone) (Migmatization in Upper (Sillimanite Zone.)
D_{2B}	?Low-angle thrusts. High-angle mylonite zones. ?Sub-listric slide zones. NNE in north ENE in south	S_2, S_1, S_0 transposed into near parallelism. ?Sinistral movement on major fault systems, including Halls Creek Fault. Uplift.	M_{2B}	Mylonitic Replacement by hydrous phases Lower Sillimanite Zone
D_{2A}	Reclined - recumbent tight - isoclinal folds. NNE in north ENE in south ?Restored NE-SW	S_2 strongly developed. Crenulation cleavage. Crenulation lineation. Elongation lineation.	M_2	Strongly isotropic. Porphyroblasts poikolitic with rotational S_1.
D_1	Reclined - ?recumbent, isoclinal folds ?NE-SW	S_1 - layer parallel. Overprinted in Lower Amphibolite Zone; largely obliterated at high grade L_1 - elongation lineation	M_1	Fine-grained. Rotational S_1.

Upper Greenschist - Lower Amphibolite Zone

In low-grade areas west of the Halls Creek Fault, D_1 folds are the most obvious structural element. The Garden Creek Anticline (Location 1, Fig. 11) is here interpreted (by Allen), from Dow and Gemuts (1969), as an isoclinal overturned F_1 fold with restored amplitude of 30 km, refolded by D_2, with the development of a schistosity overprinting an earlier layer-parallel fabric (Fig. 12). Both S_1 and S_2 are defined by muscovite-biotite. However, S_1 is the regional schistosity, and S_2 overprints only in the core of the major D_2 structure, closing to the south. Thus, peak metamorphic conditions are pre-D_2

(Fig. 13). This reinterpretation contrasts with the view of Hancock and Rutland (1984, Table 4) who maintain that "D_1?" is "localised in stratiform zones" and "D_2?" is represented by "sublistric slide zones".

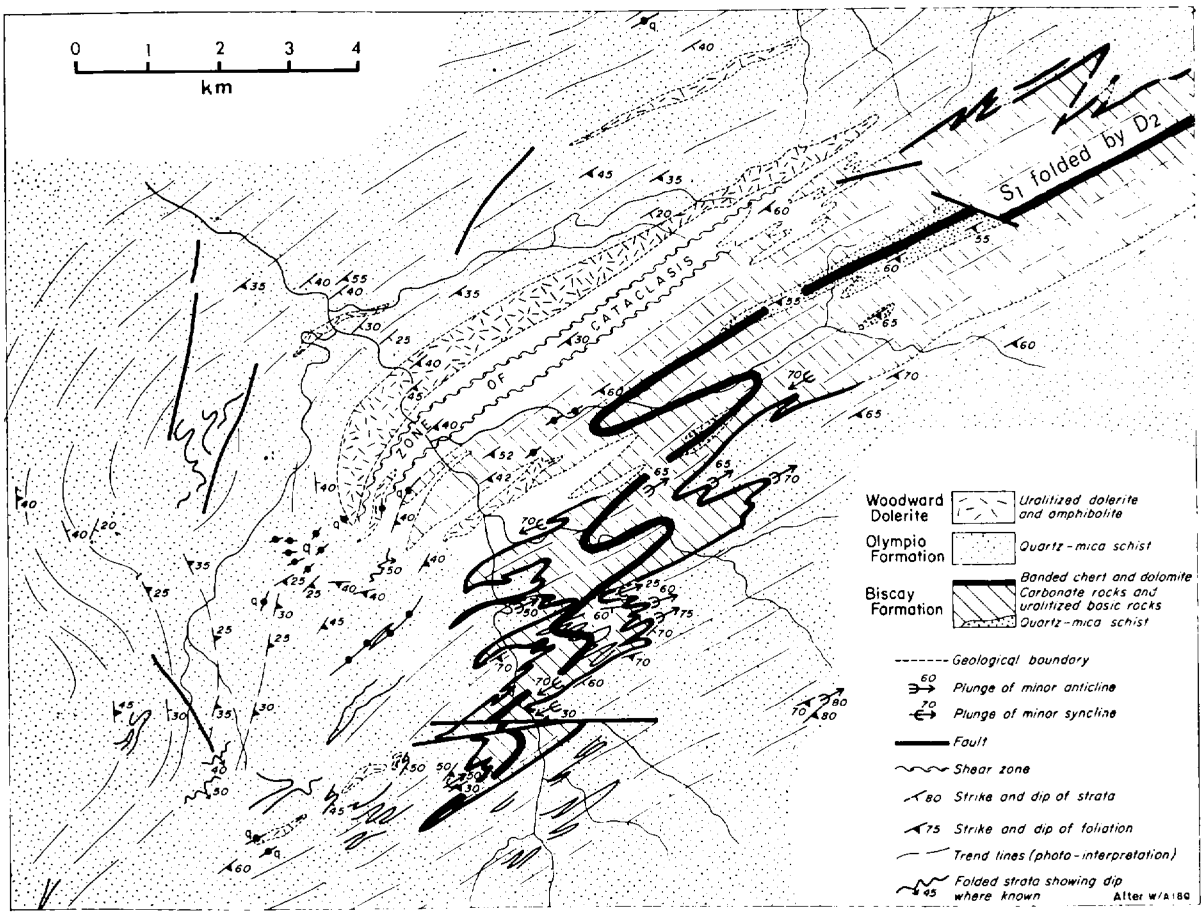

Figure 12. Interpretation of structure of the Garden Creek Anticline by Allen (adapted from Dow & Gemuts, 1969).

Lower Sillimanite Zone

The tectonothermal history of rocks from the Lower Sillimanite Zone is described and illustrated elsewhere (Allen, in preparation), and is briefly recapitulated below. Four fold events have been delineated with structures and fabrics recognisable at a variety of scales (Tables 4, 5).

D_1 No folds of D_1 generation are recognised at amphibolite grade or higher. However, there is good evidence for the presence of a heavily overprinted S_1.

1. The layer-parallel fabric in the hinges of D_2 folds is very strong in rocks of appropriate composition.

2. This early fabric is associated with metamorphic minerals (e.g. garnet).

3. S_2 is a crenulation cleavage, implying a strong preexisting anisotropy of probable tectonic origin.

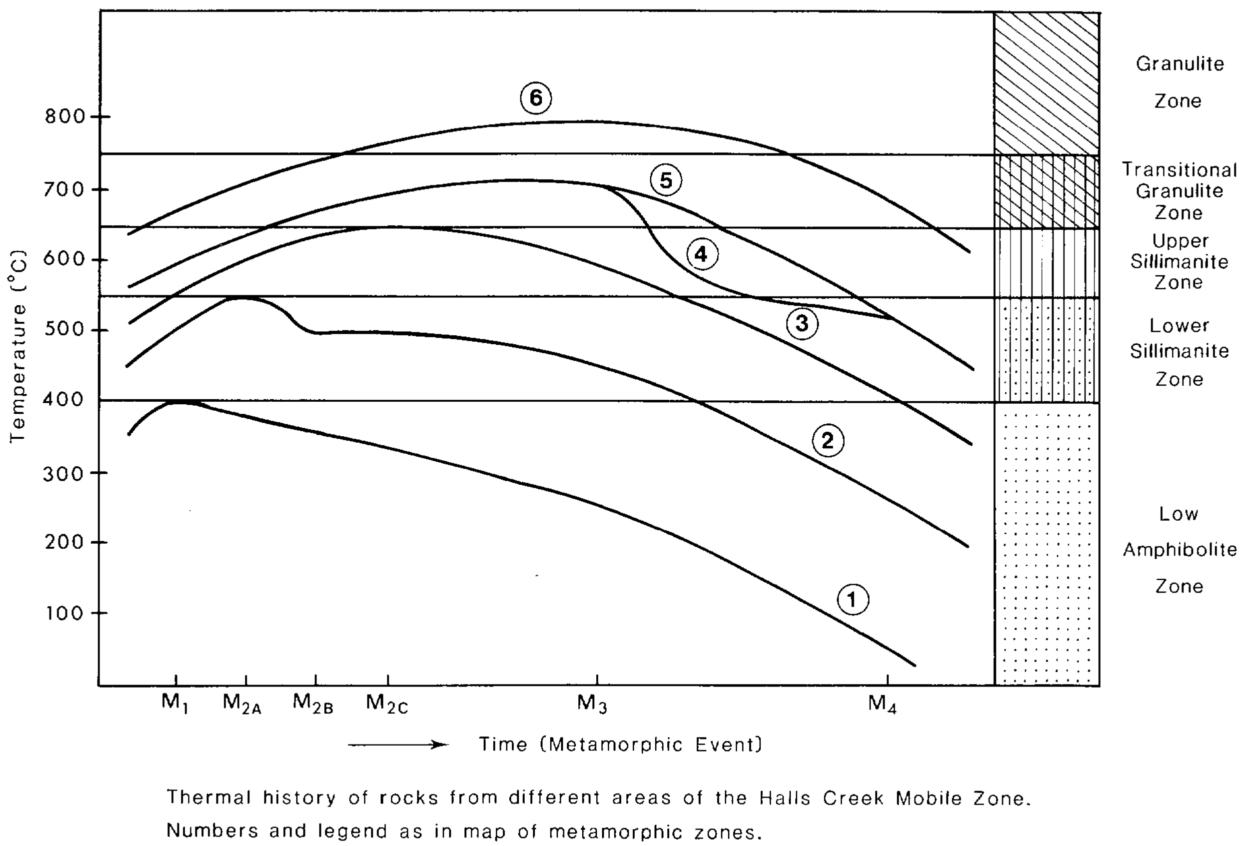

Figure 13. Thermal history of rocks from different areas of the Halls Creek Mobile Zone (after Allen, in preparation). Numbers and legend as in Figure 11.

4. Porphyroblasts wrapped by S_2 sometimes display a rotational S_1, finer than and discontinuous with S_2.

5. D_2 folds a tectonic fabric in some igneous rocks.

D_2 This is a complex event which has generally developed in two stages as indicated in Table 4:-

D_{2a} Widespread, mesoscopic folds fold S_1. S_2, axial-plane to these folds, is the regional schistosity in the high-grade areas. It is generally well-developed and easily recognised, and provides the datum from which structural and metamorphic events are put into a relative time scale.

D_{2b} This deformational event is associated with shearing along the base of D_{2a} folds, transposition, over-thrusting, and widespread, though locally discrete, mylonitisation.

TABLE 5

Paragenetic sequence of stable mineral assemblages in pelitic rocks, during deformation events within the amphibolite facies, from Allen (in preparation).

Metamorphic Event	Lower Sillimanite Zone	Upper Sillimanite Zone	Transitional Granulite Zone
M3			sill
M2c	gt-staur-andal	sill	gt
M2b	musc		
M2a	bio-gt-sill	bio-gt-sill	gt-cord-sill
M1	bio-gt-staur	bio-gt-staur	bio-gt

D_3 Macroscopic folds of D_3 generation are most evident in the high grade areas around the Ord River, north to Mabel Downs homestead,and south to White Rock bore. In the Lower Sillimanite Zone structural effects of this deformation are noted; e.g. occasional macroscopic folds and rare crenulations. New phases are not nucleated at this grade during D_3.

D_4 Macroscopic and mesoscopic folds trend NNE in the sillimanite grade area. Macroscopic folds trending ENE at the confluence of the two fold zones (Fig. 8) are considered to be rotated earlier structures. A D_4 crenulation is developed in pelitic rocks; however, a regional schistosity is not associated with this event in rocks of any grade west of the Halls Creek Fault.

Pelitic rocks from Location 2 (Fig. 11) show the sequence depicted below and in Tables 4 and 5, and Figure 13.

M_1 Garnet cores with rotational S_1, and staurolite relicts in optical continuity in the core of M_2 garnets or plagioclase.

M_{2a} Biotite (S_2 schistosity), syntectonic garnets, and fibrolite.

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.

Peak temperatures of ca. 500-550° C were recorded during M_{2a}.

Upper Sillimanite Zone

In the Upper Sillimanite Zone (Location 3; Fig. 11) effects of D_3 become more obvious. Air photos clearly show two "granitic" plutons just south of the Ord River, with S_2 folded by this event and refolded by D_4. 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 coarse-grained sillimanite replacing the S_2 biotite. There is no development of retrograde mineral phases overgrowing S_2 (as in the Lower Sillimanite Zone). Peak metamorphic temperatures of 600-630°C were registered during M_{2c}, later than in the Lower Sillimanite Zone. There is no obvious metamorphic effect of D_4 at this grade, and no new schistosity is developed (Tables 4 & 5, Fig. 13).

Transitional Granulite Zone

Entry into this zone (SE of the Mabel Downs Granodiorite; Location 4, Fig. 11) is defined by the appearance of cordierite in garnet-cordierite-sillimanite gneisses, and the concomitant disappearance of biotite. Cordierite has never been recorded in rocks of lower amphibolite grade in the Halls Creek Mobile Zone; this is most probably a reflection of the iron-rich nature of the province evidenced by:-

(1) the development of banded iron formation;

(2) the common presence (sometimes abundance) in pelites of iron-rich phases (e.g. staurolite, almandine garnet, and magnetite);

(3) felsic volcanics in the Ding Dong Downs Volcanics, the Biscay Formation, and the Whitewater Volcanics are consistently more iron-rich than their Cainozoic counterparts (Allen, in preparation).

These garnet-cordierite-sillimanite gneisses contain no biotite, except as remnant inclusions, and no other hydrous minerals. Potassium contents are very low. They are interpreted as restites after migration of H_2O and K^+ into early minimum melts (leucogranite occurs in the vicinity). Thus, metamorphic conditions at D_{2a} are estimated to be a minimum of 650°C and 4 kb. Where matrix fabrics are mylonitised, they do not develop muscovite. 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 K-feldspar perthite-sillimanite gneisses also appear in this zone. Mesoscopic D_4 folds occur; however, these rocks are now developing a granoblastic fabric, and effects of M_4 are difficult to identify. Coronas around cordierite of simplectite, with quartz-sillimanite and granular magnetite, may possibly represent M_4 fabrics.

In the lower strain area west of the Mabel Downs Granodiorite, Thornett (in preparation) 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. 11).

TABLE 6

Prograde metamorphic mineral occurrences for metabasites and calcareous rocks. Compiled by R. Allen from data of Gemuts (1971), Neville (1974), Allen (in preparation), and Thornett (in preparation).

Rock	Mineral	Lower Amphibolite	Lower Sillimanite	Upper Sillimanite	Transitional Granulite	Granulite
	Dolomite	------				
C	Calcite	------	------	------	------	------
A	Tremolite/		------	------		
L	Actinolite					
C	Diopside		------	------	------	------
A	Wollastonite		------	?	------	------
R	Grossular		------	------	------ ?	------
E	Epidote	------	------			
O	Scapolite		------	? ------		------
U	Plagioclase	------	------	------	------	
S	Quartz	------	------	------	------	
	Magnetite		------	------		
======	======	======	======	======	======	======
	Tremolite/	------				
M	Actinolite					
E	Hornblende		------	------	------ ------	
T	Cummingtonite				--- --- ---	
A	Clinopyroxene				------	------
B	Orthopyroxene					------
A	Plagioclase	------	------	------	------	------
S			Increase in An content=====>			
I	Sphene	------	------	------		
T	Epidote	------	------			
E	Chlorite	------				
S	Quartz	------	------	------	--- ---	--- -
			Decrease in quartz content=====>			

Granulite Zone

Thornett (in preparation) also 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. 11) by the reaction:

biotite + cordierite + quartz + plagioclase -> garnet + K- spar + melt

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 (in preparation) estimates peak metamorphic grade at 800^{o}C and 5.: kb. (not 870^{o} and at least 6 kb, as quoted by Hancock and Rutland, 1984, p.413). Neville (1974) also estimated temperatures of 800^{o}C in the granulite facies rocks east of the Mabel Downs Granodiorite (Location 7, Fig. 11), where two-pyroxene granulites and charnockitic granite have been recorded and which lies well within Dow and Gemuts' Zone C (high grade)(Fig. 11). (Hancock and Rutland have mapped this as Zone 11a (medium grade). Note also that they have indicated (Table 4, p.420) peak conditions at only 3-5 kb and 500-600^{o} during D_2 metamorphism, and only 400^{o}C during D_3 in Zones II and III, in contrast to the foregoing discussions).

The thermal history of rocks in the Transitional Granulite and Granulite Zones is illustrated in Tables 4 and 5, and in Figure 13.

GEOTHERMAL GRADIENT

(Allen)

The Halls Creek Mobile Zone is a high temperature/low pressure terrane. The mineralogical evidence is supported by geothermometry and geobarometry. Kyanite has been reported in the East Kimberleys from only one small area with anomalous metamorphic grade (sillimanite overgrown by kyanite in a Lower Amphibolite Zone). The lack of kyanite, coupled with the occurrence of wollastonite in marbles in granulite facies rocks, east and west of Mabel Downs Granodiorite, confirms the low pressure estimates. The maximum recorded temperature of 800^{o}C and only 5.5 kb indicates that the Halls Creek Mobile Zone developed an abnormally high geothermal gradient during orogenesis. This high gradient has been accompanied by voluminous acid and mafic magmatism (Table 3), and by maximum crustal shortening and compressive folding of D_2 and D_3 (zone II).

POST-TECTONIC GRANITES

(Plumb)

Abundant granitic batholiths in both the East and West Kimberley are undeformed and show discordant contacts with, and superimpose contact thermal aureoles upon, the structures of the regional tight upright folds in the older metasediments.

The **Bow River Granite** is mapped as a single linear batholithic complex, 400 km long and up to 30 km wide, along the western side of the Halls Creek Mobile Zone, and has been differentiated as zone III by Hancock and Rutland (1984) (Fig. 6). The batholith is homogeneous in composition and texture over large areas, but in places contains a variety of rock types ranging from coarse-grained porphyritic granite and adamellite to even-grained granite and granodiorite. Biotite-rich varieties predominate, but where granite intrudes gabbro, hornblende is developed. The characteristic feature of the granite is its porphyritic texture; lath-like, ovoid, or rhombic feldspars up to 5 cm across are set in a fine-grained groundmass of quartz and feldspar. In places the phenocrysts outline a primary foliation, and lenses of feldspar-rich segregations are common. Younger rocks, ranging from gabbro to tonalite and granodiorite, and which intrude the Bow River Granite, have been grouped as the **Violet Valley Tonalite.**

Small stocks of **Sophie Downs Granite** and **McHale Granodiorite** intrude fold cores in Halls Creek Group rocks in zone I. They have isotopic ages similar to those of the Bow River Granite, except for the Cummins Range stocks which may be older (ca. 2100 Ma).

A whole range of post-tectonic granites have been mapped in the West Kimberley (zone IV); the **Lennard Granite** most resembles the Bow River Granite. Detailed mapping in the east could almost certainly differentiate the Bow River batholith into a similar complex of separate intrusions.

These granites are spatially related to and everywhere intrude the Whitewater Volcanics and associated Castlereagh Hill/Bickleys/Mount Disaster Porphyries, and all are essentially post-tectonic in the East Kimberley. Indeed, locally they form large shallowly dipping concordant sheets with granite at the base, overlain by porphyry, and volcanics at the top, and with indistinct, rather arbitrary contacts. They have been considered to be essentially penecontemporaneous and cogenetic (Dow & Gemuts, 1969; Plumb & Gemuts,1976), and grouped together under transitional tectonism (GSA, 1971).

More recent reinterpretation of the younger metamorphic and structural events in the West Kimberley has interpolated the principal metamorphism and deformation events between the Whitewater Volcanics and Lennard Granite (Giles & Manktelow, 1979; Hancock & Rutland, 1984), rather than pre-Whitewater Volcanics and then post-Lennard Granite (cf. Gellatly et al., 1974b; Plumb & Gemuts, 1976). Geochronological data is still inadequate to reliably define the real time span or time differences of these events.

These relationships illustrate the essential continuum between the different stages in the process of cratonisation via transitional tectonism. The present author (Plumb) interprets the later deformation in the west as the initiation of the King Leopold Mobile Zone as a separate tectonic entity, with its own distinctive deformation style and timing of events during the subsequent post-cratonic evolution (Table 2, and later discussion).

TECTONIC EVOLUTION - HALLS CREEK OROGENIC SUB-PROVINCE

(Hancock)

The following discussion summarises the conclusions of Hancock and Rutland (1984) concerning the tectonic development of the Halls Creek Sub-province. More detail should be sought in this and other published works on basement geology. The discussion will proceed from a general correlation of structural, stratigraphic, and metamorphic events within the zones I to IV (Table 7), to an appraisal of the relationships between the zones and the nature of the zone boundaries. A model of tectonic evolution compatible with the data available to date will be presented.

The precise correlation of individual deformation episodes prior to upright folding remains uncertain at this stage, and this is complicated by the relatively reconnaissance nature of available geochronology. For example, Hancock and Rutland (1984) conclude that the complex history of D_1 and D_2 deformations in zone II is probably reflected in zones I and IV, marginal to the high-grade rocks, by spaced listric shear zones of uncertain affinity. Alternatively, Allen (below) considers that the same deformation events can be identified in zones I and II, and she correlates the upright (D_2) folds of zone I with D_{2A} in zone II (cf. Table 7) . Although data are not definitive, Hancock and Rutland consider that there is some evidence for thrust emplacement of zone II successions over zone I along parts of the zone boundary, prior to the upright folding event ($D_{3-4}II/D_2I$). The best interpretation of zone IV and zone II/zone III sequences is that these have been similarly juxtaposed by faulting, but the sense and magnitude remain poorly constrained at present.

Significant points of Hancock and Rutland's detailed tectonic history and zone to zone stage correlation, which are relevant to the discussion of a tectonic model for basement province evolution, are as follows:

1. Basin-margin orogenic loading appears to have been coincident with basin-floor attenuation during the accumulation of the flysch-stage succession in zone I.

2. There is evidence for continued emplacement of basic magma into zones II and III throughout the complex deformation/metamorphic history of these successions.

3. There has been continuing (and simultaneous?) high heat flow, extension (bimodal volcanism, voluminous basic magmatism, transitional tectonism), and convergence (thrusting, compressive folding) throughout the evolution of the sub-province.

TABLE 7

Correlation of structural, metamorphic, and principal intrusive events, Halls Creek Orogenic Sub-province, by Hancock. Fold nomenclature modifies and updates that of Hancock and Rutland (1984).

ZONE IV	ZONES II & III	ZONE 1
Richenda Microgranodiorite, etc.	Violet Valley Tonalite	
Lennard Granite, etc. 1840±50 Ma (late to post-tectonic)	Bow River Granite 1834±32 Ma (late to post-tectonic)	Elements of Sophie Downs & Cummins Range Granites (1834±32 Ma) (late to post-tectonic)
D_3 Upright folding with crenulation cleavage (NW)	Probable faulting (D_5)	Probable faulting (D_3)
D_{2B} Main metamorphism in West Kimberley; emplacement of McSherries Granodiorite, Kongorow Granite, Wombarella Quartz Gabbro		
Emplacement of Whitewater Volcanics and Castlereagh Hill, Bickleys, etc. Porphyries		
----------UNCONFORMITY----------		
D_{2A} Upright to recumbent folding; trends from NNE to E-W, moulding the structural grain	D_3/D_4 & M_3/M_4 Upright folding; NNE to E-W trends	D_2 Upright folding; NNE trend, flat plunges
	M_2 metamorphism; late to post- D_2 Complex recumbent deformations (D_2) with sequence interleaving; NNE to SSE; tectonic emplacement of ultramafic complexes; mylonitic foliation and lineation. Acid and basic igneous intrusives. (ca 1920 Ma)	
D_1 Recumbent folding and thrust stacking at high level	M_1 metamorphism Complex recumbent deformations (D_1) with strong layer-parallel foliation and lineation. Early acid intrusives.	D_1 Listric shear movements and probable continued deposition of Olympio Formation

4. Tectonic interleaving of sequences within the Tickalara Metamorphics (Zones II and III) has been extreme during D_1 and D_2, as indicated by strong penetrative fabrics, isoclinal regional folding, and tectonic abutment of very different metamorphic parageneses.

5. The dominant extension lineation during strong D_2 deformations in zone II is oriented NNE, along the trend of the zone boundary and this fabric is nearly penetrative.

6. Information across the Halls Creek Sub-province trend, south of Halls Creek, suggests that Halls Creek Group successions can be traced across the subdued gravity ridge which lies along strike from the main outcrop of zones II and III. A traverse across this area would yield somewhat different geology to that across the main belt of Tickalara Metamorphics.

Hancock and Rutland (1984) have proposed a tectonic model for the Halls Creek Sub-province based upon a distinctive type of linear ensialic orogen. This involved oblique convergence between a more rigid Kimberley Block basement of uncertain affinity, but subject to persistent volcanic activity, to the northwest, and a wide zone of attenuated, transitional crust to the east and south (Fig. 14). The "suture zone" between the "island continent" and converging transitional crust is postulated to lie beneath zone III, and thus is now almost entirely concealed by the later emplacement of the Bow River Granite.

Editorial Note (by Plumb): This "suture zone", if present, must crop out as the unnamed shear zone, 10 km south of the Bow River Fault (Figs 4, 5), which abuts low-greenschist facies of zone IV to the north against granulite facies of zone II to the south (see later discussion, Cratonic Structure, and excursion Stop 6B).

The alternation of oblique-slip and strike-slip, implied by this model, is in accord with the apparently anomalous coincidence of tholeiitic magma emplacement and strong orogenic movement, with the sense of the strong extension lineation in zone II parallel to the succession's long dimension, and with the "polarity" of sequence structural development outward from the orogenic core of zones II and III. The relatively "discrete" nature of gravity anomalies in the Halls Creek and King Leopold Mobile Zones, attributed to medium and high-grade metamorphic and basic complexes along the regional margins of the Kimberley Block, is also compatible with such a model, although detailed correlations between these zones remain poorly constrained at present.

Significant problems which remain are:

i) Isotopic data suggest little crustal residence time for source areas, either of metasedimentary successions or of granitoid intrusions. Since much of the siliclastic component of the metasediments was probably derived from the basement beneath the Kimberley Basin (Kimberley Block), the nature of this terrane remains unresolved.

ii) The extent to which the metamorphic/metabasic complexes, inferred to be associated with the gravity anomalies along the strike of the Halls Creek Sub-province are shear-offset equivalents, or somewhat discrete terranes, remains poorly resolved. There are clear structural and lithological similarities, for example, between the Litchfield Complex and Tickalara Metamorphics, although these appear, on present data, to have a slightly different absolute chronology.

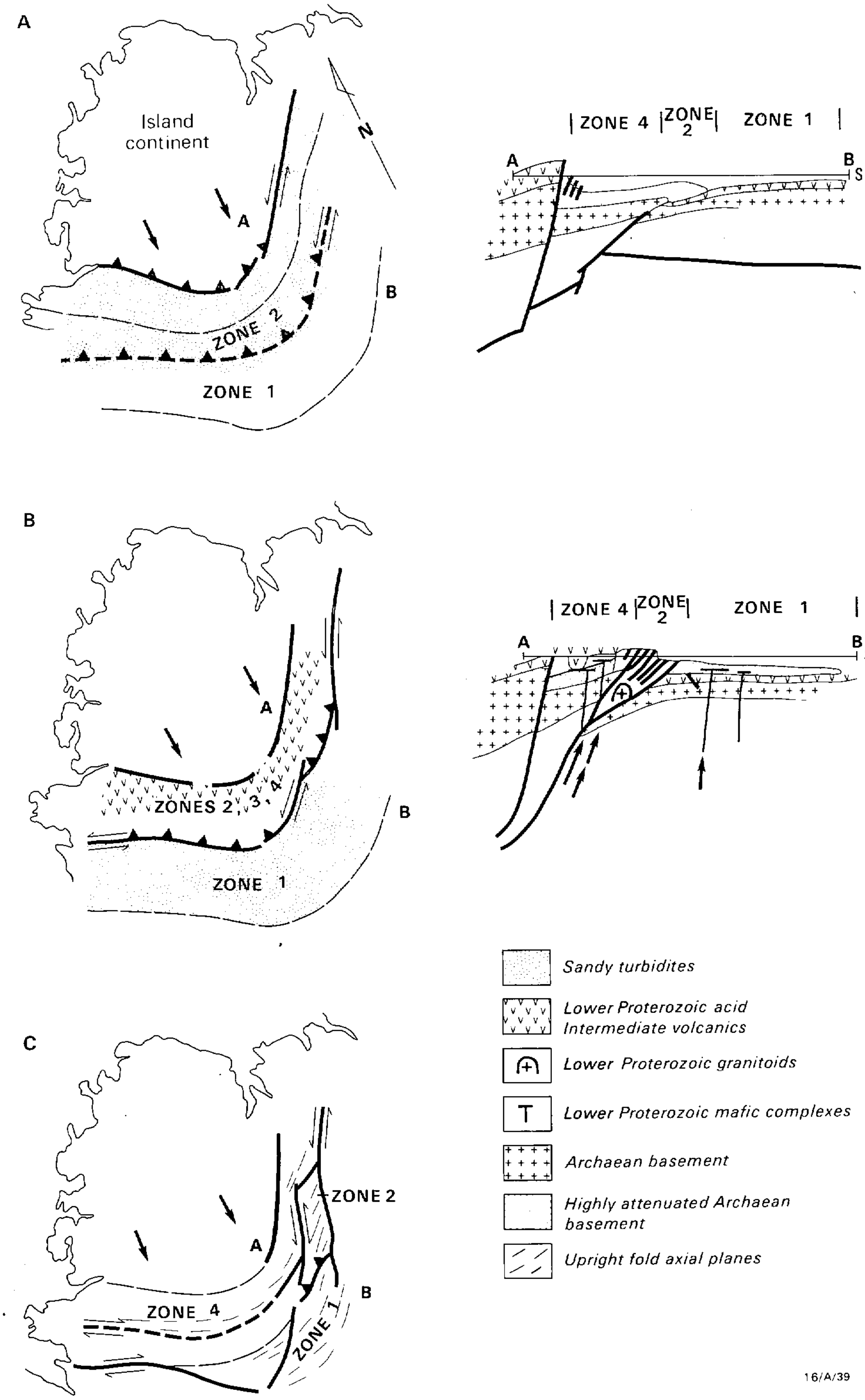

Figure 14. Schematic illustration of the evolution of the Halls Creek subprovince (after Hancock & Rutland, 1984).
A: Initiation of convergence in stratotectonic zones broadly concordant with present belts. Progradation of turbidite sand wedge derived from uplifted continental margin.
B: Zone II develops by A-subduction. Progradation continues across zone I. Basic magma invades the A-subduction complex of zone II and may be associated with dolerite emplacement in zones I and IV. Segments of A-subduction may have been separated by transform faults.
C: After locking of thrust zones, continued oblique transpression results in a moulding upright fold pattern, perhaps influenced by a regional shear couple as indicated. Major fault zones guided earliest emplacement of zone III type linear granitoid complexes.

iii) The absolute amount of tectonic strain across the exposed sub-province, prior to the upright folding, is poorly known.

In conclusion we note that the tectonic evolution of the Halls Creek Sub-province remains an elusive mixture of essentially "modern" tectonic features (strong pre-tectonic structural attenuation, isotopically immature successions, and substantial structural closure associated with tectonic development), and features more typical of Proterozoic orogens (absence of ophiolite and arc volcanics, high heat flow, bimodal volcanism and plutonism throughout the tectonic history). Data currently available are amenable to a variety of interpretations, dependent upon the bias of the examiner. Clearly much more work is necessary, both within this province and concerning its relationships to the equally well-exposed Pine Creek Sub-province to the northeast. Such can only aid the understanding of the mechanisms of Proterozoic orogeny and cratonisation of these classic early Proterozoic terranes.

DISCUSSION

(Allen)

While Allen considers that some of Hancock and Rutland's (1984) conclusions are well supported by the available evidence, others are more tenuous and, in some aspects, are fundamentally at variance with her conclusions, derived from detailed metamorphic studies.

Major problems are:

1. The definition of zones I, IIa, and IIc on metamorphic grounds (low, medium, and high grade, respectively), and separated by major faults, is not justified:

   (a) Zone IIa (Fig 6) encompasses rocks ranging from the greenschist facies/amphibolite facies boundary up to granulite facies (Fig. 11); as outlined by the metamorphic studies of Gemuts (1971), Neville (1974), Hamlyn (1977), Allen (in preparation), and Thornett (in preparation);

   (b) The mylonite zone which is used to define the boundary between zones IIa and IIc (Fig. 6) lies in the middle of the Transitional Granulite Zone, as defined by metamorphic isograds (Fig. 11), and there is no change in grade across the mylonite.

2. Grade changes within the high-grade areas, where isograds have been defined by metamorphic reactions following accepted practice, are gradational. There is no "tectonic abutment of very different metamorphic parageneses" within zones II and III as claimed. The only tectonic abutment of metamorphic facies occurs across the Halls Creek Fault and across the shear zone described from the Bow River River area.

3. Detailed mapping within high-grade areas has revealed no examples of "extreme tectonic interleaving". The only sequence repeats occur where there has been high-angle faulting along the base-Saunders Creek Formation unconformity, in the Halls Creek fault system.

4. Where they can be directly observed, faults and mylonite zones throughout the fold belt are very steep; others can be inferred to be steep from their straight traces across topography. While there may have been tectonic over-steepening during D_{2B} (which relates to the initiation of the Halls Creek fault system), no convincing evidence has been cited that

any of the faults have been initiated as low-angle thrusts. Although petrological evidence suggests that some of the ultramafic bodies underwent sub-solidus cooling at depth and were then emplaced at higher levels, the interpretation of lateral transport from the northwest remains speculative.

5. D_2 folds verge east on the eastern side of the Black Rock Antiform, and west on the western side of the structure (Fig. 10). In the White Rock area, D_2 folds verge west whereas, in the Garden Creek Antiform, D_2 folds have an easterly vergence (Fig. 13). In short, the only undisputed element of consistent easterly vergence, which is important to Hancock and Rutland's (1984) model, is the sediment transport direction.

6. No fundamental difference in structural style, orientation, or numbers of deformation episodes is perceived between different areas of the Hall Creek Mobile Zone, which cannot be explained in terms of transform movement along the Halls Creek fault system, or by a model of diachronous increase in temperature with time towards the north, and more obvious ductile deformations at higher grades.

7. The present (NNE) orientation of D_2 extension lineations in zone II "along the trend of the zone boundary" and "parallel to the succession's long dimension" is not indicative of the axis of extension during D_{2A}. All structures and fabrics earlier than D_3 (zone II) close to the Halls Creek fault system were rotated into parallelism during D_{2B}, and have a NNE trend. The extension lineation probably originally had a more easterly trend.

4. PROTEROZOIC CRATONIC BASINS

(Plumb)

KIMBERLEY BASIN

The Kimberley Basin succession is up to 5 km thick, and comprises the Speewah Group, the sub-conformably overlying Kimberley Group, and the conformably-overlying Bastion Group. It comprises quartz-rich arenites and subordinate basic volcanics, lutites, and minor carbonates. The Revolver Creek and Moola Boola Formations within the Halls Creek Mobile Zone, and the Red Rock Beds flanking the eastern edge of the mobile zone, are correlated with all or part of the succession. Extensive sills of Hart Dolerite intrude the Speewah and Kimberley Groups, and the Fish Hole Dolerite within the Red Rock Beds is a probable correlative. The central part of the Kimberley Basin is only mildly-deformed, but deformation increases suddenly adjacent to, and within, the Halls Creek and King Leopold Mobile Zones.

The stratigraphy is summarised in Table 8 and in Figures 16 and 17.

A planar unconformity has been identified throughout the basin in the middle of the King Leopold Sandstone (Williams, 1969; Plumb & Gemuts,1976), at a conglomerate marking a sudden change in palaeocurrent trends (Gellatly, Derrick, & Plumb, 1970); the "lower" King Leopold Sandstone is described with the Speewah Group in this discussion.

A feature of the basin is its uniform stratigraphy in the central part (Fig. 17), and several indicators suggest that the extent of the original sedimentary basin may not have been appreciably greater than the presently preserved structural basin. Along the southeastern margin facies changes accompany the onlap of units onto the Halls Creek Mobile Zone. The Speewah Group thins out across the King Leopold Mobile Zone, but the Kimberley Group transgresses it with little change, until covered by Phanerozoic rocks to the south.

Palaeogeographic evolution

Speewah Group: The Speewah Group is about 1.2 km thick in the northeast, thinning in the southeast and west, and the "lower" King Leopold Sandstone adds up to 500 m more (Fig. 16). The Group is only exposed along the upturned southeastern and southwestern margins of the basin; its extent beneath the main part of the basin is unknown. Palaeocurrents are from the northeast and east, with reversals in places (Gellatly et al., 1970) (Fig. 16). Red feldspathic arenites are a feature of the Group, and these become coarser towards both the southeastern and western margins. The Group is interpreted as a broad transgressive - regressive cycle, with sediment derived from elevated Halls Creek and King Leopold Mobile Zones: fluvial sands "lower O'Donnell Formation) pass up through alternating or interfingering fluvial and shallow-marine facies ("upper" O'Donnell Formation to Luman Siltstone), which then pass back into fluvial sands ("lower" King Leopold Sandstone).

The **Red Rock Beds** and **Moola Bulla Formation** are fluvial deposits, locally derived from and deposited on the other side of the Halls Creek Mobile Zone.

Kimberley Group: The characteristic feature of the Kimberley Group is the maturity and lateral uniformity of most formations (Fig. 17); the **Bastion Group** follows the same pattern. Contacts between formations are usually gradational. Mature, laterally persistent quartz sandstone units alternate with tholeiitic basalt and massively bedded red siltstone or green shale. Palaeocurrents are remarkably consistent from the north to northwest, except for some changes in trend and reversals in the west, where local

TABLE 8. SUMMARY OF STRATIGRAPHY, KIMBERLEY BASIN AND EQUIVALENTS.

UNIT	ROCK TYPES AND THICKNESS	REMARKS
Hart Dolerite	Tholeiitic dolerite, gabbro, granophyre. Up to 3000 m.	Sills intrude Kimberley &, particularly, Speewah Groups
Fish Hole Dolerite	Epidotised amygdaloidal dolerite Up to 900 m.	Sills intruding Red Rock Beds
BASTION GROUP		
Cockburn Sandstone	Quartz sandstone; minor micaceous sandstone, shale. 500 m+.	Cross-beds, ripple marks.
Wyndham Shale	Green shale, siltstone, sandstone; calcareous sandstone. 700 m.	Mud cracks, ripple bedding. Black-calcite nodules.
Mendena Formation	Alternating quartz sandstone & siltstone; dolomite. 110-150 m.	Conformable on Pentecost Sst. Ripple marks, cross-beds.
KIMBERLEY GROUP		
Pentecost Sandstone	Quartz & feldspathic sandstone; ferruginous siltstone & sandstone, glauconitic sandstone. 420-1350 m+.	Widespread consistent marker beds. Cross-beds,clay pellets.
Elgee Siltstone	Massive red siltstone; sandstone, green shale. 40- 480 m.	Distinctive massive siltstones
Teronis Member	Dolomite; red shale, fine sandstone. 0-140 m.	Locally at base of Elgee Sltst. Abundant stromatolites.
Warton Sandstone	Quartz & feldspathic sandstone; minor shale. 60-600 m.	Cross-beds, ripple marks, clay pellets.
Carson Volcanics	Tholeiitic basalt; feldspathic sandstone,siltstone, chert. 60-1140 m.	Basalt commonly altered to spilite.
King Leopold Sandstone	Quartz sandstone & granule sandstone, with some feldspar; conglomerate, micaceous siltstone. 0-1340 m.	Cross-beds. Unconformity present within unit; lower "member" conformable on Speewah Gp.
SPEEWAH GROUP		
Luman Siltstone	Micaceous siltstone, shale; minor sandstone. 0-95 m.	Mud cracks, ripple marks, cross-beds.
Lansdowne Arkose	Feldspathic & quartz sandstone, arkose; micaceous siltstone. 30-600 m.	Cross-beds,ripple marks, clay; pellets. Several consistent members.
Valentine Siltstone	Green chloritic siltstone; rhyolitic ashstone, tuff. 80-360	Ashstone is local marker.
Tunganary Formation	Feldspathic & quartz sandstone, arkose, granule sandstone; green siltstone, micaceous sandstone. 80-360 m.	Cross-beds, ripple marks, current scours in sandstones; graded bedding in siltstones.
O'Donnell Formation	Quartz sandstone, granule sandstone, quartz greywacke; green shale & siltstone. 30-523 m.	Unconformable on Whitewater Volcs. Two distinct members. Marked lateral variations.
Revolver Creek Formation	Amygdaloidal basalt, quartz sandstone, siltstone, arkose. Up to 1200 m.	Unconformable between Whitewater Volcs & Carr Boyd Group. Equivalent to Kimberley Group.
Moola Bulla Formation	Arkose, greywacke, conglomerate, siltstone. 3000 m+.	Unconformable between Halls Ck. Gp & King Leopold Sst. Probably equivalent to Speewah Gp.
Red Rock Beds	Quartz sandstone, red siltstone, conglomerate. 2 000 m +.	Unconformable between Halls Ck. Gp & Mt Parker Sst. Equivalent tp Speewah or Kimberley Gps.

unconformities are present. Sections thin markedly in the southeast, northeast, and west, and thicken locally in the west.

Synthesis: It is interpreted that, after erosion of the Speewah Group, the Kimberley Basin took the form of a broad semi-enclosed, shallow-marine basin, which persisted throughout Kimberley and Bastion Group times. Shores to the west, and perhaps northeast, supplied sediment for dispersal by strong unidirectional, perhaps longshore currents flowing towards the southeast. Sediments lapped onto downcurrent highs in the Halls Creek Mobile Zone and, perhaps, in the King Leopold Mobile Zone. A basin similar to the present North Sea is envisaged.

Hart Dolerite

The Hart Dolerite is one of the major dolerite bodies of the world; dolerite underlies the whole 160 000 km^2 of the Kimberley Basin. Where upturned along the Halls Creek and King Leopold Mobile Zones, a composite thickness of up to 3000 m is exposed in several sills, but the thickness beneath the centre of the basin is unknown; individual sills are up to 1800 m, but are commonly composite. The dolerite mostly intrudes the Speewah Group, where it encloses rafts of sedimentary rocks up to several kilometres across, and smaller bodies intrude all units of the Kimberley Group.

Compositions range from olivine dolerite and gabbro, through tholeiitic dolerite, quartz dolerite, diorite, and granophyre. The rocks show identical compositions and differentiation trends to those of classic tholeiites such as

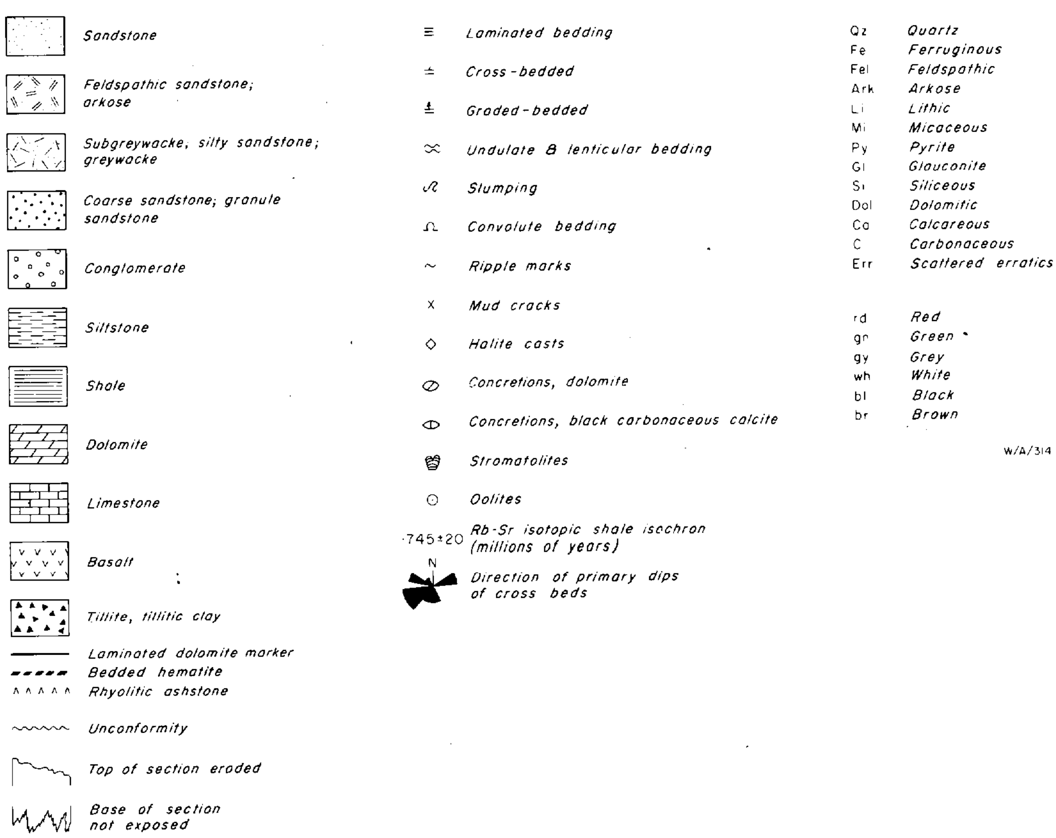

Figure 15. Lithological key to Figures 16, 17, and 19.

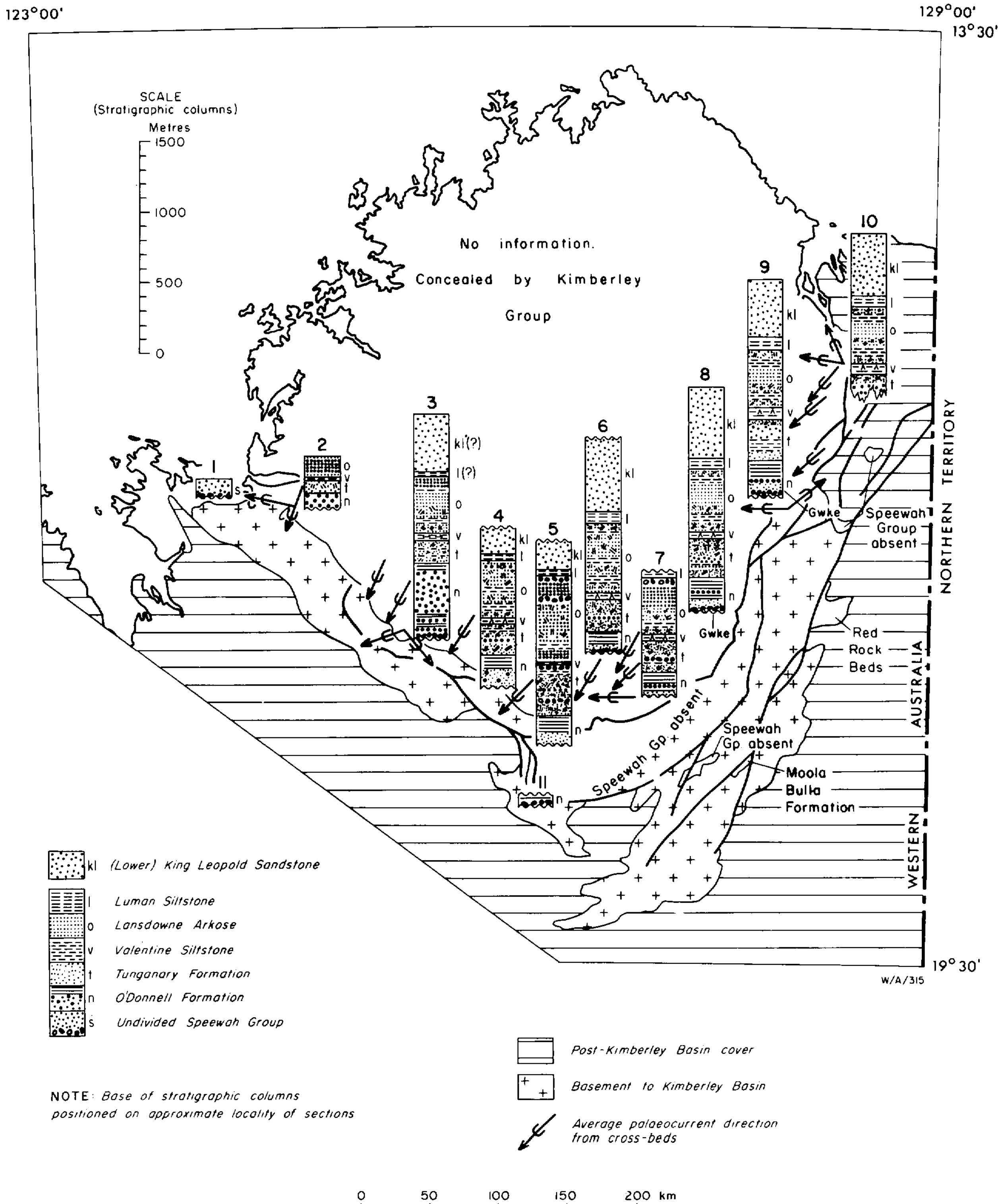

Figure 16. Diagrammatic stratigraphy and palaeocurrents, Speewah Group (after Plumb & Gemuts 1976).

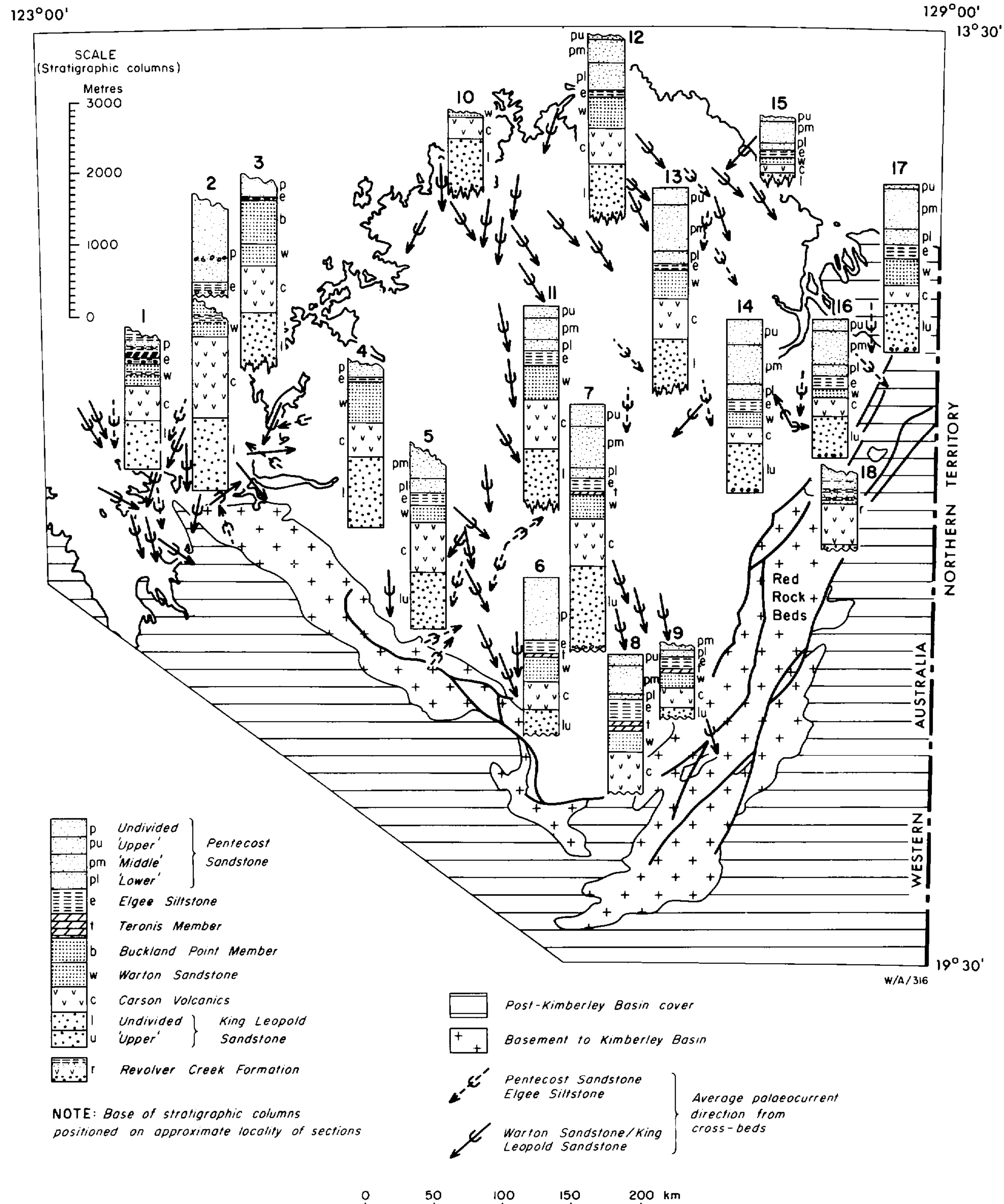

Figure 17. Diagrammatic stratigraphy and palaeocurrents, Kimberley Group (after Plumb & Gemuts, 1976).

the Palisades Sill. Flat-lying sheets of granophyre, up to 250 m thick are found at the top of the thickest sills, and have metasomatically altered the country rock when in contact with arkose. Elsewhere contact effects are negligible.

Highly altered and folded sills of **Fish Hole Dolerite** intrude the Red Rock Beds to the east of the Halls Creek Mobile Zone, and are unconformably overlain by the Mount Parker Sandstone.

BIRRINDUDU BASIN

The only units of the Birrindudu Basin in the Kimberley region are the Mount Parker Sandstone and the dolomite-rich Bungle Bungle Dolomite, totalling about 1600 m thick and exposed along the western edge of the Sturt Block; particularly in the inaccessible core of the Osmond Range. They can be correlated in detail with the more extensive Limbunya Group to the east (Sweet, 1977), and may well be continuous in the subsurface with the equivalent McArthur Basin farther east (Plumb, 1979b). The sequence is interpreted as a fluvial sand, passing up into a marginal-marine sand and carbonate complex; conglomerates and sands thinning eastwards suggest at least local derivation from the Halls Creek Mobile Zone. They will not be seen during this excursion.

VICTORIA RIVER BASIN EQUIVALENTS

The mildly-deformed stable-shelf succession of the Victoria River Basin is widespread in the Northern Territory (Sweet, 1977), but is represented only by the Helicopter Siltstone and Wade Creek Sandstone in the Kimberleys (Dow & Gemuts, 1969). A very much thicker **Carr Boyd Group** accumulated in the Halls Creek Mobile Zone, (Dow, Gemuts, Plumb & Dunnet, 1964; Plumb, 1968; Plumb & Veevers, 1971, Plumb & Gemuts, 1976), and the **Fitzmaurice Group** in the adjacent Fitzmaurice Mobile Zone of the Northern Territory (Sweet, 1977) (Figure 18).

Historically, the quartzite-rich Carr Boyd and Kimberley Basin successions were equated (Traves, 1955; Harms, 1959), but the Carr Boyd Group was later shown to overlie the Kimberley Group in a small area of overlap north of Kununurra (Plumb & Veevers, 1971); the Carr Boyd Group is entirely confined to the Halls Creek Mobile Zone and no eqivalents are known from anywhere on the Kimberley Block.

Only the Carr Boyd Group and its structure will be seen on this excursion. The stratigraphy is summarised in Table 9 and Figure 19.

Carr Boyd Group

The Carr Boyd Group aggregates 6 000 m in thickness and was deposited in a 40 km-wide strip between the Dunham-Glenhill-Ivanhoe Fault System and the Halls Creek Fault to the east; outcrops mapped on the east of the Halls Creek Fault (Plumb, 19868) are now better assigned to the Victoria Basin succession.

Four 1500 m-thick cycles, in which basal sandstones grade up into lutite-rich sequences, are separated by unconformities (Figs 18, 19). Distinctive features include marked changes in thickness and facies across the mobile zone, syndepositional fault movements, truncation of syndepositional faults by unconformities, and source areas variously from both the Kimberley and Victoria River Basin areas. Limited palaeocurrent data from the cycles show

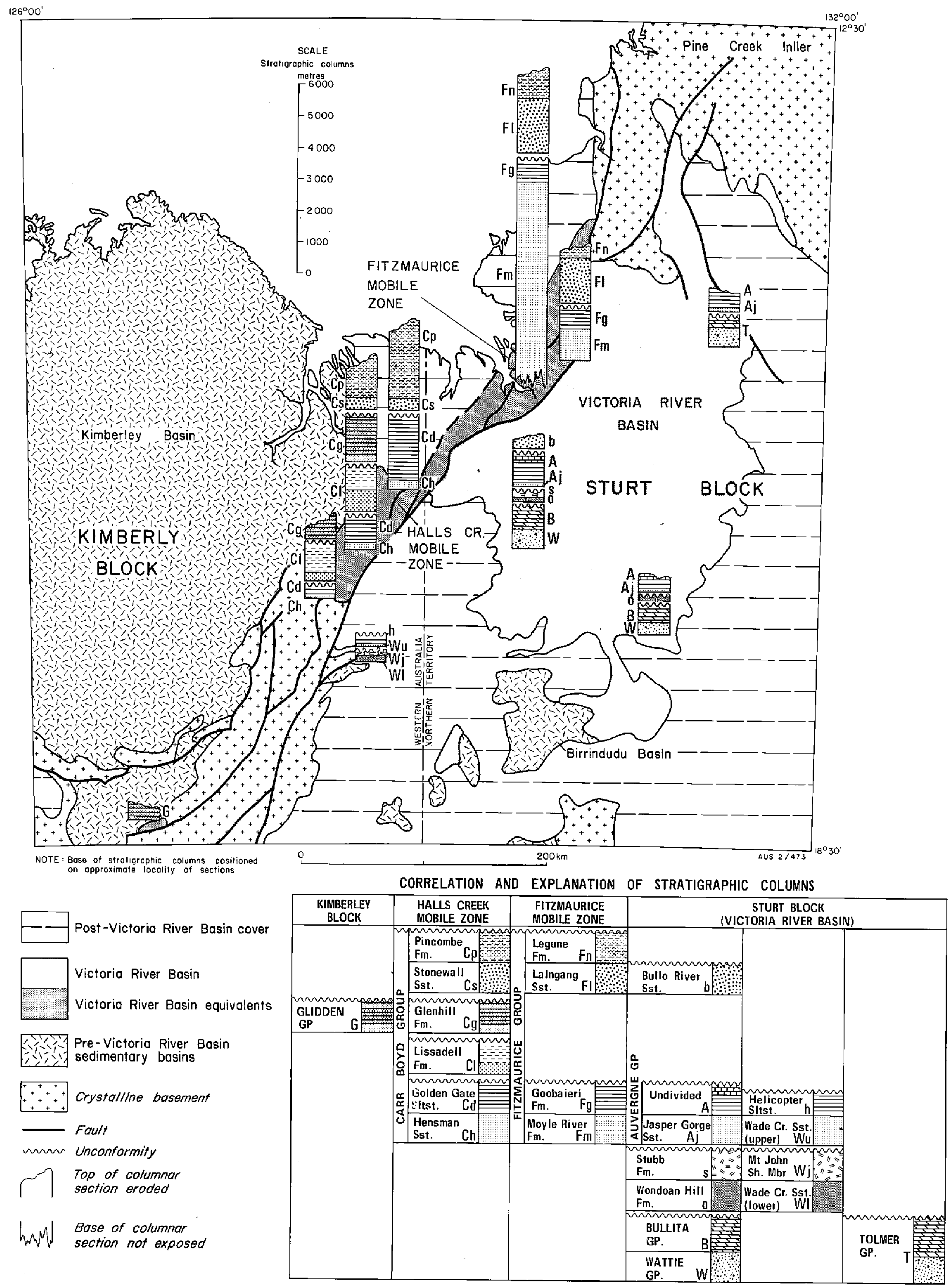

Figure 18. Diagrammatic stratigraphy and tectonic setting, Victoria River Basin and equivalents (after Plumb et al., 1981).

TABLE 9. SUMMARY OF STRATIGRAPHY, CARR BOYD GROUP.

UNIT	ROCK TYPES AND THICKNESS	REMARKS
Bandicoot Range Beds	Quartz & argillaceous sandstone, conglomerate; interbeds ferruginous sandstone; minor red shale, fine micaceous sandstone. 1035 m.	Stratigraphic position unknown; possibly overlain by Glenhill Formation.
Pincombe Formation	Red & green siliceous siltstone & fine sandstone; blocky quartz sandstone; minor micaceous shale. Up to 2500m.	Unconformable beneath Palaeozoic rocks; gradational contact with Stonewall Sst. Markedly lenticular units.
Stonewall Sandstone	Subfriable medium to coarse quartz sandstone; subordinate argillaceous & feldspathic sandstone. Granule sandstone, red shale. 300-450 m.	Unconformable on Glenhill Fm. Locally unconformable on Kimberley Gp. Some recumbent cross-beds.
Glenhill Formation	Red, green, & black, commonly laminated siltstone, shale, & fine sandstone (locally glauconitic); Blocky quartz sandstone. 600- 1500 m.	Unconformable on Lissadell Fm. Persistent basal sandstone. Mica generally minor. Alluvial fan, Carlton Gorge.
Lissadell Formation	Blocky quartz sandstone. Purple, green, & grey micaceous quartz siltstone, shale, & fine sandstone. Up to 1500 m.	Unconformable on Golden Gate Sltst. Upward gradation from quartz sandstone into laminated micaceous siltstone.
Golden Gate Siltstone	Lithic subgreywacke, red & green micaceous shale, sandy haematite (west). Black (pyritic) siltstone & shale, blocky sandstone (east). 240-2000 m.	Facies changes & thickness increases progressively from west to east.
Hensman Sandstone	Massive silicified fine to medium quartz sandstone	Unconformable on Revolver Ck Fm. & older rocks of Halls Ck Sub-prov.

unimodal currents in the basal sandstones, passing into bimodal patterns higher up (e.g. Lissadell Formation, Sect. 2). This is interpreted in terms of repeated cycles of transgression and regression controlled by movements within the narrow Halls Creek Mobile Zone and its margins. Basal fluvial sands pass up into shoreline/floodplain, offshore, and then back to shoreline/floodplain marine and, probably, lacustrine complexes.

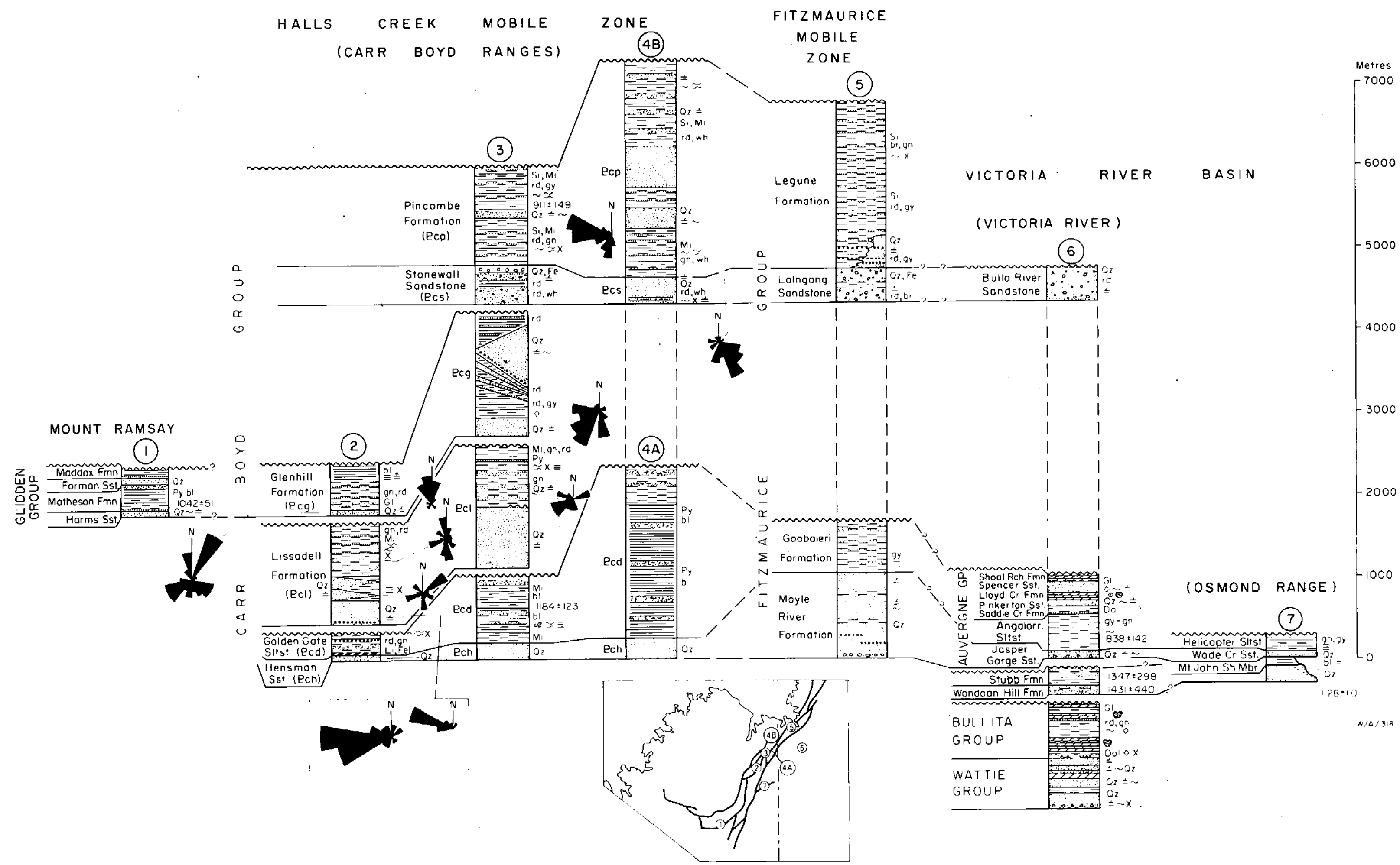

Figure 19. Diagrammatic stratigraphic columns and correlations, Carr Boyd Group and equivalents (after Plumb & Gemuts, 1976).

In the **Hensman Sandstone/Golden Gate Siltstone** cycle 270 m of near-shore sands, silts, and ironstone in the west (Sect. 2) thicken to over 2000 m of monotonous pyritic black shale in the east(Sect. 4A), in only 40 km. A westerly source agrees with the broad marine shelf which was present across the Victoria River Basin, to the east, at this time (Fig. 18).

The **Lissadell Formation** thins from 1500 m to 150 m in only 15 km, adjacent to the Carr Boyd Fault (east of Sect.3), and is absent east of the fault. An easterly sediment source, from palaeocurrents, fits the absence of sediments on the Sturt Block at this time (Figs 18 & 19). The basal sands are mature quartz sands with planar and trough cross-beds. Above this, thick tidal-channel sands (Sect. 2) interfinger with tidal-flat silt, shale, and fine sand. Tidal-flat muds dominate the upper part of the sequence.

The **Glenhill Formation** in the northeast has an easterly-derived alluvial fan deposit adjacent to the Carr Boyd Fault, which passes westward, in a distance of only 3 km, into red silts and shales (Sect. 3). In the southwest(Sect. 2), the basal sand has both unimodal and bimodal cross-beds, immediately overlain by glauconitic sands; these pass up into subtidal shales.

The basal sand of the final cycle, the **Stonewall Sandstone**, has the most convincing fluvial characteristics of all: poorly-sorted, scattered conglomerate and red shale, and thick unimodal cross- beds. Highly lenticular bedding at all scales characterises the **Pincombe Formation.** Lenses, up to 450 m thick, of cross-bedded sands alternate with red and lesser green and grey silt, shale and fine sand, interpreted as a shoreline (marine or lacustrine?) channel and mud-flat complex.

Synthesis: The Carr Boyd Group has been deformed by the strike-slip faults of the Halls Creek Mobile Zone. Distinctive facies of the Golden Gate Siltstone, and the basement below it, display individual left-lateral displacements of up to 30 km. Such displacements are not apparent in younger units; indeed, the Pincombe - Legune Formation relationships suggest little displacement at all. This, together with the evidence detailed for fault-controlled sedimentation, implies major syndepositional strike-slip control of the Carr Boyd and Fitzmaurice Groups, in the manner of the "coal-hopper" model for the Ridge Basin of California (Crowell & Link, 1982). However, one significant departure from typical fault-controlled basins is the overall absence of coarse conglomerates and breccias; sediment maturity is, overall, high. Relief was apparently relatively low; there was differential subsidence, but not complementary uplift. Another factor in maturity has the multi-cycle source of the sediments, derived, as they are, from the Kimberley and Victoria River Basins.

GLACIAL SUCCESSIONS

The Kimberley Region is well known for its very well preserved Late Adelaidean glacial successions, unconformably overlying a wide range of sequences on the Kimberley Block, Sturt Block, and at the intersection of the Halls Creek and King Leopold Mobile Zones (Plumb, 1981). They will not be seen on this excursion.

Two distinct sequences, the Landrigan and Egan Glaciations, may be directly correlated with the classic Sturtian and Marinoan sequences of South Australia, but it is the Egan (Marinoan) equivalents which are most widespread (Coats & Preiss, 1980; Plumb et al., 1981; Plumb, 1981). However, the feature for which they are best known are their excellently preserved glacial pavements; twenty have now been recorded, from 1:250 000 scale mapping alone

(Harms, 1959; Dow, 1965; Perry & Roberts, 1968; Roberts et al., 1972; Derrick & Playford, 1973; Sweet et al., 1974); in many cases the ancient glacial valleys are still preserved.

There has been a degree of dispute regarding the depositional (and topographic) setting of the tillites - mostly marine (Dow & Gemuts, 1969) or mostly continental (Perry & Roberts, 1968; Roberts et al., 1972; Sweet, 1977). Plumb (1981) has reconciled these views by recognising that early tillites (Fargoo & Landrigan) were locally derived, probably from mountain glaciers along an uplifted Halls Creek Mobile Zone; the younger (Egan) glaciation was a widespread sheet glaciation, moving from the northeast throughout, across a terrain of mostly low relief. Terrestrial conditions prevailed in the north, becoming progressively more marine towards the south.

STRUCTURE

(Plumb)

The structure of the cratonic basins of the Kimberleys is dominated by the Halls Creek and King Leopold Mobile Zones, and the Kimberley and Sturt Blocks were mildly deformed in response to movements within them. The **Halls Creek Mobile Zone** was deformed by left-lateral strike-slip displacements on several anastomosing faults of continental proportions, and this displacement was absorbed by reverse faulting and overfolding, verging towards the northeast, across the subperpendicular **King Leopold Mobile Zone** (Figs 3, 4) (Plumb & Gemuts, 1976). This is a common pattern throughout North Australia (Plumb, 1979b), but its simplicity is complicated by the apparent superposition of movements of different ages along the two zones.

There is no evidence from either geology or geophysics that the strike-slip system of the Halls Creek Mobile Zone extends south of the present outcrop limits beneath the Canning Basin. The extension mapped as the Halls Creek Fault, south from Halls Creek township, may be only a minor splay. The westerly limbs, the Angelo and Woodward Faults, appear to swing into the trend of the King Leopold Mobile Zone (as the Pinnacle Fault), in the same way as the Greenvale and Springvale-Glidden Faults farther north (Fig. 5), and parallel to the upright D_2 (zone I-IV) folds (Fig. 8). The shortening calculated across exposed Kimberley Basin rocks in the the King Leopold Mobile Zone (only half of the total width indicated from gravity) is compatible with the cumulative displacement along the faults within the Halls Creek Mobile Zone, to the west of the Halls Creek Fault itself.

Bedding dips on the stable blocks are very gentle over wide areas. Broad basins and domes and mild faulting on the **Kimberley Block** reflect superposition of structures parallel to the marginal mobile zones; deformation increases suddenly at the margins, and grades quickly into that of the mobile zones. A rectangular system of joints and lineaments parallels the mobile zones throughout; individual lineaments continue for several tens of kilometres, commonly from basement faults in the mobile zones. Along the western margin of the **Sturt Block,** movements on the Halls Creek Fault have given rise to fold axes and faults oblique to the fault, and to several large asymmetric synclines with steep northwestern limbs.

This summary will concentrate on the Halls Creek Mobile Zone, and most of the structures are detailed in Plumb (1968) and Plumb and Veevers (1971).

Halls Creek Mobile Zone

The Halls Creek Mobile Zone is defined as lying between the Halls Creek Fault in the east and the Greenvale Fault in the west, although the boundaries are in detail gradational. The structure is dominated by the anastomosing system of major strike-slip faults which crop out across it (Figs 4, 5). Vertical displacements are large, and commonly reversed by different phases of movement. Broad open folds have northeasterly axes, oblique to the faults but of geometry compatible with a related origin for them both, and zones of slaty cleavage occur locally, such as adjacent to the Greenvale Fault and in the zone between the Halls Creek and Carr Boyd Fault. However, these folds are also displaced horizontally by later movements of the faults. The major deformations just described are basically Precambrian in age. Palaeozoic displacements are much less and probably largely vertical, although horizontal slickensides have been recorded in Devonian rocks (Rod, 1966).

The **Halls Creek Fault** is generally considered to be the major controlling fault of the system, although it is difficult to demonstrate a displacement significantly greater than for some of the others. It has many features typical of fundamental strike-slip faults: long sinuous trace; near-vertical dips, to both east and west; wide (up to 6 km) sometimes composite shear zones; horizontal slickensides on its extension (Cockatoo Fault; Rod 1966); long history of intermittent movement and control of basin development; large vertical components of movement, which are periodically reversed; and it separates distinctly different geological provinces. This boundary is so fundamental that there are no datums preserved which allow any strike-slip displacement to be estimated in any of the cratonic basins. Hancock and Rutland (1984) identify left-lateral displacements of basement rocks of about 30 km, on each of three separate splays at the southern end of the fault. This can only be constrained to being post-D_2 (zone I-IV). These displacements and on other splays farther north (Fig. 5) could possibly be aggregated as they progressively merge; the physical expression of the fault zone is, in fact, most striking in the Osmond-Carr Boyd Ranges area.

As described earlier, the **Carr Boyd Fault** displaces a distinctive pyritic facies of the Golden Gate Siltstone, and a distinctive basement ridge, about 30 km, west-block-south, but the displacement seems to decrease upwards through the Carr Boyd Group. At its northern end the fault joins to the Halls Creek Fault via an ENE-striking thrust, along which basement has been thrust northwards over uppermost Carr Boyd Group. The adjacent **Revolver Creek Fault** has a small displacement of about 1.5 km at its northern end which, again, demonstrably dies out upwards during Carr Boyd Group sedimentation; the displacement farther south, beyond a cross-cutting (thrust?) fault, appears much greater. Slaty cleavage and tight fold axes, from 15^{o} to subparallel to the faults, are developed in Carr Boyd Group rocks in zones up to 10 km wide, in the wedges between the Revolver Creek and Carr Boyd and the Carr Boyd and Halls Creek Faults.

The **Bow River Fault** displays left-lateral displacement of the base of the Carr Boyd Group of about 3 km, and nil within the Glenhill Formation, but the size of the shear zone in the underlying basement suggests considerable movement pre-Carr Boyd Group. The **Glenhill Fault** probably also has horizontal displacements comparable to the Carr Boyd Fault, but lack of datums make this difficult to demonstrate.

The **Dunham- Ivanhoe Fault System** diverges from the Greenvale Fault and essentially separates the Kimberley Basin from the Carr Boyd Group. In the south the Dunham Fault, striking NNE, dips steeply to the east and shows a moderate reverse component of movement, in which Bow River Granite is faulted against Speewah Group. Locally lower Carr Boyd Group, sitting directly on the Bow River Granite, is juxtaposed against Kimberley Basin rocks. A north-trending splay, the **Dillon Springs Fault**, displaces a series of matching NNE folds in the Kimberley Basin about 30 km, west block south. The physical expression of the Ivanhoe Fault suggests similarly large movements, but any datums are covered by Phanerozoic rocks, which have also been considerably faulted.

The **Greenvale-Liamma Fault System** is a composite of faults; one set strikes about NNE and subparallel to the axes of the broad folds along the western edge of the mobile zone, the other set strikes more north. The NNE fault set dips 75-80^{o} to both east and west, with shear zones up to 3 km wide containing transposed bedding, drag folds, and axial-plane cleavage, and all indicating reverse displacements of up to 1.5 km. In the southwest, both these folds and reverse faults swing in trend through east to ESE, subparallel to the King Leopold Mobile Zone, and subparallel to the swing in trend of D_2 (zone IV) folds. The north set comprises several faults which mostly cut through, or at least diverge from, the earlier set, and consistently displace them and the regional folds up to 10 km, west-block-south. The Dillon Springs Fault parallels this latter set, and truncates the Liamma Fault. Near Dunham River, the Greenvale Fault is linked to the Dunham Fault by an ENE-striking thrust fault, dipping 30-50^{o} to the north.

ENE thrusts linking the Greenvale-Dunham, Carr Boyd-Halls Creek, and perhaps Revolver Creek-Carr Boyd Faults have been described. Several small thrusts of the same trend fault Carr Boyd Group between the Glenhill and Carr Boyd Faults. The **Osmond Fault** diverges ENE from the Halls Creek Fault into the Sturt Block, and displaces rocks up to Victoria Basin succession in a set of north-dipping imbricate thrust sheets (M. D. Muir, personal communication, 1975).

Uplift and rotation of the fault wedges, between the Revolver Creek-Carr Boyd and Carr Boyd-Halls Creek Faults, ascribed herein to these thrusts, was explained by the strike-slip "lemon-pip" model of Lensen (1958) (Plumb & Gemuts, 1976). This analogy was further extended, at a larger scale, to explain the southward plunge of metamorphic zones in the Tickalara Metamorphics and, particularly, the sudden juxtaposition of granulites (south) and low greenschists (north), by uplift across the southwesterly unnamed shear zone, just south of the Bow River Fault (Fig. 5). This shear zone must now represent the only outcrop of Hancock and Rutland's postulated major Zone II-Zone IV geosuture, but has not yet been the topic of any detailed structural mapping.

Synthesis: The total accumulative left-lateral strike-slip displacement of all the faults just described approaches 200 km. More than half of this is documented in Kimberley Basin and Carr Boyd Group rocks, and objective analysis cannot positively constrain any of it to being any older.

Repeated reactivation from Early Proterozoic to at least Permian of a similar and geometrically-compatible system of folds and faults has long been proposed (Plumb, 1968, 1979b; Dow & Gemuts, 1969; Plumb and Gemuts, 19760). However, major long-lived strike-slip or transform systems in documented modern systems have time scales of similar movement patterns measured in several tens of Ma, rather than the several hundred Ma implied by these Kimberley models.

The post-cratonisation pattern, of northeasterly thrusts and folds cut by more northerly strike-slip faults, is identical to that described in the basement rocks by Hancock and Rutland (1984). Synmetamorphic Early Proterozoic mylonitisation on a steep Halls Creek fault system (Allen, this work), is of uncertain sense of movement, as is the pre-Carr Boyd Group movement on the Bow River Fault (just described). A sinistral strike-slip Halls Creek Mobile Zone is an integral component of Hancock and Rutland's model for basement evolution, but the evidence for actual displacement is now destroyed; the oldest strike-slip displacement which they can estimate is still only post-D_2 (zone I), and is quite compatible with being part of the post-cratonisation system..

Strike-slip deformation of the Kimberley Basin can only be conclusively constrained between the Hart Dolerite and the Early Cambrian Antrim Plateau Volcanics. There must have been some folding and uplift before the Carr Boyd Group, from the Revolver Creek Formation/Mount Hensman Sandstone unconformity and the wide variety of basements down to Halls Creek Group upon which the Carr Boyd Group now sits. The reverse faults and folds at the edge of the Kimberley Basin parallel and are essentially coplanar with D_2 (zone IV), and similarly bend into the King Leopold Mobile Zone. The more northerly-trending strike-slip fault segments are geometrically compatible with having formed in the same system as the thrusts and folds, but they so ubiquitously cut and offset the folds and thrusts that they must have at least continued later; they could well be very much later, and quite separate.

The only Proterozoic strike-slip displacement that can be positively constrained is that which occurred during and after Carr Boyd Group deposition. It occurred on the same system, and individual displacements are of the same magnitude as, those faults which displace all older rocks. The oblique thrusts which demonstrably accompany the strike-slip faulting of the Carr Boyd Group, and link the Greenvale-Dunham Faults strike ENE to locally accommodate horizontal shortening; not NNE as in the regional Kimberley Basin systems. The local tight folding of the Carr Boyd Group, although oblique to the strike-slip faults in a similar orientation (NNE) to the Kimberley Basin folds, are controlled by specific high-strain fault wedges, rather forming regional folds cut later by faults. The 1050 Ma, syn/post Carr Boyd event, cannot be identified isotopically or structurally in the King Leopold Mobile Zone.

The following is one possible model which can simply explain these constraints. The regional folds and thrusts in the Kimberley Basin formed not long after sedimentation ceased, during the 1650-1550 Ma event of the Halls Creek (Bofinger, 1967) and King Leopold (Bennett and Gellatly, 1970) Mobile Zones. Movements were still sufficiently similar and related to those earlier in the basement (NW convergence?) to reactivate D_2 (zone I-IV)-D_3/D_4 (zone II) fold trends and, probably, even actual folds. Strike-slip displacements at this time remains enigmatic.

A totally new stress/strain regime developed about 1050 Ma ago or older, controlled by N-S directed slip of up to 200 km between the Sturt and Kimberley Blocks. This was accommodated by strike-slip reactivation of major faults of the Halls Creek Mobile Zone, and development of many new splays. This system can accommodate all of the strike-slip displacements now visible, and its reassembly to the pre-slip configuration has important consequences for the original shape of the Halls Creek Orogenic Sub-province.

A younger post-glacial 600 Ma thrusting/folding event was confined to the King Leopold Mobile Zone. Subsequent Palaeozoic movements along the Halls Creek Mobile Zone were probably mostly vertical; they have accumulative displacements of several kms and controlled Palaeozoic graben and horst development. Most activity occurred during the Late Devonian (Veevers & Roberts, 1968), when horizontal components were also recorded on the Cockatoo Fault (Rod, 1966).

5. MINERAL DEPOSITS

(Hancock)

Basement sequences in the Halls Creek Orogenic Sub-province host numerous interesting but marginally economic to uneconomic deposits of base and precious metals. Reference should be made to information available for particular commodities on open file at the W.A. Geological Survey. A brief commodity survey summarising some features of the styles of mineralisation is given below:

(a) **Volcanogenic base metals** (Marston [1979]): Minor deposits of copper with varied amounts of associated lead, zinc, silver and gold are found associated with meta-acid volcanic successions and hiatus points within them across the outcrop extent of the sub-province. Significant deposits include Chianti, Mangrove and Turtle Creek in the West Kimberley (zone IV west), and Ilmars, Little Mount Isa, Golf Course, Angelo, Angelo South, and Koongie Park in the East Kimberley (zone I). All deposits are too small for economic extraction as presently known. They range from "proximal" disseminated Cu mineralisation in probable subvolcanic intrusives of the upper Biscay Formation (Angelo South), to volcanic and metasedimentary-hosted Cu/Pb/Zn/As+Ag+Au occurrences in graphitic tuffaceous phyllite (Turtle Creek).

Native copper occurs in vesicular metabasalt of the Ding Dong Downs Volcanics at Saunders Creek.

(b) **Volcanogenic rare element deposits (Nb, Ta, Y):** This is a distinctive class of Nb and Ta-enriched acid volcanic and subvolcanic magmatic and deuterically upgraded magmatic deposits, associated with highly fractionated felsic and acid units of the upper Biscay Formation, in the southern Biscay Anticlinorium. Significant resources of these units with elevated Nb (>2000ppm) are present in outcrop, but the fine grainsize of host columbite-tantalite and uncertain market indicate they may have little potential.

(c) **Magmatic Chromite - Platinum Group Elements:** Platiniferous chromite bands within the lower portions of layered tholeiitic mafic complexes are known from the Panton Sill and parts of the McIntosh Gabbro near Eastmans Bore. Significant Pt grades (up to 2 dwt.) have been recorded from chromite bands in the Panton Sill (Dow and Gemuts, 1969), but evaluation has indicated a complex lenticular seam geometry and limited economic reserves.

(d) **Magmatic Cu-Ni sulphides:** These are known from the basal portions of a number of tholeiitic gabbro units within the McIntosh Gabbro, and probably span the intrusive range of this unit. The largest deposit, Sally Malay (Thornett, 1981), is located in a relatively late-tectonic gabbro-norite body emplaced into zone IIIC, but reserves remain uneconomic at present. Smaller deposits are known from a number of intrusive bodies in zone IIIA (Cabernet, Corkwood), as "xenoliths" within zone III (Sandy Creek), and in zone I (Margaret River). Nickeliferous pyrrhotite, pentlandite, and chalcopyrite are the main ore minerals, and these occur as dominantly disseminated and occasionally massive, probably structurally produced zones.

(e) **Vein gold deposits:** These were located near Halls Creek subsequent to alluvial discoveries in 1883, but recorded production is small (926.3 kg (29 784 ozs) to 1969). Smaller deposits have been found in the West Kimberley (Turtle Creek area) and associated with the Bow River Granite terranes (Mt Amherst). Deposits have been reviewed by Finucane (1939a,b,c) and little can be added to his descriptions. Deposits in zone I are hosted by post/late D_2 structural permeability in upper Biscay and lower Olympio Formation sequences and related Woodward Dolerite. Lodes were generally narrow, patchily mineralised, variably sulphidic quartz veins, and most production was from alluvial shed. No deposit has been worked to any depth. Relatively small scale mining of dominantly alluvial gold is currently the main extractive mining industry in the basement province.

(f) **Vein-style base metals, barite, and corundum:** Small occurrences are sporadically distributed through the various tectonic zones, but nowhere has production been significant. Veins are hosted in shear zones and post-upright folding veins, but all are too small to justify economic extraction. Significant occurrences are in the Little Tarraji Valley (Reid, 1959), Turtle Creek area, Mount Amherst (Finucane, 1939a), and Cummins Range areas.

The major economic mineral deposit in the Kimberley area is the **Argyle Diamond Project.** Current economic reserves at Argyle are estimated as 61 million tonnes @ 6.8 carats/tonne, and smaller operations are presently in production from alluvial shed from elements of the lamproite association in the general Argyle area. Occurrences are also known from the West Kimberley (Mt North-Mt Percy area) in younger but similar rocks, and the diamond-associated alkaline rock suite is widely represented across the area underlain by the Halls Creek province. Although not directly related to basement development (host units vary from Miocene to late Precambrian), it is almost certain that the deeply penetrating fracture systems localised by the Halls Creek and King Leopold Mobile Zones were important in channelling host lamproites to the near-surface environment.

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DAILY NOTES

DAY 1

Leader: Ken Plumb

OUTLINE

Regional Structural Setting and Kimberley Basin

The principal purpose of Day 1 is travel, from the assembly point at Kununurra to the Early Proterozoic Halls Creek Group near Halls Creek; about 350 km. The route passes right down the middle of the Halls Creek Mobile Zone, with spectacular exposure of the mega-structures of the region. Brief stops will be made at appropriate points. Opportunity will also be taken to briefly examine roadside exposures of Kimberley Basin rocks, as typical examples of the oldest, immediately post-orogenic platform cover of North Australia.

PROGRAM

Stop	Time	Geology and Locality
	0800	Assemble and depart Kununurra
1A	0800 - 0830	Drive Kununurra-Valentine Creek anticline, observing Bonaparte Basin- Carr Boyd Group-Kimberley Basin relationships and structures.
1B	0830 - 0930	Hart Dolerite and granophyre; Valentine Siltstone; Lansdowne Arkose. Valentine Creek, 17 km W Kununurra.
1C	0930 - 1000	Upper Tunganary Formation (if time permits). 22 km W Kununurra.
	20 minute drive to:-	
1D	1010 - 1030	Middle Pentecost Sandstone; glauconitic sandstone marker. Gap Point.
1E	1030 - 1050	Elgee Siltstone (if time permits). 21 km SSW Mount Erskine.
1F	1050 - 1130	Drive to Dillon Springs. Note Wyndham Shale scarps, Cockburn Sandstone, Mendena Formation en route.
1G	1130 - 1200	King Leopold Sandstone. Dillon Springs, Saw Ranges.
	1200 - 1240	LUNCH
	1240 - 1700	Drive Dillon Springs-Halls Creek area; with brief stops
1H	1300	Ragged Range.
1I	1325 - 1335	Dunham Fault, Dunham Jumpup.
1J	1405 - 1410	Mount Nyulasy
	1630	Turn-off to Saunders
	1700	CAMP, Bulman Waterhole

NOTES

1A

Kununurra lies within the Phanerozoic Bonaparte Basin. The prominent Pincombe Range to the north is an inlier of Carr Boyd Group which formed a ridge throughout most of the Palaeozoic. The Carr Boyd Range to the south similarly was the approximate basin margin, but has been further uplifted since Devonian.

The prominent scarp of the Ivanhoe Fault to the west is the edge of the Kimberley Basin. Small faulted outliers of Devonian sandstone are seen as the fault is crossed.

Stop 1B

Speewah Group and Hart Dolerite are exposed in he core of the Valentine Anticline. The Hart Dolerite granophyre is well exposed in the lower half of the scarp at 1B; in this area it is up to 250 m thick. Here the granophyre is a relatively even-grained variety, although typical elongate pyroxenes can be found in places.the granophyre commonly contains small xenoliths. Feldspathic arenites above the granophyre have been metasomatically altered for a considerable distance, making it difficult to precisely locate the contact.

The overlying Valentine Siltstone comprises green chloritic siltstone and siliceous siltstone, and the the marker beds of massive rhyolitic ashstone and siliceous siltstone which distinguishes the formation in the East Kimberley. A tuff bed marks the top of the unit in this section.The tuffs are discontinuous; sometimes one is present, sometimes two. Ashstones contain phenocrysts of quartz and feldspar in a siliceous groundmass, or a groundmass of sericite, chlorite, quartz, and feldspar. Rhyolitic tuffs show occasional shattered quartz phenocrysts in a cryptocrystalline felsic groundmass. Some fine acid rock fragments may be present.

The contact with the overlying Lansdowne Arkose is gradational; only the lowermost beds will be seen.

Stop 1C

In the East Kimberley, the Tunganary Formation is more quartz-rich and coarser grained than in the west. Flaggy feldspathic and siliceous sandstones, at the top, are gradational into the Valentine siltstone.These are underlain by distinctive boldly-outcropping cross-bedded granule sandstones. In a full section (not seen here), these are then underlain by green micaceous siltstones and quartz sandstones.

Stop 1D

The Pentecost Sandstone is very uniform throughout the whole Kimberley Basin. Several unnamed members, separated by consistent silt markers, may be mapped everywhere, except in the extreme west.

The base of the middle Pentecost is defined by a consistent unit of ferruginous-glauconitic sandstone and siltstone, Note the low-angle cross-bedding, and the intraformational folds in one bed of green silt. 50 km to the west traces of stratiform copper have been followed over a strike length of some 40 km.

The overlying middle Pentecost is typically a monotonous pink feldspathic sandstone or arkose, with regular thin bedding, low-angle planar or shallow-trough cross-beds,clay pellets, limonite-stained spots (after what?), and blocky rubble outcrop due to regular thin shale partings. The feldspar content decreases southwards.

The underlying lower Pentecost is more quartz- rich and silica cemented, and have regular planar cross-bed sets about 30 cm thick.

Stop 1E

The Elgee Siltstone is a distinctive massive red siltstone with scattered thin green interbeds - a classic redbed - throughout the Kimberley. In the south it has a dolomitic Teronis Member at the base. Small amounts of stratiform copper occur in the lower beds over about 100 km along the Chamberlain River.

The siltstone grades up, via passage beds, into the Pentecost Sandstone. Pink and red cross-bedded ferruginous-silty sandstone interbeds form individual cross-bed sets 30-50 cm thick. Note the low-angle cross-beds, some recumbent cross-beds, and abundant shale pellets; some beds are shale pellet conglomerates. The base of the Pentecost Sandstone is taken at the first pink to white quartz sand.

1F

The high scarps of monotonous green shale and siltstone to the west of the road are Wyndham Shale, capped by Cockburn Sandstone. The green shales distinguish it from underlying shaley units. Road cuttings of sand and shale are the Mendena Formation, a passage unit between the Pentecost Sandstone and Wyndham Shale. The high mesa of the Cockburn Range in the distance illustrates the gradual flattening of structure into the Kimberley Block.

Stop 1G

The conglomerate which defines the boundary between the "upper" and "lower" King Leopold Sandstone has been mapped right along the Saw Ranges to the south, but is missing at this northern end; apparently faulted out by a fault slightly oblique to strike.

The "lower" King Leopold Sandstone is a distinctive strongly cross-bedded argillaceous sandstone with scattered quartz pebbles. Williams (1969) has interpreted it as a fluviatile deposit.

At this point, the overlying "upper" King Leopold Sandstone is a very different well-sorted , regularly bedded, silica-cemented quartz sandstone. Some pebbles appear again higher up section. Williams has interpreted this unit as a shallow-marine deposit.

1H

The regular truncation of strike ridges of the Saw Ranges to the west of the road can only be due to a concealed fault; the Dillon Springs Fault is extrapolated to run approximately along the line of the road. Its offset, about 30 km, is seen in the excellent match between the folds of the Valentine Creek area, to the northeast, and those to the west, between the Saw Ranges and Dunham River - Ragged Range.

Small prominent hills in the valley to the east, between the Saw and Carr Boyd Ranges, are Devonian Cockatoo Sandstone lying along traces of the Dunham-Ivanhoe, Dillon Springs, and Glenhill Faults, and "hardened" by quartz veining. Near 1H a small outcrop of the sandstone lies across the Dillon Springs Fault, with marked unconformity on Kimberley Group.

The Ragged Range itself is composed of Late Devonian Ragged Range Range Conglomerate Member, and attests to the extreme stability of the region between the end of the Proterozoic and Late Devonian. The fossil-bearing conglomerate is underlain at the base of the scarp by fossiliferous early Middle Cambrian Blatchford Formation, which in turn overlies the Early

Cambrian Antrim Plateau Volcanics. Despite 100% cliff exposure, no obvious structural or lithological break is visible between the Blatchford Formation and Ragged Range Conglomerate Member - an extreme example of a paraconformity.

Stop 1I

Proceeding to the next point, the Dunham Fault is crossed after a few minutes, where Carr Boyd Group to the east is faulted against Kimberley Basin succession to the west. Flat-lying Antrim Plateau Volcanics filling the exhumed valley to the west and unconformably overlying strongly-folded and faulted Kimberley Basin rocks demonstrate the Proterozoic age of principal deformation of the Basin. The Volcanics have only been gently tilted by later faulting.

The Dunham Fault is exposed in a road cut at Dunham Jump-Up. The fault dips steeply to the east, and small drag folds indicate a reverse component of displacement at this point; Bow River Granite to the east is faulted against Speewah Group. In the Speewah Group of the O'Donnell Range immediately to the southwest, the trace of the ENE thrust fault dipping 30-50^{o}N, which joins the Greenvale and Dunham Faults, can be seen. This is interpreted as related to the predominant strike-slip movement, evidenced from the Dillon Springs arm at 1H.

Immediately to the northeast basal Carr Boyd Group sits on the granite basement. This requires some east-block uplift to expose this basement, pre-Carr Boyd Group. During deposition, the Carr Boyd Group basin then subsided relative to the Kimberley Basin, and thus subsequent east-block relative uplift or left-lateral strike-slip displacement is required to produce the apparently anomalous Kimberley Basin - Carr Boyd Group juxtaposition just traversed.

Proceeding south from the Jump-Up, along the valley of granite along McPhee's Creek, the Dunham Fault has a striking physiographic expression to the west of the road: a bold scarp against the O'Donnell Range, and mesoscopic drag folds clearly visible in the Speewah Group to the west; knife-edge ridges of siliceous, steep east-dipping fault zones farther south. To

1J

Mount Nyulasy is Bow River Granite, and will be looked at later (6C). The granite intrudes low-grade Halls Creek Group rocks at the base of the Carr Boyd Range scarp to the east.

Three unconformities can be seen in this scarp at the southern tip of the Carr Boyd Ranges: between the Halls Creek Group/Revolver Creek formation; Revolver Creek Formation/Hensman Sandstone; and Golden Gate Siltstone/Lissadell Formation. Beyond the main ridge, out of sight, the Antrim Plateau Volcanics are unconformable on the Lissadell Formation.

Several thick silicified E-W shear zones have just been passed in the granite. Only one of them, the Bow River Fault, affects the Carr Boyd Group, but without the silicification and width in the granite. The others stop at the unconformity. Considerable precratonic faulting has occurred, but of uncertain sense of movement.

The Argyle diamond mine is situated at the southern extremity of this ridge of the Carr Boyd Ranges, at the intersection of a small cross fault with one of the major shear zones of the region: it truncates the Carr Boyd Group and also separates greenschist facies from granulite facies in the basement. It must be Hancock and Rutland's Zone II-Zone IV suture (see 6B).

The highway south from here traverses the various metamorphic zones of the basement, decreasing southwards; the subject of Days 4-6. The Halls Creek Fault is seen standing up as a prominent scarp or ridge in several places to the east. Most of the prominent high country on the skyline to the west of the road is post-tectonic Bow River Granite.

DAY 2

Leader: Steve Hancock

OUTLINE

Stratigraphic and Structural Evolution of the Halls Creek Group

Days 2 and 3 are designed to examine the stratigraphy and structure of the Halls Creek Group and associated rocks, in the most completely preserved section and at low metamorphic grade, in the centre of Zone I (Fig. ##).

PROGRAM

Stop	Time	Geology and Locality
2A	0730	Units 3 and 2 of Ding Dong Downs Formation, and Saunders Creek Formation, on the western side of the D_2 anticline of the Saunders Creek Dome.
2B		Upper Ding Dong Downs Volcanics and Saunders Creek Formation, near Bulman Waterhole.
2C		Lower Biscay Formation, and passing through a faulted contact into the lower and middle Olympio Formation.
	1200 - 1300	LUNCH, near Ding Dong DOwns outstation.
2D		Section through the middle and upper Biscay Formation and the Woodward Dolerite sequence, Woodward Creek area. Examination of stratiform D_1 structures, in a D_2 hinge area.
	1700	CAMP, Bulman Waterhole.

NOTES

See main text for details of stratigraphy and structure.

DAY 3

Leader: Steve Hancock

OUTLINE

Day 3 continues the Halls Creek Group section from Day 2

PROGRAM

Stop	Time	Geology and Locality
3A	0730	Middle Biscay stratigraphy in a D_2 closure zone (brief stop only).
3B		Traverse from the Sophie Downs Granite northwards, through lower and middle Biscay Formation stratigraphy with tight D_1 structures, into progressively increasing D_2 strain northwards.
	1200 - 1300	LUNCH
3C		Post-orogenic sequence of Moola Bulla Formation, between "old" and "new" Halls Creek townships.
3D		Multiple intrusive gabbros - McIntosh Gabbro and Alice Downs Ultrabasics - syn-D_2 Zone II, Upper Panton River. Multiple intrusive events and composite intrusion; chromitite zones.
	1700	CAMP, Panton River crossing.

NOTES

See main text for details of stratigraphy and structure.

DAY 4

Leader: Rosemary Allen

OUTLINE

Metamorphism of the Halls Creek Group, and Igneous Rocks

The purpose of Days 4 and 5 is to see the Halls Creek Group sequence of Days 2 and 3, from Saunders Creek Formation through the Biscay Formation, where it has been metamorphosed up to sillimanite grade, in and adjacent to the Black Rock Anticline. Mylonite zones associated with the Halls Creek Fault will be seen, plus the relationships of various syntectonic intrusive rocks to the metamorphic and deformation phases.

Day 3 will concentrate principally on rocks in the Upper Sillimanite Zone of the Amphibolite Facies. A section will seen through the metamorphosed Alice Downs Ultrabasic.

PROGRAM

Stop	Time	Geology and Locality
	0730	Depart Panton River camp. Pass over McIntosh Gabbro & andalusite-sillimanite schists.
4A	0800 - 0930	Alice Downs Ultrabasics, Panton Sill. Alice Downs track, 3 km E highway.
4B	1000 - 1100	Wollastonite-bearing calc-silicates. 0.5 km S McKenzies Spring
4C	1100 - 1200	Travel to Dougal's Yard. "Dougals Tonalite, if time permits.
	1200 - 1230	LUNCH
	1230 - 1330	Across country to Wills Creek by 4WD
4D	1330 - 1530	Wills Creek. Quartzites of Saunders Ck Fm & faulting along basal unconformity. Westerly splay of Halls Creek Fault defining western margin of Black Rock Anticline. Interbedded pillow basalts & acid volcanics, Unit 1, Biscay Fm, capping carbonate bed. Bimodal volcanics, Unit 2. "Black Rock Tonalite", if time permits.
4E	1530 - 1630	West of Wills Creek. Mylonitised acid volcanics, Unit 2, Biscay Fm. Pelites with strong S_2 regional schistosity, metamorphosed to sillimanite grade.
4F	1630 - 1700	Wills Creek to Dougals Bore. Impure quartzites, garnet-sillimanite schists, carbonate beds - Unit 2, Biscay Formation. Foliated (Woodward?) dolerite.
4G	1700 - 1730	East of Dougals Bore. Thick carbonates of Unit 4, Biscay Fm.
	1730	CAMP, Dougal Bore.

NOTES

Stop 4A

The Panton Sill has been folded into a southerly plunging syncline, 11 km long, 3 km wide, and about 1 km thick, and disrupted by transverse faults. It is surrounded by metamorphic rocks and metamorphic rocks are exposed in the core of the syncline.

The sill is layered, with individual bands up to 100 m thick. Most of the rocks contain secondary minerals after olivine and pyroxene, formed when the sill was metamorphosed in the Lower Sillimanite Zone of the Amphibolite Facies, during M_{2A} (see Fig ##). Metamorphic conditions are estimated at about 550° and 4 kb. The basal contact is poorly exposed and strongly sheared. A lower ultramafic cumulate zone is separated from an overlying gabbroic zone by a faulted and sheared contact. The contact with metamorphic rocks is exposed in the core of the syncline.

The base of the section consists of massive dark-green altered and serpentinised peridotite, in which relict ragged olivine crystals are partly pseudomorphed by cryptocrystalline serpentine, and set in a groundmass of fine decussate tremolite and chlorite laths. Irregular grains of chromite and magnetite are common accessories.

Above this, a series of tremolite-chlorite schists and serpentinite are derived from peridotite, troctolite, and pyroxenite. Ragged tremolite laths are intergrown with and replaced by pale green or colourless chlorite. Magnetite and chromite grains outline the boundaries of olivine crystals, which are pseudomorphed by decussate clusters of tremolite and chlorite laths. Similarly, chain-like spinel grains enclose decussate tremolite laths, and probably represent pre-existing boundaries of pyroxene or olivine crystals. Segregation bands of chromitite occur, and secondary magnetite is present as a weathering feature.

These ultramafics grade up into dark-green coarse-grained uralitised gabbros and cream-coloured uralitised leucogabbros. Rhythmic banding is preserved, and ragged amphibole-rich bands up to 5 cms wide are common. The texture ranges from allotriomorphic granular to ophitic. Plagioclase ranges from andesine to bytownite, and is sometimes saussuritised. Hornblende has replaced all original pyroxene, and may be replaced along cleavage by biotite.

Stop 4B

Foliated and banded calc-silicate rocks are interlayered with amphibolite, gabbro, and garnetiferous gneiss of the Olympio Formation. They are metamorphosed to the Upper Sillimanite Zone of the Amphibolite facies (Fig. 11).

Large zoned boudins of wollastonite-garnet-diopside rock occur within white marble. Large crystals of pink granular garnet are associated with green diopside and epidote; in some cases large patches of xenoblastic carbonate minerals surround the garnet and epidote. Some of the boudins are composed almost entirely of granular twinned diopside interspersed with blebs of calcite and sheaves of wollastonite. Idioblastic sphene is concentrated around the margins of the wollastonite. Minor amounts of scapolite are also present.

This assemblage of minerals coexists during regional metamorphism at high temperatures under low partial pressures of CO_2. (Wollastonite has also been reported from granulite facies areas west and east of the Mabel Downs

Granodiorite).

Stop 4D
Wills Creek Section

The western splay of the Halls Creek Fault defines the western margin of the Black Rock Anticline. Saunders Creek Formation quartzites overlie the fault to the west. Thus, this major faulting is along the basal unconformity separating the basement volcanics from the rift sequence. The great difference in competencies between the Ding Dong Downs Volcanics and the quartzites of the Saunders Creek Formation make this zone of weakness a prime locus for dislocation. On the north bank of Wills Creek, the near vertical Halls Creek Fault cuts through a steep cliff face. A zone of serpentine separates quartzites on the west from a granite/gabbro complex in the Black Rock Anticline. On the south bank brecciated quartzite marks remobilisation of the fault involving the quartzite immediately overlying it.

Saunders Creek Formation quartzites crop out in a thin discontinuous strip forming high ridges marking the western boundary of the Halls Creek Fault, and can be mapped from east of White Rock Bore in the south, to east of Sally Malay Bore in the north, a distance of some 50 km. The two high quartzite ridges on the south bank of Wills Creek (separated by a fault) were mapped by Dow and Gemuts as Mabel Downs Granodiorite. The quartzite is white to pale buff, very pure, and very well sorted. It represents a beach deposit, rather than the braided stream facies evident in the type area at Saunders Creek. A little farther north, towards the Ord River, banding formed by a small quantity of heavy minerals displays complex refolding. In places the quartzite is extensively silicified with a ramifying system of quartz veins.

Overlying the Saunders Creek Formation are the bimodal volcanics which form Unit 1 of the Biscay Formation. In some areas (for example, the McClintock Dome) this unit consists entirely of basalt. North of the Black Rock Anticline, thick ignimbrites (the Corkwood East Suite) make up the complete sequence. In the Wills Creek area, 3-5 beds of pillow basalts (the thickest being approximately 5m thick) are interbedded with acid volcanics. The pillows show chilled margins and zones of fine amygdales and, although deformed, stacking relations indicate the beds are younging to the west. The basalt is fine-grained and shows no evidence of spilitisation. (The geochemistry is discussed in an earlier section.) The acid volcanics are thinly interbedded (10 cm - 1m thick), and in places show bottom "rip-up" structures. The leucocratic rock is very compact, with lenses up to 5 mm long of micas interpreted as replacing glass lapilli flattened parallel to bedding. In thin section, primary igneous zoned feldspars occur with small spessartine-rich garnets (up to 13% MnO_2) These small volume pyroclastics could be interpreted as being very distal from the vent. Alternatively, secondary phreatomagmatic eruptions could have occurred as the hot ash cloud interacted with the cold sea water, most of the material becoming re-airborne and leaving very little deposited sub-aqueously. Unit 1 is capped by a carbonate bed of variable thickness, in this area approximately 20 cm thick, but north of the Black Rock Anticline tens of metres thick.

The lower portion of Unit 2, overlying this carbonate bed, is also dominantly volcanic. In the Wills Creek area further acid volcanics are interbedded with pillow basalts, their character and chemistry being very similar to the leucocratic material and basic volcanics in the underlying unit.

Stop 4E

A little further up sequence, acid volcanics from Unit 2 of the Biscay Formation have been mylonitised. Along strike to the north of the Black Rock Anticline, this bed is many tens of metres thick. In outcrop in these northern areas, the rocks are pale pink to buff coloured, fine-grained, and have a characteristic sparsely-pitted surface due to the weathering out of feldspar phenocrysts. The large (up to 1 cm diameter) rounded feldspars are randomly distributed in a fine-grained matrix. These felsic volcanics are interpreted from their wide distribution, rapid variation in thickness, poor sorting, and lack of internal stratification, as ignimbrites of ash-flow origin and sub-aerial deposition. The variation in thickness of this bed is interpreted as due to ponding in palaeo-valleys and thinning over palaeo-highs. Superimposed on this variation is the structural thinning due to mylonitisation seen at Stop 4E. This rock has a schistose fabric (seen in thin section to be mylonitic - modified S_2) which wraps the few large rounded feldspar phenocrysts. Tiny almandine-rich garnets in this outcrop are formed late in the metamorphic history, although in the northern areas they span the metamorphic history, having cores with minute quartz inclusions (M_1), an intermediate zone with sillimanite inclusions (M_{2a}), and euhedral overgrowths (M_{2c}).

Overlying the acid volcanics are garnet - sillimanite schists. Upright, open-tight D_4 folds, plunging shallowly to the NNE, fold a well developed S_2. This area is metamorphosed to the Upper Sillimanite Zone of the amphibolite facies, with parageneses appropriate to that grade. Geothermometry gives consistent estimates of $630 \pm 20^{\circ}C$ in the Black Rock Anticline, and south of the Mabel Downs Granodiorite. However, in the high strain zone of frequent mylonitisation, cooling temperatures of about $450^{\circ}C$ are consistently recorded.

Stop 4F

On the track back to Dougal's Bore we cross thinly interbedded impure quartzites, garnet-sillimanite schists, and carbonate beds of Unit 2 of the Biscay Formation. Foliated dolerite obliterates much of Unit 3 here, as elsewhere. The foliation is S_2 in high-grade areas, with a strong L_1/L_2 elongation lineation. Thus, while this dolerite is most probably Woodward Dolerite, it was possibly intruded later, pre-D_2 but post or syn-D_1, and therefore not directly correlatable. (Unit 1 and most of Unit 2 of the Biscay Formation, north of the Wills Creek section examined earlier and south of the Ord River, are obliterated by foliated dolerite.)

Stop 4G

Unit 4 of the Biscay Formation is composed of a thick sequence of carbonate beds showing complex refolding.

DAY 5

Leader: Rosemary Allen

OUTLINE

The morning of Day 5 will concentrate on rocks in the Lower Sillimanite Zone of the Amphibolite Facies, and the afternoon on relationships of various phases of the Mabel Downs Granodiorite. After leaving camp we will travel south through gneiss, invaded by anatectic granites, at the base of the Olympio Formation. A section through the Biscay Formation in the Lower Sillimanite Zone demonstrates a high-strain area with frequent mylonite zones, involving many different rock types, and illustrates the variation along strike from the Wills Creek section of Day 4.

PROGRAM

Stop	Time	Geology and Locality
5A	0730	Depart Dougals Yard. Paragneisses of Olympio Fm.
5B	0730 - 0830	Dougals Yard - White Rock. "White Rock Leucogranite", Mabel Downs Granodiorite.
5C	0830 - 1100	1.5-2.0 km section, White Rock Ck - Wills Ck. Pillow basalts, Unit 4, Biscay Fm. Unit 3: garnet-staurolite schists, carbonates, carbonaceous schists, metabasalts, folded BIF, metadolerites, acid intrusive. Abundant mylonite zones affecting wide range of rock types. Folded acid volcanics, Unit 2.
	1100 - 1130	Return, Wills Ck - White Rock Ck.
	1130 - 1200	Drive out to highway.
	1200 - 1300	LUNCH. Ord River. Examine mylonite outcrop, see 5E.
5D	1330 - 1400	"Melon Patch Granite" invaded by Mabel Downs Granodiorite. Corkwood Track.
5E	1400	Note mylonite zone of Corkwood Track, seen in outcrop at lunch.
5F	1400 - 1430	Xenoliths of McIntosh Gabbro in Mabel Downs Granodiorite. (Can be omitted if seen at Dougals Tonalite, 4C)
5G	1430 - 1530	D_{2A} folds cut by Mabel Downs Granodiorite. 5 minutes north of Corkwood Track.
5H	1530 - 1600	Basic intrusives & Mabel Downs Granodiorite folded by D_3 & D_4.
5I	1600 - 1630	Hornblende tonalite & K-Spar granite of Mabel Downs Granodiorite. Corkwood Track.
5J	1630 - 1730	S_2 folded by D_3 & D_4 in "White Rock Leucogranite. South of Ord River.

CAMP, Ord River.

NOTES

Stop 5A

Quartzo-feldspathic gneisses, granite gneisses, leucogneisses, and banded gneisses, are all metamorphosed variants of the lutites and arenites of the Olympio Formation. Carbonate beds are intercalated at the base of the Formation, and foliated metadolerites invade the sequence. In this section, the gneisses contain variable amounts of biotite, hornblende replaced by pyroxene, and occasional small corroded almandine garnets. Cordierite occurs just north of Dougal's Bore, south of the Ord River, and also to the west of "Dougal's Tonalite". Thus, Dougal's Bore is just below the Transitional Granulite Zone isograd.

Stop 5B

Outcrops of the hornblende-bearing tonalite (the main phase of the Mabel Downs Granodiorite), faulted against the "White Rock Leucogranite", will be briefly examined beside the track. This will allow comparison with the mylonitised version of the leucogranite. Both granitoids will be examined in more detail in the afternoon.

Stop 5C
White Rock Creek Section

East down White Rock Creek, towards Wills Creek. Working down the stratigraphy, from the top of the Biscay Formation.

Unit 4:Spectacular outcrop of beautifully preserved pillow basalts, in cliffs on either side of White Rock Creek (pillows, water -washed, polished - photogenic in the creek bed!). White quartzite occupies the interstices between the pillows. Thin intercalated carbonates are all that remain to represent the thick sequence east of Dougal's Bore (Stop 4G).

Unit 3: Metapelite; garnet-staurolite schist; mylonitic fabric. Carbonate bed fractured, disrupted, and mylonitised, intruded by "White Rock Leucogranite" also mylonitised. Upright D_4 folds in metapelite, folding a strong S_2 schistosity (metamorphic segregation with garnet-rich bands).

Unit 2: Two carbonate beds folded and refolded. Metapelite-garnet schist, mylonite fabric. Thick sequence of pillow basalts. Carbonaceous schist. Mylonitised meta-pelites with "banana folds" (curved axial traces). BIF isoclinally folded by D_2. Acid volcanics. These acid volcanics are phenocryst rich (as is the bed of acid volcanics at the top of Unit 2 by Sally Malay Bore). The mechanism by which phenocrysts were fractionated may have been aeolian fractionation, that is, the winnowing out of the fine ash from the plume. D_4 folds are upright and shallowly plunging to the NNE.

Unit 1: Unit 1 has been faulted out in this area.

Stops 5D-5J

Several stops illustrate variants and relationships of the Mabel Down Granodiorite. Relationships are described in the main text.

DAY 6

Leader: Ken Plumb

OUTLINE

Late and Post-Tectonic Igneous Rocks

Day 6 completes study of the metamorphic rocks by briefly visiting an outcrop of granulite facies rocks near Turkey Creek, and then looks at lithologies of the post-tectonic suite of Whitewater Volcanics, Castlereagh Hill Porphyry, and Bow River Granite in the McPhee's Creek area. A shear zone of retrogressed granulites in the Bow River will be studied, which almost certainly represents the outcrop of Hancock and Rutland's Zone II-Zone IV suture.

PROGRAM

Stop	Time	Geology and Locality
	0730 - 0800	Drive Ord River - Turkey Creek
6A	0800 - 0930	Tickalara Metamorphics; hornblende-granulite subfacies. 1 km W Turkey Creek Post Office.
6B	0930 - 1130	Retrogressed granulites and shear zone. Bow River bridge.
6C	1130 - 1200	Typical Bow River Granite at Mount Nyulasy, en route to:-
	1200 - 1245	LUNCH
6D	1245 - 1415	Section through Bow River Granite- Castlereagh Hill Porphyry contact. 5 km S Pompeys Pillar.
6E	1430 - 1630	Whitewater Volcanics. 4 km NNW McPhees Creek bore.
	1630 - 1700	Drive to Dunham River bridge
		CAMP

NOTES

Stop 6A

Irregular tectonic inclusions of pyroxene granulite are enclosed within intricately folded garnetiferous cordierite-sillimanite or hornblende-pyroxene gneisses. Dark bands and clots of biotite, garnet, and aluminosilicates alternate with leucocratic quartz-feldspathic material. Cordierite forms irregular black vitreous bands and swirls. Large garnet porphyroblasts are scattered throughout the pelites. Biotite-rich reaction rims surround the inclusions of basic granulite.

Pelitic assemblages include:

quartz - garnet - biotite - oligoclase - cordierite - sillimanite

quartz - microcline - andesine - hornblende - biotite - clinopyroxene - garnet

The pyroxene granulites contain:

bytownite - clinopyroxene - hornblende - quartz

clinopyroxene - labradorite - cummingtonite - quartz

In the same area, 2-pyroxene granulites, containing both orthopyroxene and clinopyroxene, have developed from rocks of suitable composition. The rocks definitely lie in the granulite facies.

Stop 6B

Spotted retrogressed granulite. Large cordierite xenoblasts have been replaced by muscovite and minor chlorite, to give the rock a spotted appearance. The groundmass of the rock consists of quartz and saussurite after plagioclase feldspar.

Gemuts (1971) related the retrogression to the intrusion of the Bow River Granite. He did not appreciate that north of the Bow River the grade of regional metamorphism decreases suddenly from granulite facies to low greenschist. A large fault (the Argyle diamond deposit lies immediately adjacent to it) truncates the southern end of the Carr Boyd Ranges, but its extension within the basement to the southwest is obscured by poor outcrop. If extrapolated to the southwest it corresponds to the northern limit of the high-grade rocks, and passes roughly through this point. The foliation within the retrogressed rocks parallels this postulated fault. Much of the zone comprises an intimate mixture of rock types that could not be mapped at 1:250 000 scale.

Plumb and Gemuts explained the juxtaposition by uplift of the northern edge of the metamorphic belt along the "cross fault" by Lensen's (1958) "lemon pip" model of strike-slip faulting. It is now apparent that this zone must represent the outcrop of Hancock and Rutland's suture between Zone II and IV, if such in fact exists. Indeed, it is the only place where it can outcrop without being destroyed by the Bow River batholith adjacent to the high-grade zones.

The zone has not been mapped in detail or any structural analysis carried out. A lengthy stop is scheduled to allow time to see what can be found.

Stop 6C

Typical exposure of the post-tectonic Bow River Granite has massive texture, large ovoid rimmed K-feldspar megacrysts, and green epidotised plagioclase.

Note the east-west shear zones in the granite; part of the Bow River Fault. Only the most northerly, the named Bow River Fault, affects Carr Boyd Group, but with greatly decreased movement. The vertical sense of displacement on each of these shears is the same, south-block-up, which is the same as that between the metamorphic zones at 6B. However, these zones are steep and post-Bow River Granite.

Stop 6D

Along the eastern side of the McPhee's Creek - Pompeys Pillar valley the Bow River Granite is overlain by a shallowly-dipping sheet of porphyritic granophyre equated with the Castlereagh Hill Porphyry. Where they occur together, the Porphyry is indistinguishable from intrusive phases of Whitewater Volcanics; they are considered to be cogenetic. The Porphyry intrudes the Volcanics, and both are regionally intruded by the Bow River Granite. Relationships in this section are equivocal. The change in rock types is sudden, but the actual contact is not exposed. Both units grade at the contact. The section could be depth zones of the same or a composite intrusion.

The Bow River Granite here is medium to coarse and even-grained, compared to the porphyritic phase at 6C. Xenoliths are abundant, and a prominent set of joints dipping 30° E suggest a structure concordant with the porphyry sheet. At the contact the granite is coarser grained, and lacks xenoliths.

The typical Porphyry is a fine-grained porphyritic granophyre or micrographic adamellite, comprising saussuritised plagioclase phenocrysts ca. 1-2mm and sparse quartz, in a groundmass (<1 mm) of granophyric to micrographic quartz and K-spar and chloritised ferromags. The K-spar is mainly orthoclase. Small sedimentary and igneous xenoliths up to 15 cm are common. Towards the contact this rock grades, over a thickness of about 150 m, into a coarser more even-grained microadamellite, in which plagioclase and K-spar are in about equal quantities and size (0.5-5 mm). K-spar includes both microcline and orthoclase, and granophyric texture disappears. Plagioclase is commonly replaced by relatively coarse epidote and ragged laths of brown biotite are abundant at the contact.

Time may not allow the full gradation to be seen.

Stop 6E

The Whitewater Volcanics are confined to Hancock and Rutland's Zone IV. In the West Kimberley they are tightly folded and sheared by D_{2B} (zone IV). In the East Kimberley they are unsheared and are folded only little more than the overlying Kimberley Basin rocks; locally the unconformity can be hard to detect. They are definitely post-tectonic in the east. This is one such outcrop.

As mapped, the volcanics include intrusive material; there is probably considerably more which cannot be readily distinguished from the extrusives. The volcanics are commonly massive, structureless, and continuous over wide areas. They have been interpreted as being predominantly welded ashflow tuffs, although shards and other diagnostic features are rarely preserved. This outcrop preserves some probable shards or pumice fragments, compaction bands, and breccia fragments.

Gellatly et al. (1975) have documented a transition in the west from basal high-K andesites to rhyodacite higher up. Phenocrysts of quartz and sericitised plagioclase are set in a cryptocrystalline groundmass of feldspar, quartz, chlorite, and devitrified glass. Chlorite commonly pseudomorphs amphibole, and less commonly pyroxene. Sedimentary bands occur at some levels, but not in this outcrop.

The 30 minute walk into the section passes through the steeply-dipping wall of the silicified Dunham Fault.

DAY 7

Leader: Ken Plumb

OUTLINE

Zone IV and Carr Boyd Group

This day is designed to briefly look at undifferentiated Halls Creek Group of Zone IV for the first time, and the Bow River Granite - Castlereagh Hill Porphyry - Whitewater Volcanics relationships again, in the Golden Gate Inlier of the northern Carr Boyd Ranges. This will be followed by a brief look at rock types of the Carr Boyd Group and structures associated with the Carr Boyd Fault. The excursion will conclude at Kununurra.

PROGRAM

Stop	Time	Geology and Locality
	0730 - 0900	Travel to Carr Boyd Ranges
7A	0900 - 1030	Halls Creek Group and Halls Creek-Cockatoo Fault, below Mount Hensman
7B	1030 - 1130	Bow River Granite and Castlereagh Hill Porphyry relationships. Golden Gate Country. 15 km NE Ord Dam
7C	1130 - 1230	Carr Boyd Fault. 12km NE Ord Dam
	1230 - 1330	LUNCH
7D	1330 - 1445	Golden Gate Siltstone. W side of Ord Dam
7E	1445 - 1515	Lower Lissadell Formation. E side Ord Dam
7F	1515 - 1545	Middle Lissadell Formation. 2km N Ord Dam
7G	1545 - 1630	Glenhill Formation. 4 km n Ord Dam
	1630 - 1715	To Kununurra

EXCURSION ENDS. OVERNIGHT KIMBERLEY COURT

NOTES

The Carr Boyd Group is characterised by rapid facies changes in some units, but each of the unconformably-separated cycles have their own distinctive characteristics. The outcrops examined are represented by Sections 4A and # in Figure ##. Detailed sections are described in Dow et al. (1964).

Stop 7A

The Halls Creek Group of Hancock and Rutland's Zone IV comprises quartz-rich wackes and slates of turbiditic origin, and lies in the low greenschist facies. They are lithologically similar to the Olympio Formation. Some tuff and conglomerate has been recorded from this area. Folding is invariably tight to isoclinal about steep axial planes (D_2, zone II) and slaty cleavage is ubiquitous. This area is the only one accessible to this excursion but has not been mapped since the 1963 regional mapping, and thus no detailed structural analysis or stratigraphy is available.

This outcrop lies within the Halls Creek Fault Zone, the western splay of which has the most striking physiographic expression and continues northwards as the Cockatoo Fault, and was a major influence on the development of the Phanerozoic Bonaparte Basin.

Stop 7B

In the Golden Gate Country the Castlereagh Hill Porphyry again forms a Flat-lying sheet above Bow River Granite.The porphyry is in turn overlain by, and intrudes, the (cogenetic?) Whitewater Volcanics. A gradation is again seen between the granite and porphyry, and may well represent depth zones of the same intrusion (cf. 6D).

A series of exposures shows a gradation from coarse adamellite with typical large ovoid K-feldspar megacrysts, into a finer-grained even-grained adamellite. All are characterised by similar two feldspars and chloritised biotite. Several hundred metres north of the last outcrop we can see the adamellite grades into a fine-grained porphyry, with phenocrysts of similar feldspars to those in these outcrops.

Stop 7C

At this point Carr Boyd Group is faulted against the "basement" granite, porphyry, and volcanics. It is in the zone where the north-striking strike-slip Carr Boyd Fault is swinging in trend to ENE, which geometrically requires the movement to be accommodated by thrusting. The sedimentary succession is about the Pincombe Formation - Stonewall Sandstone contact. Major joints and small faults dip steeply to the east.Joints nearby show shallow south-plunging slickensides. The fault is mostly beneath soil cover, but one small breccia outcrop appears to dip about 60-70° east. What does the geometry of the small folds indicate?

Stop 7D

The Golden Gate Siltstone displays the most striking facies change in the Carr Boyd Group. The beds in this exposure are probably from the upper member of the unit.

Uniform laminated green and red chloritic siltstone has scattered lenses of flaggy fine-grained sandstone and some black chert. Other sedimentary structures are deficient. Some small pods of coarse pyrite can be seen; to the east of the Carr Boyd Fault pyrite pods are abundant in black shales.

The siltstone here occurs within a major fault zone. It has been intensely deformed and a slaty cleavage developed. Several shallow-dipping faults can be seen; Swarbrick (1965, Geol. Surv. W. Aust. ann. Rep. 1964) has postulated gravitational gliding tectonics to explain similar shallow faults around the dam site.

Stop 7E

The lower Lissadell Formation is a massively outcropping silicified fine-medium-grained quartz sandstone, characterised by steep planar and trough cross-beds, in regular sets 15 to 30 cm thick. These grade up into flaggy sandstones with shale partings. NO cross=beds have been measured here, but farther west they are unidirectional, and taken to suggest a (?)fluvial origin.

Stop 7F

The upper Lissadell Formation is characterised by thinly-interbedded purple and green micaceous siltstone, shale, and sandstone, with lenticular and wavy bedding, ripple bedding, mud cracks, and red shale partings. Bidirectional palaeocurrents indicate a tidal-flat deposit.

Stop 7G

The basal Glenhill Formation here is characteristically a massive red-brown cross-bedded friable (?fluvial) quartz sandstone with unidirectional palaeocurrents. The overlying silts of the Glenhill Formation are everywhere typically thin-bedded or laminated, and deficient in mica. In this section they comprise red and black siltstones and shales. A few kilometres to the northwest a thick alluvial fan grades into redbed silts. At this locality an exhumed vertical fault surface separates the two sequences.