Journal of Structural Geology, Vol. 12, No. 5/6, pp. 703 to 714, 1990
Printed in Great Britain

0191-8141/90 $03.00 + 0.00
Pergamon Press plc

Structural development of the King Leopold Orogen, Kimberley region, Western Australia

I. M. TYLER and T. J. GRIFFIN

Geological Survey of Western Australia, Mineral House, 100 Plain street, East Perth, WA 6004, Australia

(*Received* 10 *February* 1989; *accepted in revised form* 9 *February* 1990)

Abstract—The King Leopold Orogen consists of two tectonic units: the Hooper Terrane, a complex of Early Proterozoic metasedimentary rocks, migmatites, felsic volcanics, basic sills and granitoid intrusions; and folded rocks of the overlying Early Proterozoic Kimberley Basin succession and a Late Proterozoic glacigene sequence.

The oldest deformation (D_1) affects metasedimentary rocks of the Hooper Terrane and is characterized by layer-parallel structures confined to zones of high strain. D_1 was accompanied by a metamorphic event (M_1), which was locally high grade. D_2 post-dates the felsic volcanics but pre-dates granitoid intrusion and consists of upright NW-trending folds. D_3 post-dates deposition of the Kimberley Basin succession and, in the Hooper Terrane, takes the form of WNW- to NW-trending shear zones which combine dextral, sinistral and south-side-up movements. In the northwest the Kimberley Basin succession is folded and faulted by D_3 to form the Yampi Fold Belt. Two fold phases are recognized. D_{3a}, which comprises flat-lying folds and N-directed thrusts, is refolded by D_{3b}, comprising folds and thrusts linked to shear zones in the Hooper Terrane. D_3 was accompanied by amphibolite-facies metamorphism (M_2). D_4 post-dates deposition of Late Proterozoic glacigene rocks, and produced SW-directed folds and thrusts to form the Precipice Fold Belt. Throughout the area discussed the contact between the Hooper Terrane and the Kimberley Basin succession is sheared or thrust.

D_1, D_2 and M_1 are Early Proterozoic in age with D_1 and M_1 possibly forming in an extensional environment, while D_2 may represent a (?) sinistral strike-slip environment. D_3 and M_2 are the result of Middle to Late Proterozoic intracratonic compression and may be related to a collision located to the southwest. D_4 accompanied Late Proterozoic to Early Phanerozoic sinistral faulting in the Halls Creek Orogen. A major crustal structure of probable D_2 age separates the Hooper Terrane from (?) Archaean basement under the Kimberley Basin. It controls the northeast limit of the Yampi Fold belt (D_3) and ramping of thrusts in the Precipice Fold Belt (D_4), and could represent the site of an early Proterozoic terrane boundary.

INTRODUCTION

PROTEROZOIC rocks in the Kimberley Region of northern Western Australia crop out in the Halls Creek and King Leopold Orogens, as well as the Kimberley and Birrindudu Basins (Fig. 1). Both the orogens consist of two tectonostratigraphic units: a crystalline complex comprising deformed and metamorphosed Early Proterozoic plutonic, volcanic and sedimentary rocks; and folded rocks of the overlying Early Proterozoic Kimberley Basin succession and a Late Proterozoic glacigene sequence. Outside of the zone affected by orogenic deformation rocks of the Kimberley Basin succession and the glacigene sequence are little deformed and metamorphic grade is low. The Proterozoic rocks all form part of the Northern Australian Shield of Plumb *et al.* (1981). They are unconformably overlain by Palaeozoic rocks of the Canning, Bonaparte and Ord Basins.

The region was mapped by joint field parties from the Bureau of Mineral Resources (BMR) and the Geological Survey of Western Australia (GSWA) in the early 1960s (Dow & Gemuts 1969, Gellatly *et al.* 1974, Plumb & Gemuts 1976). Subsequent work has concentrated on the Halls Creek Orogen (see summaries in Hancock & Rutland 1984, Plumb *et al.* 1985) with little new information reported from the King Leopold Orogen. This paper presents a structural reassessment of the central and northwestern parts of the King Leopold Orogen (Fig. 2) based on the results of a remapping programme commenced by the GSWA in 1986. The results are important to the understanding of the structural and tectonic evolution of the King Leopold Orogen and its relationship to the Halls Creek Orogen, and to other Proterozoic orogenic belts in northern Australia.

STRATIGRAPHY

Hooper Terrane

In the King Leopold Orogen the crystalline complex was named the Hooper Terrane by Griffin (1989). It comprises five main components (Fig. 2) all of which were described in detail by Sofoulis *et al.* (1971) and Gellatly *et al.* (1974). The oldest component is a sequence of metasedimentary rocks comprising turbiditic sandstone and phyllite, with minor felsic and intermediate tuff. In the Halls Creek Orogen similar metasediments occur in the Olympio Formation of the Halls Creek Group, and Gellatly *et al.* (1974, 1975) suggested that the units may be equivalent. The lower units of the Halls Creek Group, dated at *ca* 1880 Ma by Page (1988, U–Pb on zircons), however, are not present in the study area and no base, or basement, to the sequence is recognized. The metasedimentary rocks are intruded by thick layered basic sills (?equivalent to the Woodward Dolerite of the Halls Creek Orogen).

Granitoid rocks and migmatite near Mount Joseph were regarded by Gellatly *et al.* (1974) as being the product of *in situ* partial melting of the metasedimentary

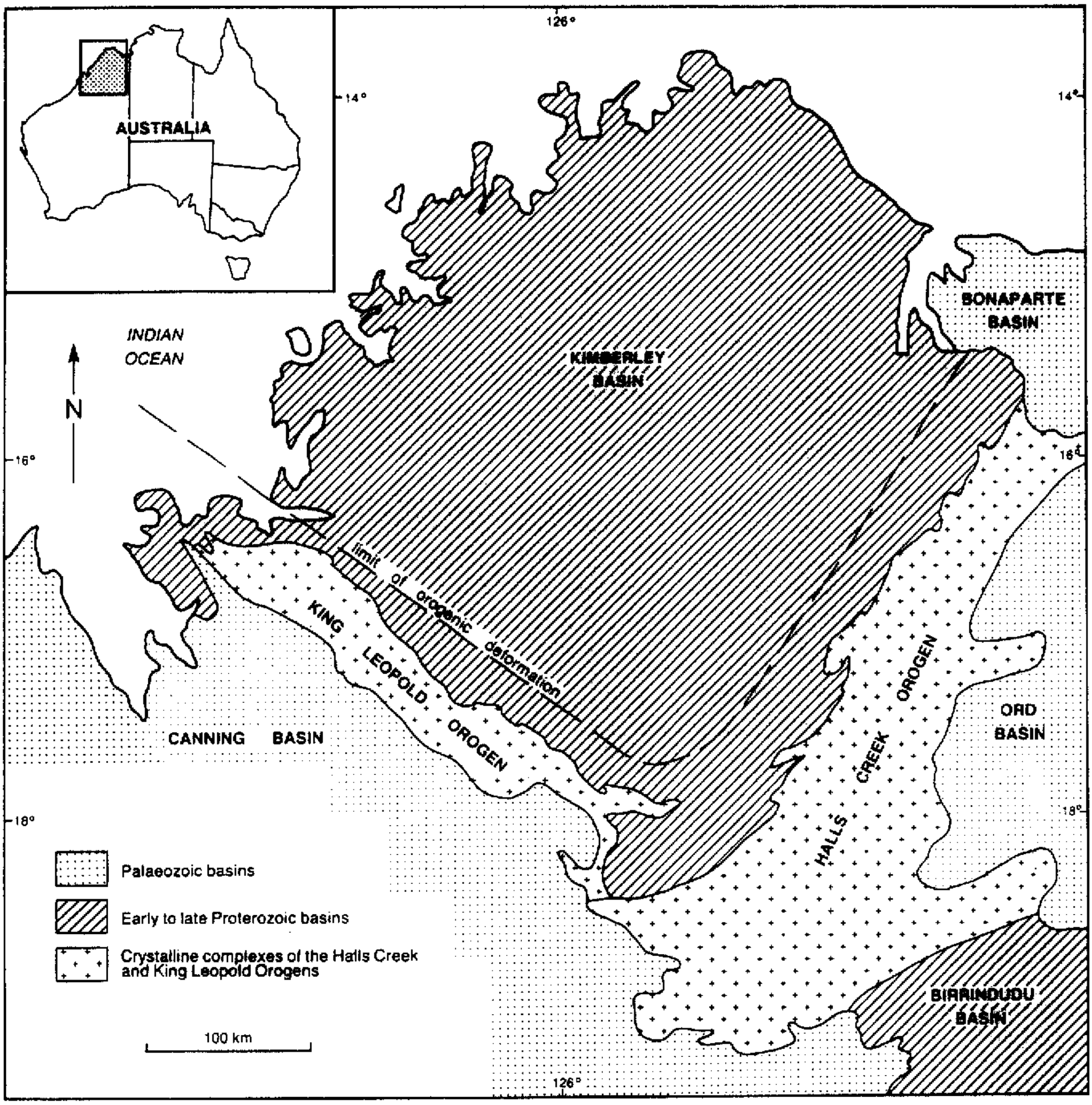

Fig. 1. Map showing the main tectonic units of the Kimberley region of Western Australia.

rocks. Gellatly *et al.* (1974) also recognized a foliated biotite-granite, the Kongorow Granite, some components of which may also have been generated by the partial melting.

The metasedimentary rocks, basic sills, anatectic granitoid and migmatite are unconformably overlain by felsic volcanic rocks (Gellatly *et al.* 1974). These are similar to the Whitewater Volcanics which crop out in the Halls Creek Orogen (Dow & Gemuts 1969, Gellatly *et al.* 1974) and from which zircons have given an U–Pb date of *ca* 1850 Ma (Page & Hancock 1988).

All these rocks were intruded by batholiths of tonalite, granodiorite, monzogranite and syenogranite which give a Rb–Sr date of *ca* 1840 Ma (cf. Page 1976, Page *et al.* 1984). These granitoids appear to be equivalent to the Bow River Granite in the Halls Creek Orogen (Gemuts 1971, Gellatly *et al.* 1974).

Kimberley Basin succession

The Hooper Terrane is overlain by the shallow marine Kimberley Basin succession (Table 1) (see also Plumb *et al.* 1981). The contact, which will be discussed in detail below, was formerly thought to be an unconformity (Gellatly *et al.* 1974, Sofoulis *et al.* 1971) but has recently been reinterpreted by Griffin & Myers (1988 a,b) as a thrust. The Kimberley Basin succession consists of two groups. The lowest is the Speewah Group, a sequence of quartzose and feldspathic arenites interbedded with mudstone and minor acid volcanics. This is conformably

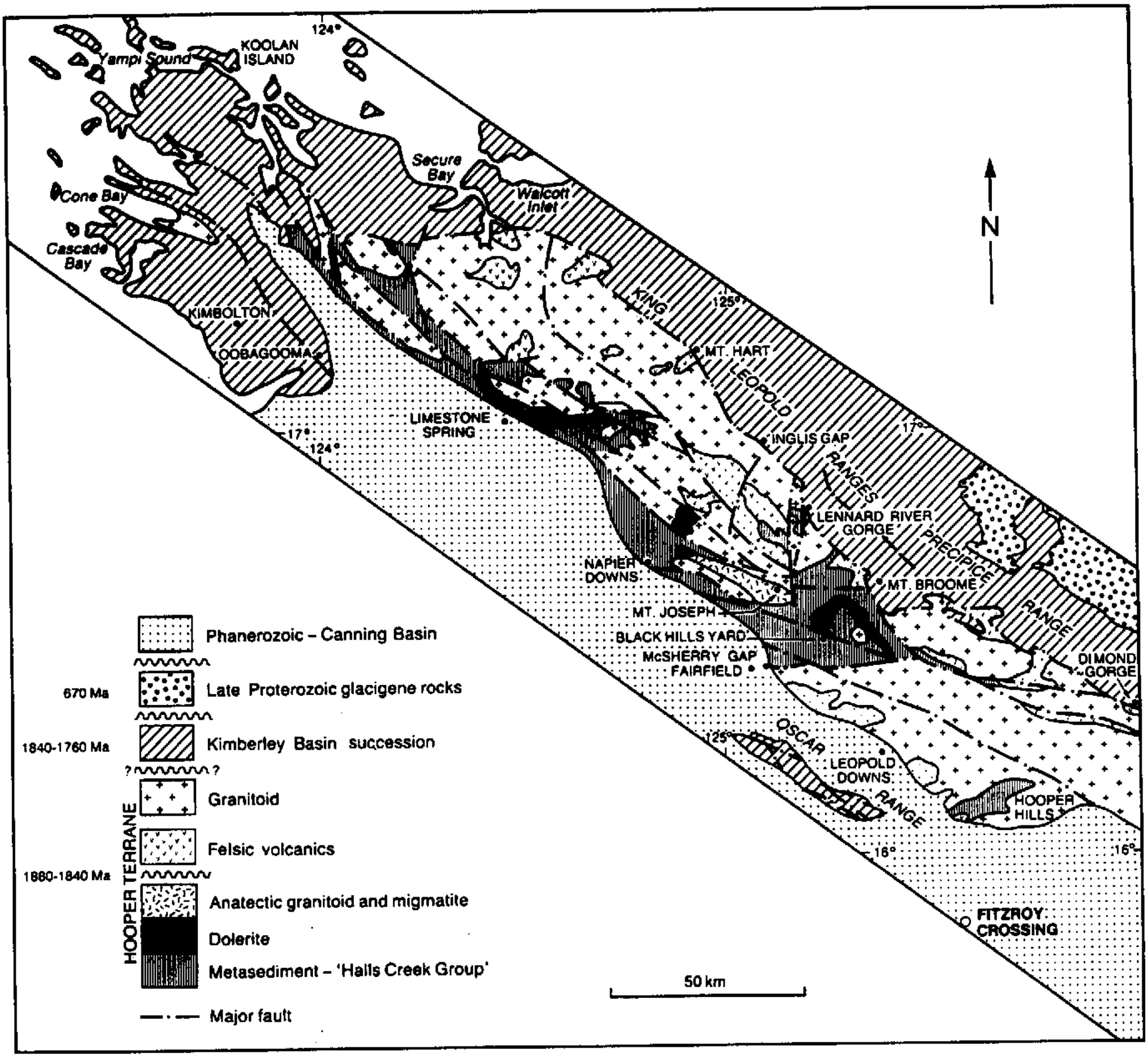

Fig. 2. Simplified geological map of the central and northwestern parts of the King Leopold Orogen.

overlain by the Kimberley Group which consists of mature sandstone and siltstone together with tholeiitic basalt.

The Speewah and Kimberley Groups are intruded by a series of very extensive dolerite sills collectively called the Hart Dolerite that give a Rb–Sr date of *ca* 1760 Ma (cf. Page 1976).

The Kimberley Group is unconformably overlain by Late Proterozoic glacigene rocks of the Mount House Group (Derrick & Playford 1973).

STRUCTURE

Four periods of deformation (D_1–D_4) are recognized in the King Leopold Orogen and they range in age from Early Proterozoic to Late Proterozoic–Early Palaeozoic.

D_1

The oldest deformation (D_1) is only seen in the metasedimentary rocks of the Hooper Terrane mainly as a layer-parallel foliation (S_1). A few tight to isoclinal small-scale folds (Fig. 4a) are associated with it in zones of high strain. Large-scale folds are not recognized, but the metasedimentary rocks were tilted prior to the deposition of the overlying felsic volcanics.

D_2

The second deformation (D_2) produced upright open to tight folds at all scales (Figs. 3 and 4b). The folds generally have NW-trending axial surfaces and typically plunge moderately or steeply NW or SE. An axial-planar crenulation cleavage (S_2) is well developed (Fig. 4b) and can be recognized in metasedimentary rocks

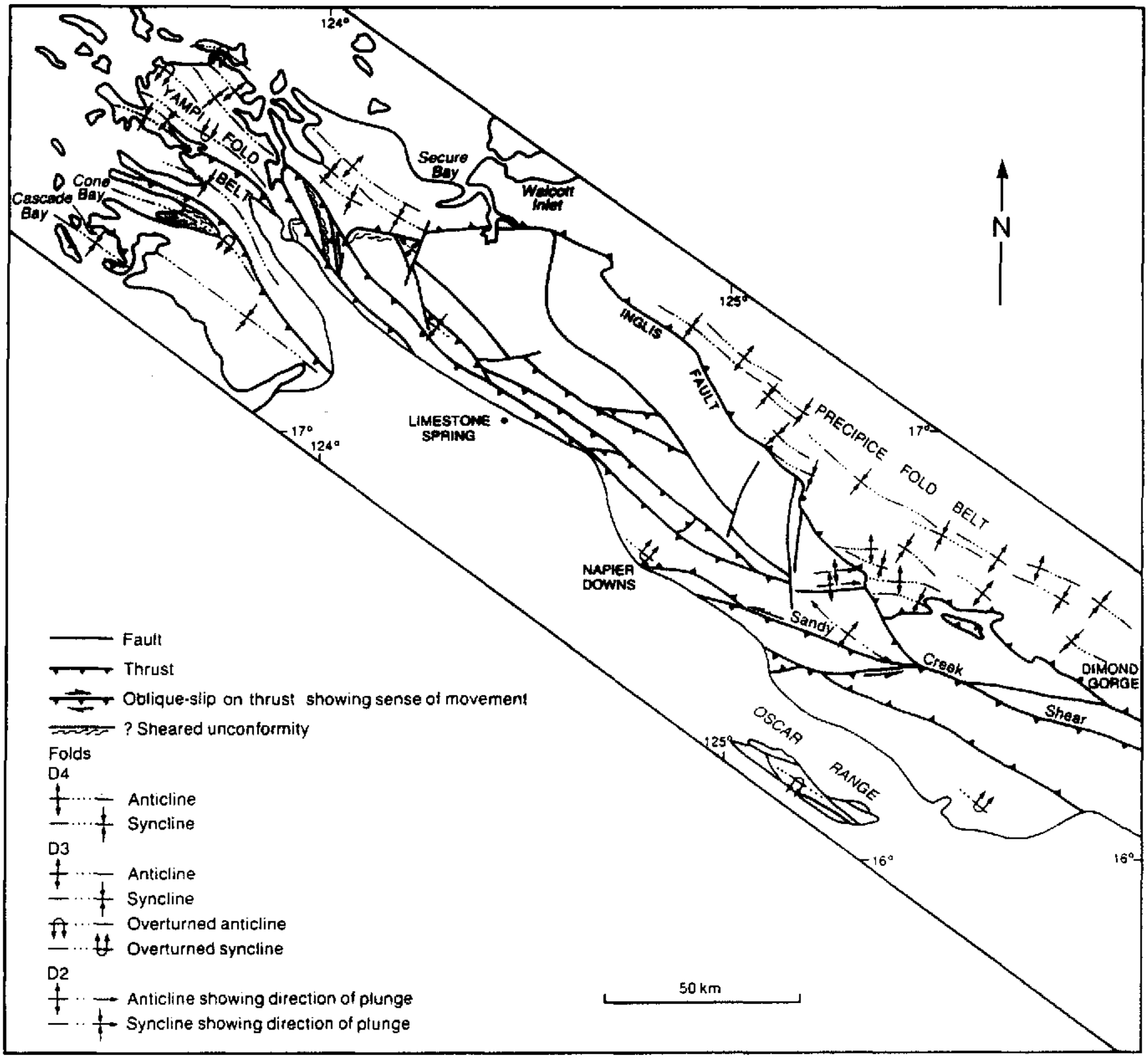

Fig. 3. Map showing the main structural features of the central and northwestern parts of the King Leopold Orogen.

throughout the orogen. A bedding–cleavage intersection lineation (L_2) is also prominent. Gellatly *et al.* (1974) reported folds in an area 11 km to the west of Mount Broome (Figs. 2 and 3) that plunged steeply SSW. They attributed these to an older fold phase. However, fieldwork during this study (Griffin *et al.* in press) has shown that there is only one phase of folding in this area that post-dates tilting during D_1. The axial surfaces of the D_2 folds here maintain a WNW trend and dip steeply to the SSW while bedding is steep to vertical and trends NNE. The SSW plunges reflect the steep intersection of bedding with the S_2 cleavage. No folds have been observed that have SSW-trending axial surfaces (Griffin *et al.* in press).

The D_2 event has folded leucosomes in the migmatites near Mount Joseph (Fig. 4c) and therefore post-dates the high-grade metamorphic event that produced them (M_1; Griffin *et al.* in press). Metamorphic grade during the M_1 event elsewhere in the orogen was low (Griffin *et al.* in press, Tyler *et al.* in press). D_2 also post-dates the felsic volcanics, folding them near Mount Broome (Figs. 2 and 3). However, D_2 pre-dates the main phase of granitoid intrusion.

D$_3$

In the Hooper Terrane the third deformation has taken place on large-scale shears that trend WNW and dip steeply SSW or locally NNE. They affect all rocks within the Hooper Terrane. In the Yampi area the shear zones are seen to cut into the Kimberley Basin succession where they are orientated parallel to the axial surfaces of large-scale folds.

Rootless, intrafolial folds, usually of early formed quartz and pegmatite veins, are common in the shear zones (Fig. 4d). Shear criteria (cf. Berthé *et al.* 1979, Simpson & Schmid 1983) generally show south-block-up movement (Fig. 4e). In the Yampi area the main shears

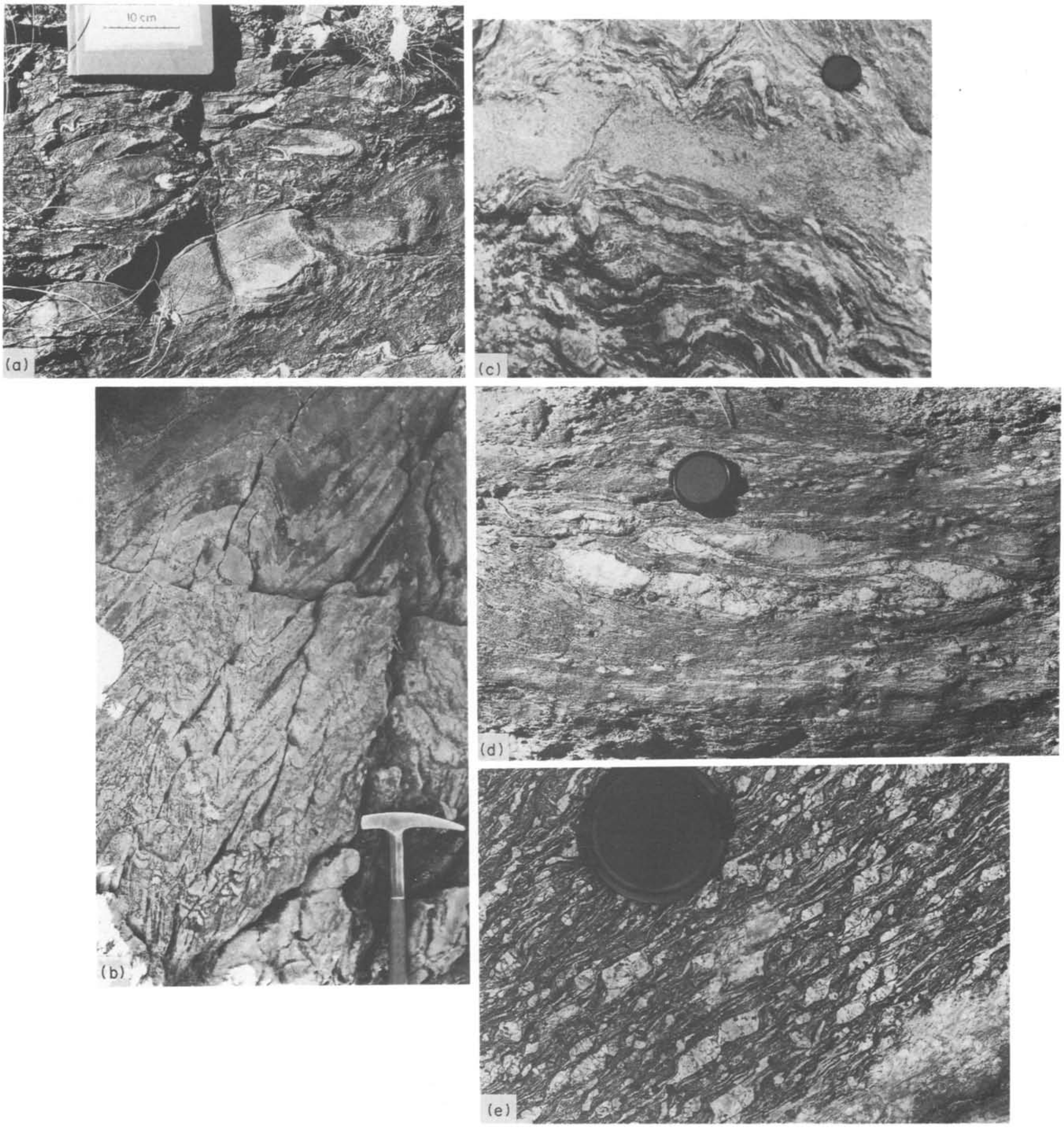

Fig. 4. (a) Tight to isoclinal, small scale D_1 fold closures in metasedimentary rocks of the Hooper Terrane northeast of Oobagooma. A later crenulation cleavage (S_2) is present. (b) Open to tight D_2 folds in metasedimentary rocks of the Hooper Terrane northeast of Oobagooma. An axial plane crenulation cleavage is well developed in the bottom left of the photograph. The hammer is 30 cm long. (c) Open to tight D_2 folding of migmatite leucosomes near Mount Joseph. The folds are cut by a later granitoid vein. The lens cap is 5 cm in diameter. (d) Isoclinal, rootless intrafolial D_3 fold in a shear zone south of Mount Joseph. Porphyroblasts of garnet may also be seen. The lens cap is 5 cm in diameter. (e) Sheared porphyritic granite exposed in the Sandy Creek Shear 35 km ESE of Black Hills Yard. Shear criteria indicate south (left) to north (right) movement. The lens cap is 5 cm in diameter.

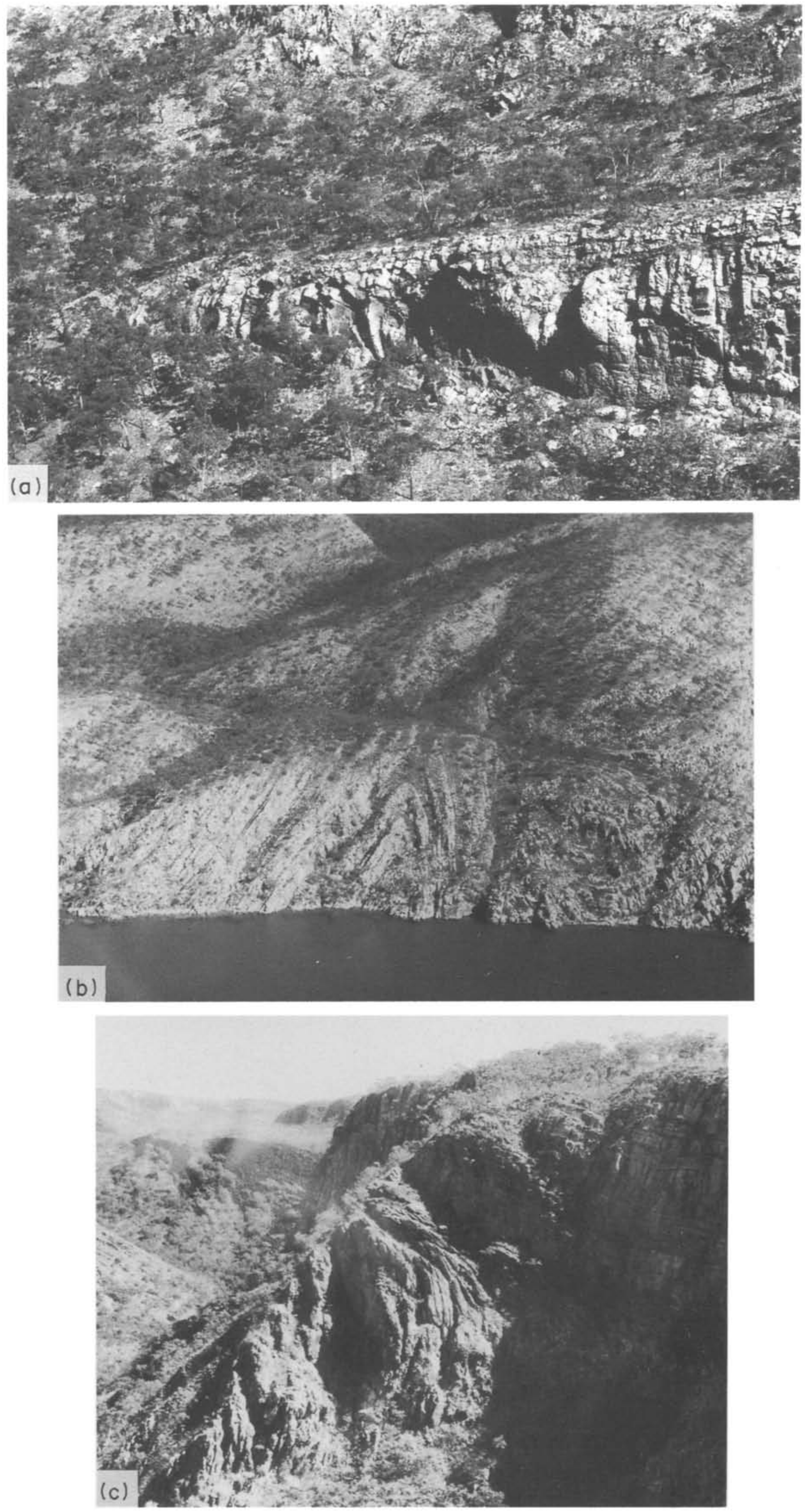

Fig. 5. (a) Aerial view of a large-scale near isoclinal D_{3a} fold closure in King Leopold Sandstone, Cascade Bay. (b) Aerial view of a tight large-scale steeply-inclined N-facing chevron-style D_{3b} fold in Warton Sandstone south of Koolan Island. The cliff is 100 m high. (c) Aerial view of the contact between the Kimberley Basin succession and the Hooper Terrane near Secure Bay. A strong, upright D_3 shear fabric in the underlying granitic rocks is deflected indicating southward (right to left) transport of the overlying sediments of the Kimberley Basin succession. The cliff is 120 m high.

Table 1. Stratigraphy of the Kimberley Basin and Late Proterozoic glacigene rocks (after Plumb & Gemuts 1976 and Coats & Preiss 1980)

Basin	Group	Formation
	Mount House Group (*ca* 670 Ma)	Estaughs Formation
		Throssell Shale
		Traine Formation
		Walsh Tillite
	unconformity	
Kimberley Basin (1840–1760 Ma)		Hart Dolerite and Wotjulum Porphyry sills
	Kimberley Group	Pentecost Sandstone
		Elgee Siltstone
		Warton Sandstone
		Carson Volcanics
		King Leopold Sandstone
	Speewah Group	Luman Siltstone
		Lansdowne Arkose
		Valentine Siltstone
		Tunganary Formation
		O'Donnell Formation
	sheared and thrust contact (?unconformity)	
	Hooper Terrane (1880–1840 Ma)	

in the Hooper Terrane are linked by NW-trending splays that show dextral strike-slip movement (Fig. 3). South of Black Hills Yard an E-trending segment of the Sandy Creek Shear has a sinistral sense of movement (Fig. 3). These structures are interpreted as oblique ramps (cf. Hossack 1983) linking the main shear zones and are consistent with an overall SSW–NNE transport direction. Stretching lineations are well developed in shear zones in granitoid rocks and vary in orientation from down-dip on the main shears to sub-horizontal on some of the oblique shears. The strain during D_3 was strongly partitioned into the shear zones and in many areas rocks between the shears have remained virtually unaffected. Refolding of D_2 structures occurs only in the vicinity of the shears where metasedimentary rocks can develop a second crenulation cleavage (S_3) that dips at gentle to moderate angles into the shear zones. This is particularly well developed in the area between McSherry Gap and Black Hills Yard (Fig. 2).

In metasedimentary rocks near Limestone Spring and to the south of Mount Joseph, porphyroblasts of staurolite and garnet occur in the shear zones, and display sigmoidal inclusion trails consistent with syntectonic growth (cf. Bell 1985, Bell *et al.* 1986) under amphibolite-facies conditions. Elsewhere andalusite, staurolite, biotite and garnet porphyroblasts are all seen to overgrow, and therefore post-date, the S_2 crenulation cleavage. Porphyroblast growth is therefore regarded as separate from the M_1 event (which pre-dates D_2) and a later M_2 event is recognized (Griffin *et al.* in press) occurring synchronously with D_3. Granitoid intrusions have all recrystallized during this M_2 event with an early set of basic dykes in granitoid rocks east of McSherry Gap showing epidote–amphibolite-facies mineral assemblages (Griffin *et al.* in press). Lower grade (typically greenschist-facies) mineral assemblages occur in metasedimentary rocks in the Yampi area, and to the north of Black Hills Yard.

Folds in metasedimentary rocks near Napier Downs (Figs. 2 and 3) have moderately- to gently-plunging axes and trend WNW. An axial plane schistosity dips to the NNE. A foliation in granitoid rocks 8 km to the east has a similar orientation with shear criteria (tails on feldspar phenocrysts) indicating north-side-up movement. This is interpreted as evidence of backthrusting during D_3. Folding with axial surfaces dipping moderately NNE also occurs in the Hooper Hills (Figs. 2 and 3).

In the Yampi area, rocks of the Kimberley Basin succession have been affected by two phases of folding and thrusting. Folding extends to the NNE as far as Koolan Island, and the structures form part of what will be referred to here as the *Yampi Fold Belt* (Fig. 3). It is felt that fold and fault structures in the Oscar Range (Fig. 2), where deformed conglomerate has a NNW-trending schistosity and dips steeply south, also belong to this fold belt. Shear criteria (tails on pebbles in the conglomerate) indicate south-block-up movement.

D_3 deformation in the Yampi Fold Belt can be divided into two fold phases, D_{3a} and D_{3b}. The first fold phase (D_{3a}) produced large-scale, near isoclinal folds (Fig. 5a) with gently-inclined to recumbent axial surfaces that dip SSW. An axial plane cleavage (S_{3a}) is developed. In Cascade Bay (Fig. 3) a thrust contact is exposed between granitoid rocks and King Leopold Sandstone with the sandstone transported to the north. Granitoid rocks below the contact display well developed *S–C* fabrics (cf. Berthé *et al.* 1979) with shear criteria showing a consistent S to N sense of movement. Small- and medium-scale layer-parallel isoclinal folds are developed in the metasedimentary rocks above the thrust.

The second fold phase (D_{3b}) consists of large-scale, N-facing folds with moderately to steeply SSW-dipping axial surfaces (Fig. 5b). An axial-planar cleavage (S_{3b}) locally crenulates S_{3a}. Few small-scale fold structures are seen because of the massive nature of the quartzites that form the majority of the Kimberley Basin succession. D_{3b} structures die out immediately north of Koolan Island.

D_{3a} structures have only been recognized to the south of Cone Bay (Fig. 2) where they are refolded by D_{3b}. The Cone Bay Inlier (Fig. 3) comprises granitoid rocks and metasedimentary rocks of the Hooper Terrane exposed in the core of an asymmetrical, D_{3b} fold whose northern limb is overturned. A distinctive quartz-phyric microgranite is exposed within the inlier. The occurrence of granite pebbles in arkoses immediately overlying this granite that have a similar composition and texture suggests that, although the contact between the inlier and the Kimberley Basin succession is sheared, movement may have only been local, possibly reflecting flexural-slip on an unconformity during folding.

D_4

The fourth deformation period (D_4) involved SW-directed thrusting and large-scale folding (Griffin & Myers 1988 a,b, Griffin 1989) that affected rocks of both the Kimberley Basin succession and the Late

Table 2. Summary of the tectonic evolution of the King Leopold Orogen

Age (Ma)	Deposition	Igneous event	Deformation	Metamorphism
			D_4 (Precipice Fold Belt)	
670	Mount House Group			
——unconformity—major period of erosion——				
1760–670			D_3 (Yampi Fold Belt)	M_2
1760		Hart Dolerite		
	Kimberley Basin			
——?unconformity?—major period of erosion——				
		granitoids		
1850–1840			D_2—sinistral strike-slip	
		felsic volcanics		
——unconformity—period of erosion——				
		Kongorow Granite dolerite sills	D_1—listric faulting	M_1—migmatites
1880	'Halls Creek Group'			

Proterozoic glacigene sequence. In the Precipice Range area (Fig. 2) the basal unconformity of the glacigene rocks is folded. An axial plane cleavage is present in the underlying Kimberley Group rocks that can be traced through the unconformity into the overlying Mount House Group. There is no evidence of the D_3 deformation affecting rocks in this area, other than open warping of the Kimberley Basin succession prior to deposition of the Mount House Group. Folds and thrusts form what is here named as the *Precipice Fold Belt* (Figs. 2 and 3), which can be traced WNW as far as Mount Hart.

Folds and thrusts trend WNW and fold axial surfaces dip gently to steeply NNE. Axial surfaces may also dip steeply SSW, and fold axes tend to be sub-horizontal. Many folds display sharp hinges, but immediately above thrusts folds are more ductile (displaying rounded hinges), and are recumbent. An axial plane cleavage (S_4) is developed. Griffin & Myers (1988a,b) and Griffin (1989) described the contact between the Hooper Terrane and the Kimberley Basin at the Lennard River Gorge, Inglis Gap and Dimond Gorge as a thrust, which they named as the Inglis Fault. Previously this contact had been thought to be an unconformity (e.g. Derrick & Playford 1973). The contact has now been inspected at various localities between Cascade Bay in the northwest to Dimond Gorge on the Fitzroy River in the southeast (Fig. 2). Nowhere is an unconformable relationship preserved, and the contact is always sheared, either as a result of D_3 deformation as at Cascade Bay and Cone Bay, or as the result of movements during D_4 as seen between Secure Bay and Dimond Gorge. D_3 structures in the Hooper Terrane may be deflected by the D_4 movements on the contact (Fig. 5c).

Minor shear zones are developed on bedding surfaces in the overlying sedimentary rocks of the Kimberley Basin. The S_4 cleavage is deflected by the shear zones to give a consistent NNE to SSW sense of movement.

TECTONIC IMPLICATIONS

The tectonic evolution of the King Leopold Orogen involved a series of igneous, structural and metamorphic events which took place intermittently from the Early Proterozoic to the Late Proterozoic–Early Palaeozoic. These events are summarized in Table 2.

The D_1 deformation is characterized by small-scale layer-parallel structures confined to zones of high strain. Large-scale fold structures are not seen. No evidence of structural inversion of the metasedimentary rocks has been found in the study area (see also Hancock & Rutland 1984) and the deformation is consistent with listric faulting and shearing at a relatively high structural level (e.g. Hatcher & Williams 1986). This may have occurred either as part of a thrust system (Boyer & Elliott 1982) or an extensional fault system (Gibbs 1984). The Woodward Dolerite in the Halls Creek Orogen has MORB chemistry (Sun *et al.* 1986). If the dolerite sills in the King Leopold Orogen are equivalent then this, together with an early metamorphic event (M_1) that locally reached high-grade, suggests that D_1 developed in an extensional environment (cf. Wickham & Oxburgh 1985, 1987) about 1880 Ma ago. The turbiditic sediments could have been deposited within this extensional environment.

The D_2 deformation took place between 1850 and 1840 Ma, post-dating the extrusion of the felsic volcanics but pre-dating the intrusion of the granitoids. It has generally produced upright folding with moderately to steeply plunging axes. This deformation appears to correspond to two events ("D_3" and "D_4") described by Hancock & Rutland (1984) from their "Lennard River Inlier". These authors separated E-trending folds ("D_3" of Hancock & Rutland 1984, fig. 6 inset) from NW-trending folds ("D_4" of Hancock & Rutland 1984) north of Black Hills Yard. From our observations noted above only one axial-planar cleavage (S_2) is present in the area. The two orientations of folds are separated by a D_3 shear zone and the easterly orientation of the folds near Mount Broome is interpreted as the result of reorientation of D_2 folds during D_3. An "S_4" fabric identified in the McSherrys Granodiorite by Hancock & Rutland (1984) is here attributed to D_3.

The lack of an E-trending fold phase in the central part of the King Leopold Orogen during D_2 is a serious flaw in the model of Early Proterozoic orogeny in the

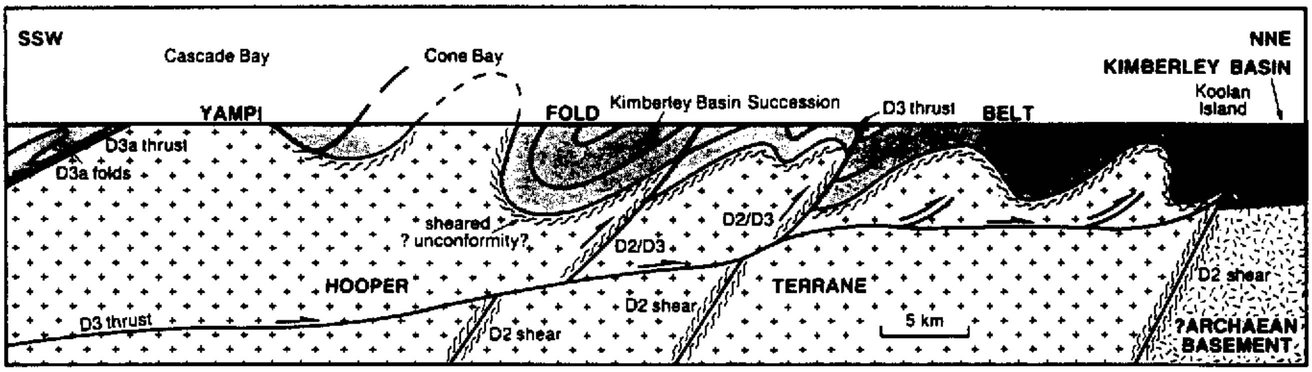

Fig. 6. Diagrammatic cross-section illustrating the structure of the Yampi Fold Belt.

Kimberley region presented by Hancock & Rutland (1984). They considered that the Early Proterozoic histories of the King Leopold and Halls Creek Orogens reflected movement on a conjugate shear zone system marginal to an 'island continent' (the Kimberley Craton). The E-trending "D_3" folds of Hancock & Rutland (1984) were interpreted by them as the result of dextral movements on faults such as the Sandy Creek Shear. The dextral movements were complemented by conjugate sinistral movements on NNE-trending faults in the Halls Creek Orogen to the east. Both movements were interpreted as the result of an overall southerly movement of the Kimberley Craton during the Early Proterozoic.

It is suggested here that structures such as the Sandy Creek Shear were present during D_2 as steep strike-slip faults that controlled folding. The overall trend of D_2 (i.e. northwesterly) is actually consistent with sinistral movements. Movement on this fault system took place after eruption of the felsic volcanics. Intrusion of granitoid rocks took place after D_2. Elongation of the batholiths parallel to the strike of the orogen, suggests that their emplacement was controlled by the major shear zones that had controlled the D_2 deformation.

The tectonic setting of the Early Proterozoic events is not clear from the data available, but may reflect oblique convergence or collision between the Kimberley Craton and cratonic crust that now underlies the Canning Basin. Arguments for intracratonic orogeny in the adjacent Halls Creek Orogen citing the continuity of the Biscay and Olympio Formations (Hancock & Rutland 1984), depend on the timing of collision and the location of any suture. Recently published geochemical data from the Halls Creek Orogen (Ogasawara 1988) suggests that subduction of oceanic crust may have occurred. Further work on the Early Proterozoic geochemical and metamorphic evolution of the King Leopold Orogen is currently in progress.

Intrusion of granitoid rocks was followed by a period of uplift and erosion. This effectively signalled the cratonization of the Hooper Terrane and its incorporation as an integral part of the Kimberley Craton. The Hooper Terrane was buried, along with the Kimberley "island continent" of Hancock & Rutland (1984), by the stable shelf deposits of the Kimberley Basin succession.

The Hart Dolerite (*ca* 1760 Ma, cf. Page 1976) is one of the most extensive dolerite bodies in the world (Griffin & Grey 1990) and has been derived either from enriched mantle or from interaction of depleted mantle with Archaean crust and/or lithosphere (Sun *et al.* 1986). The tectonic event necessary to generate such large volumes of basic magma is not recognized in the presently exposed Proterozoic rocks of the Kimberley region. However, it may have involved continental breakup at the margins of the North Australian Shield or passage of the Kimberley region over a mantle plume.

The D_3 deformation post-dates the intrusion of the Hart Dolerite. Deformation within the Kimberley Basin that does not form part of the King Leopold Orogen takes the form of broad-scale open warping (Plumb & Gemuts 1976). This occurred before deposition of the Late Proterozoic glacigene rocks (*ca* 670 Ma, Coats & Preiss 1980), and probably is the result of the overall compression that produced the D_3 deformation in the orogen. Deformation is Middle to Late Proterozoic in age.

A striking feature of the Yampi Fold Belt is the abrupt curtailment of folding northeast of Koolan Island. This may be attributed to the re-activation of the pre-existing steep D_2 shears in the Hooper Terrane, with these structures controlling ramping of the D_3 thrusts (cf. Wiltschko & Eastman 1983). The relationship between pre-existing structures in the Hooper Terrane and D_3 structures in both the Hopper Terrance and the Yampi Fold Belt is summarized in Fig. 6.

Speculation as to the tectonic event that caused the D_3 deformation must take account of the NE vergence of the structures. This suggests that collision may have occurred to the southwest at the margin of the Northern Australian Shield, possibly related to deformation and metamorphism in the Rudall Complex of the Paterson Orogen at *ca* 1.3 Ga (cf. Chin & de Laeter 1981). The remoteness of D_3 from the collision is attested to by the intracratonic setting and the absence of any related igneous activity. D_3 re-activated the Early Proterozoic zone of crustal weakness. The accompanying M_2 metamorphism is characterized by the growth of andalusite (Gellatly *et al.* 1974, Griffin *et al.* in press). This suggests that perturbation of the geotherm, rather than substantial tectonic thickening, was the cause of metamorphism, a situation characteristic of intracratonic Middle Proterozoic orogenies in central Australia (e.g. Clarke *et al.* 1987).

The D_4 deformation post-dates the Late Proterozoic glacigene rocks. Thrusts and folds verge SW and movement is interpreted in terms of the extensive Late Proterozoic to Early Palaeozoic sinistral strike-slip faulting in the Halls Creek Orogen (e.g. Dow & Gemuts 1969). The amount of southwestward movement decreases along strike to the WNW, so that the Kimberley Basin rocks are largely undeformed south of Walcott Inlet, where the D_4 deformation is apparently limited to shearing along the contact with the underlying Hooper Terrane (e.g. Fig. 5c).

The Inglis Fault places younger rocks on older rocks, a relationship typical of normal faulting as pointed out by Stewart (1988). However, the Inglis Fault is the sole thrust to the D_4 deformation with movement concentrated on a pre-existing unconformity, preserving the original stratigraphic relationship. Thrust structures above the Inglis Fault do place older rocks on younger rocks (Griffin *et al.* in press). The Inglis Fault varies from a steep to a relatively flat-lying structure. Where the contact is steep, granitoid rocks in the underlying Hooper Terrane contain steeply-dipping D_3 shear zones and an associated foliation. Where the contact is flat-lying Hooper Terrane rocks show little if any shearing. The pre-existing D_3 structures have caused the Inglis Fault to ramp (cf. Wiltschko & Eastman 1983). High level structures in the Precipice Fold Belt that face NNE are interpreted as the product of large-scale back thrusting above the ramp (Fig. 7). Ramping has caused out of sequence thrusting (cf. Coward 1980, Butler 1985) with thrusts cutting already deformed rocks. This can also result in younger rocks (which are tightly folded, and locally overturned; see Derrick & Playford 1973, Griffin *et al.* in press) being placed on older rocks. The high-level nature of this deformation is indicated by the lack of any significant metamorphism that can be attributed to tectonic thickening. Vertical movements on shear zones in the Hooper Terrane that can be related to D_4 have not been recognized.

Griffin & Myers (1988a,b) suggested that the Inglis Fault represented a Proterozoic terrane boundary (cf. Jones *et al.* 1986) separating rocks of the Hooper Terrane from rocks deposited in the Kimberley Basin (referred to as the Gibb River Terrane by Griffin 1989). The contact between these units is everywhere tectonized, however, their original relationship was unconformable and they represent, therfore, proximal terranes (Gray 1986).

Shears that control ramping of the Inglis Fault also appear to have controlled the northeast limit of the Yampi Fold Belt. These shears are interpreted to represent a fundamental structure that has controlled deformation throughout the Proterozoic and may well form an Early Proterozoic terrane boundary between the Hooper Terrane and (?)Archaean basement interpreted to underlie the Kimberley Basin (cf. Hancock & Rutland 1984, Sun *et al.* 1986).

CONCLUSIONS

The King Leopold Orogen has been affected by four deformation events (D_1–D_4) and two metamorphic events (M_1 and M_2) that have taken place intermittently from the Early Proterozoic to the Early Palaeozoic.

The earliest events (D_1, D_2, M_1) recognized in the Hooper Terrane, together with the generation, intrusion and extrusion of basic and acid magmas, occurred in the Early Proterozoic (*ca* 1880–1840 Ma) and represent an initial extensional environment followed by (?) sinistral strike-slip deformation. The (?)sinistral strike-slip event probably reflects oblique convergence or collision between the Kimberley Craton and cratonic crust now underlying the Canning Basin. It is not clear whether these events occurred as part of an intracratonic orogeny or as part of a plate tectonic Wilson Cycle.

Following uplift and erosion, the now cratonized

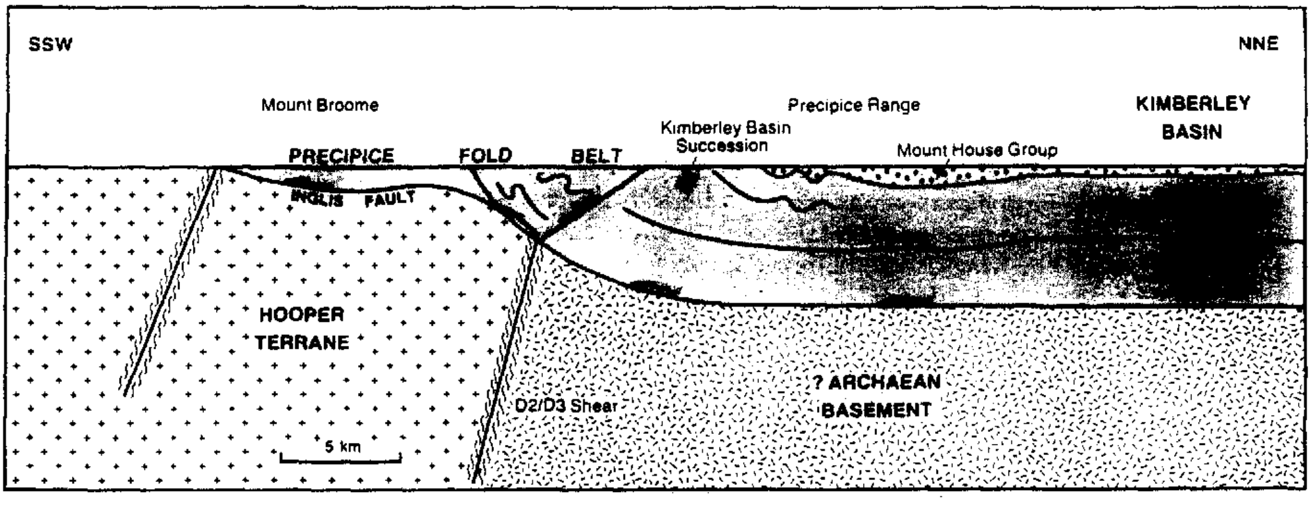

Fig. 7. Diagrammatic cross-section illustrating the structure of the Precipice Fold Belt.

Hooper Terrane acted as part of the basement to the Kimberley Basin. Intrusion of the Hart Dolerite into the Kimberley Basin succession marks the end of sedimentation and may represent a period of continental break-up at *ca* 1760 Ma.

The D_3 deformation, which formed the Yampi Fold Belt, occurred in the Middle to Late Proterozoic and appears to represent intracratonic compression that is possibly related to a collision located to the southwest of the orogen. M_2 metamorphism is syntectonic with D_3 and is the result of local perturbation of the geotherm. In the Hooper Terrane the D_3 deformation has reactivated steep shear zones that probably formed during D_2. As has been noted by several previous authors the tectonic grain established during the Early Proterozoic events has controlled or strongly influenced all subsequent tectonism (e.g. Plumb & Gemuts 1976, Plumb *et al.* 1981, 1985, Hancock & Rutland 1984).

The D_4 deformation occurred in the Late Proterozoic to Early Palaeozoic and results from the southwestward thrusting of the Kimberley Basin over the Hooper Terrane. This is consistent with the sinistral movements on faults in the Halls Creek Orogen. The resulting folds and thrusts form the Precipice Fold Belt.

Ramping of the D_4 thrust system has been controlled by a major pre-existing basement structure. This basement structure also controls the northeast limit of the Yampi Fold Belt and may represent the boundary between the Early Proterozoic Hooper Terrane and (?)Archaean basement underlying the Kimberley Basin. As such it may represent the site of an Early Proterozoic (D_2) terrane boundary.

Acknowledgements—This paper is published with the permission of the Director of the Geological Survey of Western Australia. The Authors thank John Myers, Peter Dunn and Bob Halligan for numerous discussions on Kimberley geology. John Myers read an earlier version of the manuscript. Paul Hoffman and an anonymous referee are thanked for their reviews.

REFERENCES

Bell, T. H. 1985. Deformation partitioning and porphyroblast rotation in metamorphic rocks: a radical reinterpretation. *J. metamorph. Geol.* **3**, 109–118.

Bell, T. H., Fleming, P. D. & Rubenach, M. J. 1986. Porphyroblast nucleation, growth and dissolution in regional metamorphic rocks as a function of deformation partioning during foliation development. *J. metamorph. Geol.* **4**, 37–68.

Berthé, D., Choukroune, P. & Jegouzo, P. 1979. Orthogneiss, mylonite and non coaxial deformation of granites: the example of the South Amorican Shear Zone. *J. Struct. Geol.* **1**, 31–42.

Boyer, S. E. & Elliott, D. 1982. Thrust systems. *Mem. Am. Ass. Petrol. Geol.* **66**, 1196–1230.

Butler, R. H. W. 1985. Thrust tectonics: a personal view. *Geol. Mag.* **122**, 223–232.

Chin, R. J. & de Laeter, J. R. 1981. The relationship of new Rb–Sr isotopic data from the Rudall Metamorphic Complex to the geology of the Paterson Province. *West. Aust. geol. Surv. Ann. Rep.* 1980, 80–87.

Clarke, G. L., Guiraud, R., Powell, R. & Burg, J. P. 1987. Metamorphism in the Olary Block, South Australia: compression with cooling in a Proterozoic fold belt. *J. metamorph. Geol.* **5**, 291–306.

Coats, R. P. & Preiss, W. P. 1980. Stratigraphic and geochronological reinterpretation of late Proterozoic glaciogenic sequences in the Kimberley region, Western Australia. *Precambrian Res.* **13**, 181–208.

Coward, M. P. 1980. The Caledonian thrust and shear zones of N.W. Scotland. *J. Struct. Geol.* **2**, 11–17.

Derrick, G. M. & Playford, P. E. 1973. Lennard River, Western Australia—1:250000 Geology Series. *West. Aust. geol. Surv. Explan. Notes* SE 58–8.

Dow, D. B. & Gemuts, I. 1969. Geology of the Kimberley Region, Western Australia: the East Kimberley. *Bull. West. Aust. geol. Surv.* **120**.

Gellatly, D. C., Derrick, G. M. & Plumb, K. A. 1975. The geology of the Lansdowne 1:250 000 sheet area, Western Australia. *Aust. Bur. Miner. Resour. Geol. Geophys. Rep.* **152**.

Gellatly, D. C., Sofoulis, J., Derrick, G. M. & Morgan, C. M. 1974. The older Precambrian geology of the Lennard River 1:250000 sheet area, Western Australia. *Aust. Bur. Miner. Resour. Geol. Geophys. Rep.* **153**.

Gemuts, I. 1971. Metamorphic and igneous rocks of the Lamboo Complex, East Kimberley Region, Western Australia. *Bull. Aust. Bur. Miner. Resour. Geol. Geophys.* **107**.

Gibbs, A. D. 1984. Structural evolution of extensional basin margins. *J. geol. Soc. Lond.* **141**, 609–620.

Gray, G. G. 1986. Native terranes in the Central Klamath Mountains, California. *Tectonics* **5**, 1043–1054.

Griffin, T. J. 1989. A major thrust between the Gibb River and Hooper Terranes in the King Leopold Orogen, West Kimberley region. *Prof. Pap. West. Aust. geol. Surv. Rep.* **26**, 69–81.

Griffin, T. J. & Grey, K. 1990. Kimberley Basin. In: *Geology and Mineral Resources of Western Australia. Mem. West. Aust. geol. Surv.* **3**, 293–304.

Griffin, T. J. & Myers, J. S. 1988a. Geological Note: a Proterozoic terrane boundary in the King Leopold Orogen, Western Australia. *Aust. J. Earth Sci.* **35**, 131–132.

Griffin, T. J. & Myers, J. S. 1988b. Reply to discussion: a Proterozoic terrane boundary in the King Leopold Orogen, Western Australia. *Aust. J. Earth Sci.* **35**, 591–593.

Griffin, T. J., Tyler, I. M. & Playford, P. E. In press. Explanatory notes on the Lennard River 1:250,000 geological sheet (3rd edn). *West. Aust. geol. Surv. Rec.*

Hancock, S. L. & Rutland, R. W. R. 1984. Tectonics of an early Proterozoic geosuture: the Halls Creek Orogenic Sub-province, northern Australia. *J. Geodynam.* **1**, 387–432.

Hatcher, R. D., Jr. & Williams, R. T. 1986. Mechanical model for single thrust sheets. Part I: taxonomy of crystalline thrust sheets and their relationships to the mechanical behaviour of orogenic belts. *Bull. geol. Soc. Am.* **97**, 975–985.

Hossack, J. R. 1983. A cross-section through the Scandinavian Caledonides constructed with the aid of branch line maps. *J. Struct. Geol.* **5**, 103–111.

Jones, D. L., Silberling, N. J. & Coney, P. J. 1986. Collision tectonics in the Cordillera of western N. America: examples from Alaska. In: *Collision Tectonics* (edited by Coward, M. P. & Ries, A. C.). *Spec. Publs. geol. Soc. Lond.* **19**, 367–387.

Ogasawara, M. 1988. Geochemistry of the early Proterozoic granitoids in the Halls Creek Orogenic Subprovince, northern Australia. *Precambrian Res.* **40/41**, 469–486.

Page, R. W. 1976. Reinterpretation of isotopic ages from the Halls Creek Mobile Zone, northwestern Australia. *Bur. Miner. Resour. J. Aust. Geol. Geophys.* **1**, 79–81.

Page, R. W. 1988. Geochronology of early to middle Proterozoic fold belts in northern Australia: a review. *Precambrian Res.* **40/41**, 1–19.

Page, R. W. & Hancock, S. L. 1988. Geochronology of a rapid 1.85–1.86 Ga tectonic transition: Halls Creek Orogen, northern Australia. *Precambrian Res.* **40/41**, 447–467.

Page, R. W., McCulloch, M. T. & Black, L. P. 1984. Isotopic record of major Precambrian events in Australia. *Proc. 27th Geol. Cong. Moscow*, **5**. VNU Science Press, Amsterdam, 25–72.

Plumb, K. A., Allen, R. & Hancock, S. L. 1985. Proterozoic evolution of the Halls Creek Province, Western Australia. *Aust. Bur. Miner. Resour. Geol. Geophys. Rec.* **1985/25**,

Plumb, K. A., Derrick, G. M., Needham, R. S. & Shaw, R. D. 1981. The Proterozoic of northern Australia. In: *Precambrian of the Southern Hemisphere* (edited by Hunter, D. R.). *Devel. Precambrian Geol.* **2**. Elsevier, Amsterdam, 205–307.

Plumb, K. A. & Gemuts, I. 1976. Precambrian geology of the Kimberley region, Western Australia. *25th Int. Geol. Congr. Excursion Guide* **44C**.

Simpson, C. & Schmid, S. M. 1983. An evaluation of criteria to deduce the sense of movement in sheared rocks. *Bull. geol. Soc. Am.* **94**, 1281–1288.

Sofoulis, J., Gellatly, D. C., Derrick, G. M., Fairbridge, R. A. & Morgan, C. M. 1971. The geology of the Yampi 1:250,000 sheet area SE/51-3 Western Australia. *Aust. Bur. Miner. Resour. Geol. Geophys. Rec.* **1971/1**.

Stewart, A. J. 1988. Discussion: A Proterozoic terrane boundary in the King Leopold Orogen, Western Australia. *Aust. J. Earth Sci.* **35**, 598–591.

Sun, S. S., Jaques, A. L. & McCulloch, M. T. 1986. Isotopic evolution of the Kimberley Block, Western Australia. *4th Int. Kimberlite Conf., Geol. Soc. Aust.* (Abs.) **16**, 346–348.

Tyler, I. M., Griffin, T. J. & Playford, P. E. In press. Explanatory notes on the Yampi 1:250,000 geological sheet (2nd edn). *West. Aust. geol. Surv. Rec.*

Wickham, S. M. & Oxburgh, E. R. 1985. Continental rifts as a setting for regional metamorphism. *Nature* **318**, 330–333.

Wickham, S. M. & Oxburgh, E. R. 1987. Low-pressure regional metamorphism in the Pyrenees and its implications for the thermal evolution of rifted continental crust. *Phil. Trans. R. Soc. Lond.* **A321**, 219–242.

Wiltschko, D. V. & Eastman, D. B. 1983. Role of basement warps and faults in localizing thrust fault ramps. *Mem. geol. Soc. Am.* **158**, 177–190.