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Front cover: Evan Richard Stanley was the first Government Geologist for Papua, and produced the first comprehensive geological accounts of the New Guinea and Papua territories. He died tragically young in 1924. A bibliographical paper by H.L. Davies appears in this issue. Cover design by Mary Silver.

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Regional structure and evolution of the Redbank-Mount Zeil thrust zone: a major lineament in the Arunta Inlier, central Australia

A. Y. Glikson[1]

The western part of the Arunta Inlier, central Australia, consists of major northward-tilted blocks separated by major thrust faults—the Anmatjira, Napperby, Redbank-Mount Zeil and Mount Sonder-Mount Razorback faults—associated with major Bouguer gravity anomalies. The Redbank-Mount Zeil thrust zone (RTZ) separates a granulite-facies suite to the north from a paragneiss-migmatite-orthogneiss suite to the south. This fault is marked by major radiometric, magnetic, and morphological discontinuities, and consists of northward-dipping protomylonite, mylonite, ultramylonite, and phyllonite, formed under a heterogeneous ductile shear regime. Kernels of granulite, paragneiss, and migmatite abound. The RTZ truncates all other structures and postdates all juxtaposed units. Dynamothermal activity along the RTZ about 1000-900 Ma ago may be reflected by possibly reset Rb-Sr ages in blastoporphyritic gneisses and migmatite to the north and south, respectively. Major Palaeozoic movements are indicated by Devonian fanglomerate (Brewer Conglomerate), while younger reactivation is suggested by morphological features. Two alternative models are considered: (1) an antecedent of the RTZ formed an early boundary between an older igneous-dominated granulite block to the north and a younger amphibolite-facies paragneiss belt to the south prior to about 1600 Ma ago; or (2) contemporaneous granulite and paragneiss terrains representing different depth zones within a vertically zoned crust were allochthonously juxtaposed by the thrusting. The uplift of basic granulites along the RTZ is estimated from thermobarometric measurements to be at least 20 km, accounting for the Papunya Bouguer anomaly high of more than 500 $\mu m/s^2$. The emplacement of deep-seated basic intrusions, the ensuing geothermal rises, and crustal anatexis may have been genetically and temporally related.

Introduction

The Proterozoic Arunta Inlier and the associated late Proterozoic-Palaeozoic Amadeus and Ngalia sedimentary basins in central Australia are bordered and transected by major latitudinal thrust faults, including, from north to south, (a) the Napperby thrust fault (Wells & Moss, 1983; Stewart & others, 1980); (b) the Redbank-Mount Zeil thrust zone (RTZ) and Harry Creek deformed zone (Marjoribanks, 1975; Offe, 1983; Shaw & others, 1984); (c) the Mount Sonder-Mount Razorback thrust fault, Blatherskite nappe and Arltunga nappe complex along the northern margin of the Amadeus Basin (Forman, 1966; Stewart, 1967; Shaw & others, 1984); and (d) the Woodroffe thrust fault (Major, 1973) (Figs 1, 2, 3). The age relations of major movements along faults (a), (c), and (d) are indicated by deformation of late Proterozoic-Palaeozoic sedimentary units. On the other hand, as the RTZ is confined to the Arunta basement terrane, its age relations with the younger basins cannot be directly observed. The age of a possible equivalent of the RTZ in the eastern Arunta Inlier—the Harry Creek deformed zone—has been discussed by Allen & Black (1979).

This paper considers the relations between the RTZ and juxtaposed units with the aim of elucidating the regional setting and the evolution of the RTZ. The significance of marked radiometric, aeromagnetic, and Bouguer gravity anomalies associated with the RTZ is considered in relation to crustal structure, bearing in mind the models of Forman & Shaw (1973), Anfiloff & Shaw (1973), Mathur (1976), and Lambeck (1984). Petrofabric and tectonic analysis of sections of RTZ is currently underway (R.D. Shaw, personal communication, 1985) and the resolution of some of the questions formulated in this paper must await detailed isotopic studies.

The Redbank-Mount Zeil thrust zone

Regional outline

In the southwestern part of the Arunta Inlier (Fig. 1) the Mount Hay, Mount Chapple, Redbank Hill, and Mount Zeil granulite-gneiss massifs (northern block) are separated from a paragneiss-migmatite-orthogneiss terrane (southern block) by a major lineament, termed here the Redbank-Mount Zeil thrust zone (RTZ) (Figs 2, 3). The RTZ consists of interleaved units of protomylonite*, mylonite, ultramylonite, and phyllonite, containing relic kernels of intact to retrogressed gneiss. Foliation dips at shallow (about 30°) to steeper angles northward, while lineation plunges at high pitch (about 70°) northeastward. In the southernmost central part of Narwietooma 1:100 000 Sheet area and in Macdonnell Ranges 1:100 000 Sheet area the RTZ strikes west-northwest to west, constituting the northern margin of a well-exposed part of the southern block (Figs 2, 3). Complete sections of the RTZ are fully exposed west of longitude 132°43'E (south of Redbank Hill), where the RTZ lies between northward-dipping, ridge-forming, granulites of the Mount Zeil massif to the north and deformed migmatite/gneiss to the south (Fig. 4a, b). The boundaries of the RTZ in this sector are gradational, and mylonitisation is identified both within the main thrust zone and along subsidiary faults that transect adjacent terranes. Thus, the migmatite/gneiss terrane between the RTZ and the Mount Sonder-Mount Razorback thrust fault to the south is pervasively deformed, as manifested by numerous east-west faults and mylonite zones. West of Redbank Hill towards Mount Zeil the RTZ progressively narrows from about 2 km to a few hundred metres. The southern escarpment of Mount Zeil and lower escarpments to the east consist of resistant northward-dipping granulite slices interspersed by soft deformed zones (Fig. 4b).

The RTZ bifurcates east (at about 132°27'E) and west (at about 132°10'E) of Mount Zeil. The northwestern branch reappears at Mount Heughlin, where a narrow zone of mylonite crops out high on the southern escarpment (Fig. 5a). The southwestern branch of the RTZ can be intermittently traced to the north of Glen Helen homestead, where it is marked by phyllonite, then further west towards Derwent Creek. In this and other discontinuously exposed terranes, the RTZ is identified by the change from granulite-facies gneiss in the north to amphibolite facies paragneiss and migmatite in the south. On this criterion, it appears that west of Mount Zeil the principal thrust fault is represented by the southern fault branch, since granulite occurs between the two fault branches in this area (Fig. 2). The delineation of the RTZ is greatly assisted by the radiometric map, where sharp contrast exists between K-U-Th-poor granulites and K-U-Th-rich granite/migmatite terrane (Fig. 9). However, on this radiometric criterion, the northern fault branch of the RTZ appears as the principal fault, since pronounced radiometric highs occur between the two fault branches as well as south

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* as defined here, protomylonites—10-50% matrix; mylonites—50-90% matrix; ultramylonites—90-100% matrix

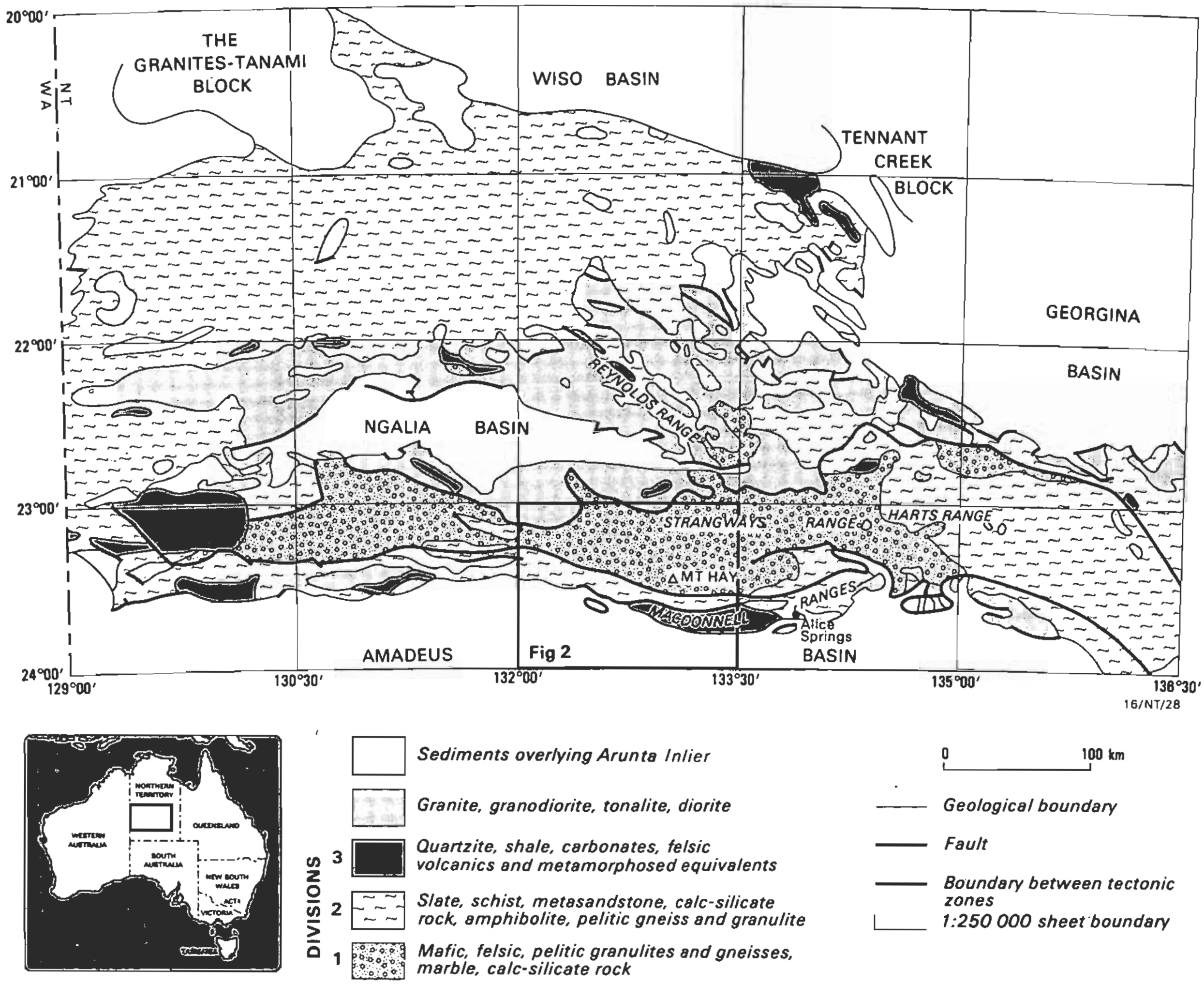


Figure 1. Geological sketch map of the Arunta Inlier, central Australia.

of the southern branch. This conflict is likely to be related to the occurrence within the granulite terrane of isolated radiometric highs (Fig. 9). The two faults branches merge at about longitude 130°03′E, where granulite, including a fault-bounded sliver of quartzite (Fig. 5d), is juxtaposed with paragneiss west of Derwent Creek.

The identification of the RTZ is complicated in places by variations in the style of deformation along the fault. In the east, the zone is represented mainly by protomylonitic to mylonitic and, less commonly, phyllonitic units. In the Mount Zeil area, where the thrust zone is narrowest (Fig. 4), ultramylonite predominates. West of Mount Zeil and in the Dashwood Creek area phyllonites abound. The RTZ is difficult to trace west of Dashwood Creek, owing to discontinuity of outcrop, although sporadic occurrences of phyllonite and mylonite in this area indicate its proximity. Well-exposed sections across the RTZ occur (1) between longitudes 132°32′E and 132°40′E (southwest of Redbank Hill); (2) along the southern escarpment of the Mount Zeil ridge (132°19′E–132°25′E); and (3) near Dashwood Creek, between Glen Helen homestead and Mount Heughlin.

Rock types

Sections across the RTZ expose a complete transition from undeformed country rock to ultramylonite. Southwest of Redbank Hill, granulite exposed about 1.5 km north of the RTZ discloses little or no superposed deformation. A few hundred metres from the deformed zone, quartz grains display incipient deformation lamellae, subgrain aggregates, and marginal recrystallisation (Fig. 7A). Progressive mylonitisation within the shear zone is represented by more extensive recrystallisation of quartz to microcrystalline aggregates interspersed with little-deformed grains of feldspar and kinked biotite. The most intensely deformed parts of the RTZ include interbanded ultramylonite, mylonite, and protomylonite, isoclinally folded along northeast-pitching axes parallel to the regional lineation of the country rocks (Fig. 6Ac). Advanced ductile deformation is marked by new biotite growth around recrystallised quartzofeldspathic lenses (Fig. 7Ab). Complete progression from protomylonite to biotite-quartz-albite phyllonite can be seen (Fig. 7Aa–d), analogous to the sequence described by Bell & Etheridge (1973). Advanced deformation is represented by epidote-rich phyllonite, epidote being younger than and replacing biotite (Fig. 7Ag). Accessory ilmenite is replaced by sphene. Ultramylonite includes strongly aligned sericite-quartz microcrystalline aggregates, including microporphyroblasts of epidote. Relict grains of feldspar display undulose extinction and embayed and recrystallised boundaries. Microcrystalline quartz in the mylonite often forms ribbon aggregates (Fig. 7Ac). The RTZ in this area includes sillimanite-garnet-biotite-quartz schist (Fig. 7Ah), containing accessory opaque oxide and tourmaline. The garnet and sillimanite are deformed, and, therefore, clearly predate the mylonitic deformation.

Relics of weakly deformed granulite occur within the RTZ. The largest is a well-preserved enclave of mafic granulite, about 800 × 600 m, forming a prominent dark hill (Figs. 4a, 5c). Samples from this body consist of fresh poikiloblasts of hypersthene with inclusions of amphibole and plagioclase, xenoblastic clinopyroxene containing similar inclusions, granoblastic labradorite, minor opaque oxide, and young biotite (Fig. 7Ae). Except for minor fracturing and crystal bending, these rocks display surprisingly little evidence of their incorporation in a major thrust zone. However, in places, strongly retrogressed mafic mylonite occurs in the vicinity of the basic granulite. These assemblages contain corroded amphibole grains replaced and enveloped by foliated microcrystalline biotite (Fig. 7Af). Other components of the rock are microcrystalline quartz mosaics, near-cryptocrystalline feldspar mosaics, epidote, and sphene. With advanced deformation, amphibole is completely replaced by biotite, resulting in biotite-epidote-quartz phyllonite (Fig. 7Ag).

West of the basic enclave is a thick belt of phyllonite and mylonite. The former consists of foliated muscovite, microglomeroblasts of epidote, mosaics of quartz, and accessory opaque oxide (Fig. 7Ad). The mylonite contains relic fragments of feldspar and garnet set in a flow-textured matrix of biotite and ribbon quartz (Fig. 7Aa, b, c). Epidote, muscovite, apatite, and opaque oxide are accessories. The incipient transformation of felsic gneiss into sericite schist is represented by development of oriented flakes of muscovite and granular epidote within aggregates of deformed K-feldspar, plagioclase, and microcrystalline quartz mosaics.

The southern part of the RTZ contains felsic augen gneiss derived from the migmatite/gneiss terrane of the southern block and its deformed equivalents. Augen gneiss may include composite coarse-grained glomeroblasts of plagioclase/microcline containing inclusions of quartz, accessory apatite, and iron oxide, thought to represent deformed and recrystallised porphyritic granite. Another common rock type is a banded biotite gneiss containing sphene-biotite-iron oxide clots. Moderate mylonitisation of this rock is represented by deformation of biotite and recrystallisation of quartz.

Where the RTZ crops out at the base of the Mount Zeil escarpment (Fig. 4), the fault separates felsic granulite and granulite facies gneiss to the north from banded biotite gneiss/migmatite to the south. The latter is intruded by three bodies of partly amphibolitised gabbro enveloped by K-feldspar-dominated felsic gneiss aureoles. In this area the thrust fault occurs as a narrow (about 300 m) zone of mylonite and ultramylonite. The thrust zone contains little-deformed amphibolite to granulite facies gneiss relics interspersed with mylonites. A section through the RTZ southeast of Mount Zeil (at about 132°25′E) encountered the following rock types (from south to north).

- —Chloritoid-bearing biotite-chlorite-muscovite phyllonite. Anhedral prismatic fine-grained chloritoid parallels or intersects the foliation defined by mica, and is clearly the youngest phase in the rock. Embayed quartz grains form microcrystalline aggregates.
- —Banded epidote-quartz mylonite. Recrystallised euhedral and ribbon quartz aggregates dominate, surrounding relics of corroded and clouded plagioclase and accessory biotite, chlorite, and iron oxide.
- —Muscovite-biotite-chlorite phyllonite, including relic corroded and clouded feldspars.
- —Ultramylonite, consisting of an assemblage of microcrystalline biotite, quartz, albite, and epidote, including relic grains of plagioclase and lenses of felsic gneiss.
- —Deformed orthopyroxene-amphibole-biotite-plagioclase (antiperthite)-quartz banded granulite. The rock shows undulose extinction and strain-recrystallisation of quartz, and clouding of feldspar.
- —Ribbon quartz mylonite, containing well-rounded fine feldspar grains and minor amphibole set in strongly undulating, laminated to ribbon aggregates of microcrystalline quartz alternating with cryptocrystalline flow matrix.
- —Orthopyroxene-amphibole-biotite-plagioclase intermediate granulite, with minor garnet, apatite, and iron oxide, biotite being the youngest phase.
- —Deformed garnet-orthopyroxene-clinopyroxene-amphibole-biotite-plagioclase-quartz granulite, displaying extensive strain recrystallisation of quartz, feldspar clouding, and alteration of pyroxene to biotite and chlorite.

A section through a northern branch of the RTZ east of Mount Zeil (about 23°23′S, 132°26′E) transects the following rock types (from south to north).

- —Porphyroblastic garnet gneiss, containing coarse-grained augen of K-feldspar and medium-grained anhedral garnet set in a fine-grained biotite-poor quartz-feldspar aggregate. Deformation is reflected by quartz recrystallisation and feldspar clouding.
- —Banded garnet-clinopyroxene-amphibole-biotite-quartz gneiss, with minor apatite, allanite, rutile, and iron oxide. Garnet replaces biotite and iron oxide. Little deformation is discernible.
- —Deformed banded felsic garnet-biotite gneiss, showing extensive recrystallisation and undulose extinction of quartz, feldspar clouding, and bending of grains.
- —Fine-grained biotite-clinopyroxene-amphibole-plagioclase mafic granulite, showing no superposed deformation. Biotite is the latest mineral, replacing amphibole.
- —Garnet-amphibole-biotite-plagioclase-quartz felsic gneiss. Minor cataclasis is represented by biotite-coated fractures.

These sections represent intimate interleaving across the RTZ of mylonite, phyllonite, and relic amphibolite to granulite facies gneiss. Relic granulite increases in abundance northward.

Attitude of the RTZ at depth

In any discussion of the nature of the RTZ, two classes of thrust faulting need consideration: (1) 'thin-skinned' thrust tectonics, where the dip becomes shallower with depth; and (2) 'thick-skinned' thrust tectonics, where the dip steepens with depth (Coward, 1983). Thin-skinned tectonics, typical of overthrust layered supracrustal units, commonly consist of listric fault systems linked to decollement detachment, such as along the Moine thrust (McClay & Coward, 1981), in the Canadian Rocky Mountains (Price, 1981), and in the Appalachians (Hatcher, 1981). Thick-skinned thrusts, on the other hand, occasionally reactivate earlier basement lineaments (Prucha & others, 1965). Examples of these occur in the southern Alps and Pyrenees (DeSitter, 1964) and in the Laramide uplift of the Rocky Mountains (Stearns, 1975).

Deep seismic reflection data indicate near-constant angles of about 30–35° to a depth of 25–30 km for some of the thrusts (Brewer & others, 1981). However, downward-steepening thrust faulting is suggested from the southern edge of the Himalayas (Coward, 1983). Inherent in the upward-shallowing geometry of thick-skinned thrusts is the development of a local tensional stress field within the wedge overlying the shallower dipping fault segment, producing ductile thinning or extension 'keystone faults' (Wise, 1963). Possibly, some of the fracturing observed in granulite of the southwest Arunta Block is of such an origin. The extra energy involved in the

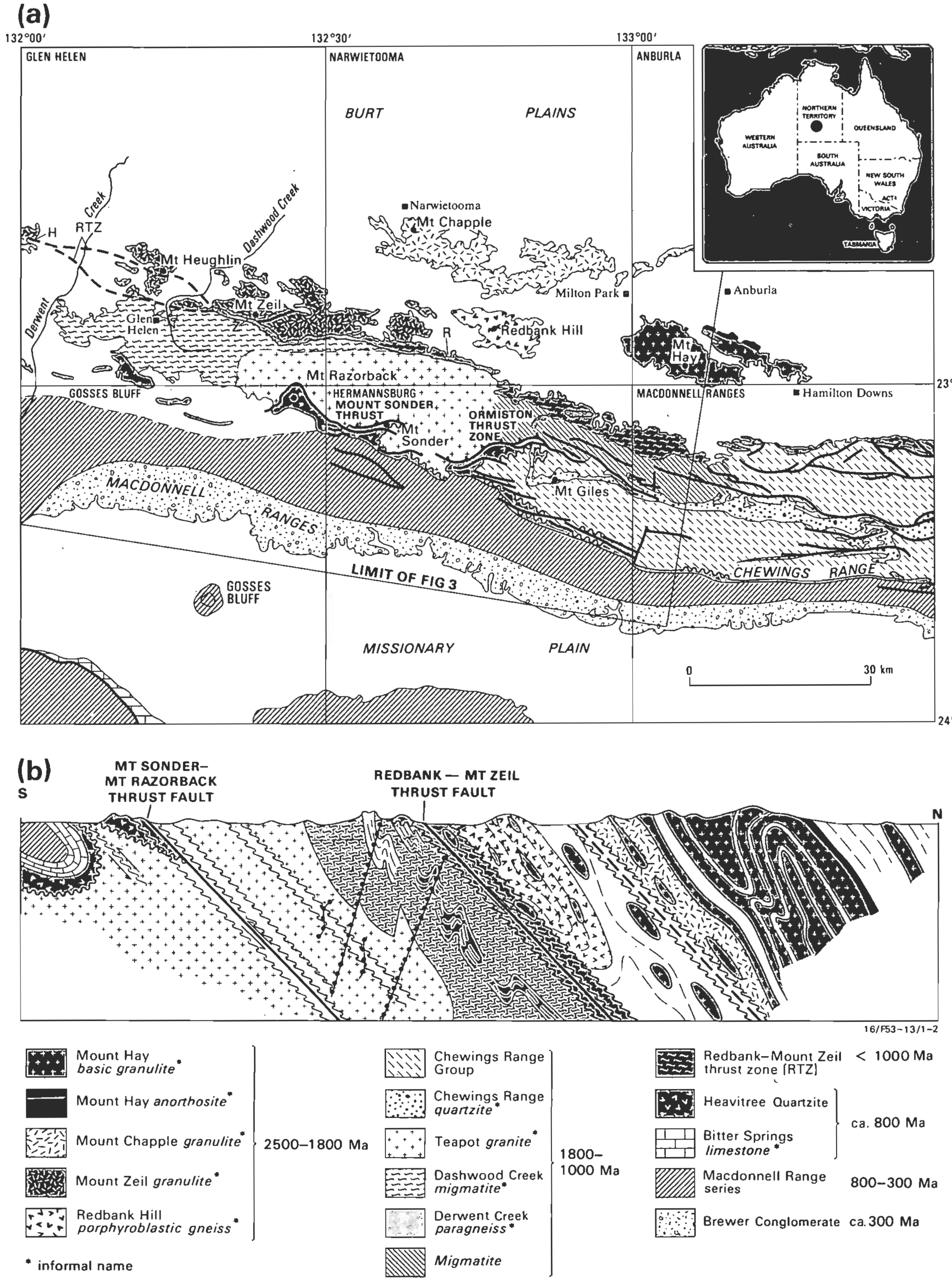


Figure 2. (a) Geological sketch map of the Hermannsburg 1:250 000 Sheet area.
The frame outlines the southern and eastern limits of Fig. 3. Letters indicate locations of Figs 4a,b and 5.
(b) A schematic north–south cross-section through the terrain shown in Fig. 2a, showing the principal geological units and their interpreted field relations.

Figure 3. LANDSAT imagery of part of the Hermannsburg 1:250 000 Sheet area.
For location and explanation of morphological and geological features refer to Fig. 2.

development of steep thrusts makes them less common than shallow-angle slides. The development of deep crustal thrusts may be accompanied by isostatic readjustment in the underlying mantle.

The above considerations are pertinent to the deep structure of the RTZ. Contrary to the Napperby thrust fault (Wells & Moss, 1983; Stewart & others, 1980) and to the Mount Sonder-Mount Razorback thrust fault (Forman, 1966; Marjoribanks, 1975) (Fig. 5b), which affect footwall sedimentary units, the RTZ is nowhere seen in contact with Amadeus Basin sequences. Consequently, no stratigraphic markers are available to allow correlation between the northern and the southern blocks. Further assessment of the nature of the RTZ with depth awaits the completion of current seismic reflection studies. Some idea on the amount of uplift of the northern granulite terrane is furnished by thermobarometric estimates (Glikson, in press). The occurrence of garnet-orthopyroxene-clinopyroxene-biotite-amphibole-plagioclase-quartz assemblages in the Mount Chapple massif allows an estimate of P from the pressure-dependant reactions:

anorthite + enstatite = 1/3 grossular + 2/3 pyrope + quartz . . . (1)

anorthite + diopside = 2/3 grossular + 1/3 pyrope + quartz . . . (2)

anorthite + 2 enstatite = pyrope + diopside + quartz . . . (3)

Reactions (1) and (2) have been calibrated by Perkins & Newton (1981) from measured thermodynamic data, and reaction (3) was calibrated by Hensen (1981). For an estimate of T, Ellis & Green's (1979) calibration was used for the reaction:

1/3 pyrope + 2/3 hedenbergite = 1/3 almandine + 2/3 diopside . . . (4)

Calculation of electron probe data in terms of these equilibria has yielded the following results for basic granulite of Mount Chapple:

S188—P = 8.1 kb; T = 770°C
S194—P = 7.3 kb; T = 680°C

considered to represent minimum blocking pressure and temperature values. This suggests that granulite was uplifted along the RTZ from crustal depths of at least 20 km.

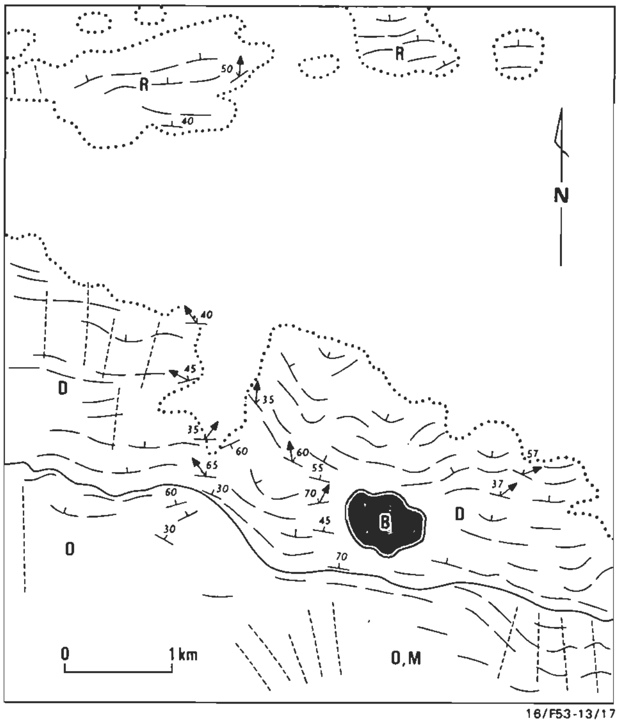
Regional units juxtaposed with RTZ

Elucidation of the origin of the RTZ requires consideration of regional rock units juxtaposed with the hanging wall (northern block) and the footwall (southern block). In particular, the relations between these units are relevant to the question of the age of the RTZ.

Northern block

The Mount Hay ridge (Figs 2, 3) consists of (1) mafic granulites containing bands and stringers of felsic to intermediate gneiss; (2) anorthosite-cumulate pyroxenite units; and (3) minor supracrustal paragneiss (Glikson, 1984). The dominant structural grain outlined by compositional banding and by weak gneissosity strikes west-northwest; northerly deflections occur at the western and eastern ends of the ridge. Banding and foliation generally dip northward.

(a)



(b)

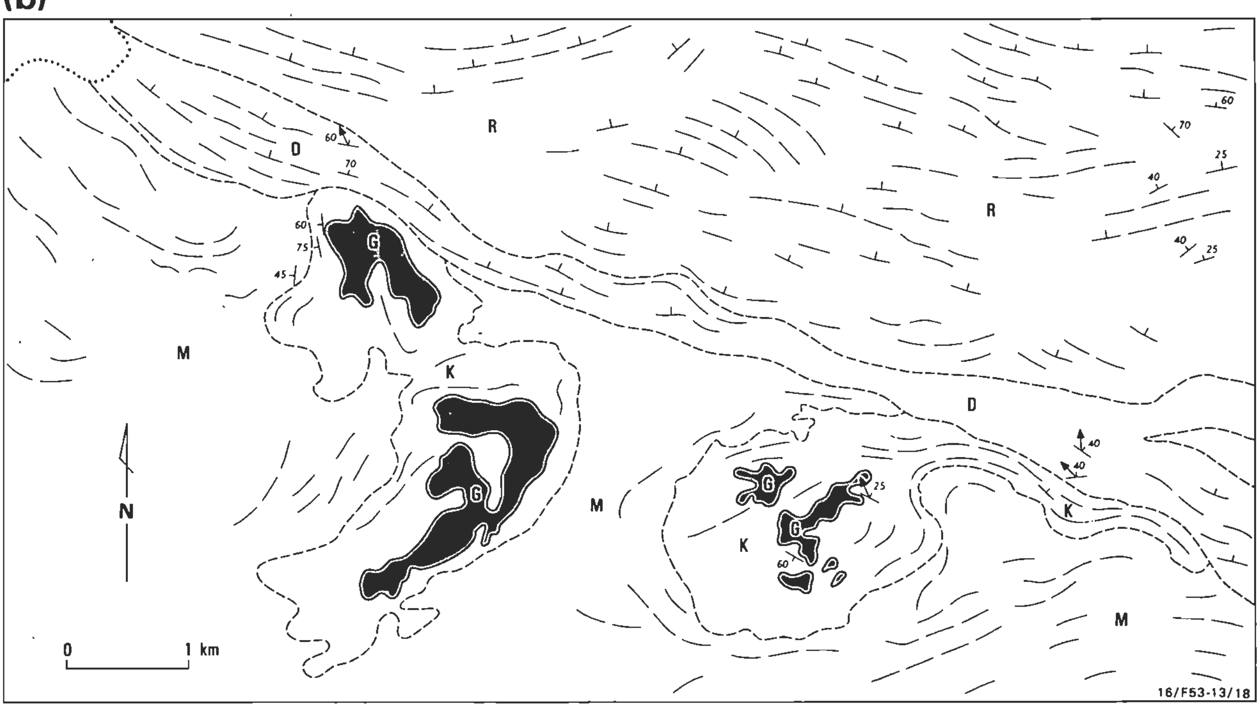
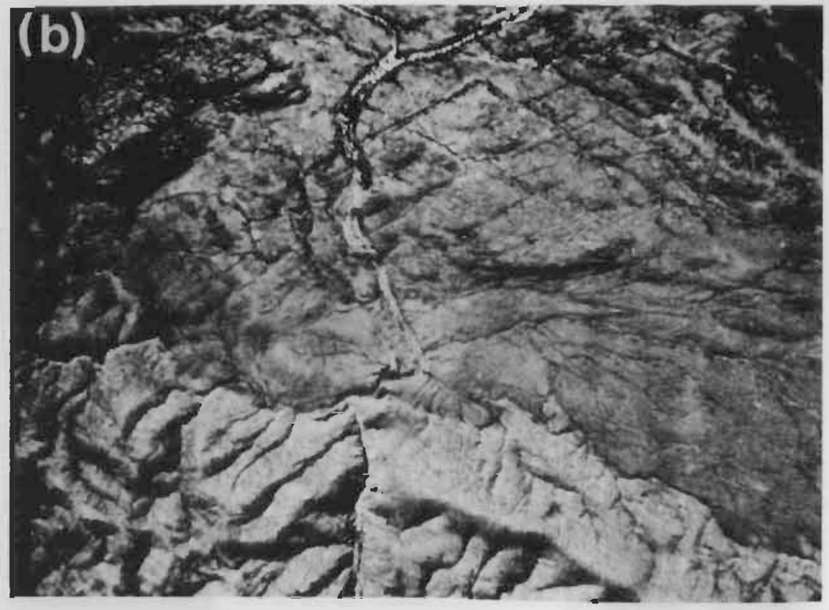


Figure 4. Geological sketch maps of parts of the Redbank–Mount Zeil thrust zone (RTZ). (a) Southwest of Redbank Hill (about 132°40′E, 23°24′S), location R in Fig. 2. (b) South of Mount Zeil (about 132°21′E, 23°24′S), location Z in Fig. 2.
R—granulite and granulite facies gneiss; M—migmatite; P—orthogneiss; D—Redbank-Mount Zeil thrust zone; G—gobbro; K—K-feldspar-rich gneiss envelope around gabbro; B—basic granulite.

Fold axes and penetrative lineation plunge steeply at about 50–90° east-northeast (Fig. 8b). Steeply plunging antiforms occur in the east and northeast. In places, marked changes in trend are not obviously related to folds and may reflect faults, the traces of which are difficult to identify, owing to the uniformity of juxtaposed granulites. In some areas, the intersection of penetrative gneissosity and closely spaced joint systems makes discrimination of these fabrics on aerial photographs difficult; for example, in the western part of the Mount Hay ridge.

The Mount Chapple granulites form a narrow 55 km long east-west ridge, including intermediate to felsic granulite and gneiss, which engulf abundant mafic granulite. Pods and veins of granitic gneiss intrude the granulites, and evidence of partial melting is widespread (Glikson, in press). The strike of compositional banding and gneissosity varies between west-northwest and west (Fig. 8a), and foliations dip mostly northward. Penetrative lineation, expressed as feldspar-quartz rodding on foliation planes, plunges steeply northeastward, corresponding to axes of reclined isoclinal folds (Fig. 8b). Jointing is oriented at high angles to the metamorphic banding and has a mainly longitudinal strike.

Redbank Hill is about midway between the Mount Chapple ridge to the north and the RTZ fault scarp to the south. Outcrops typically comprise very coarse-grained, amphibolite facies, recrystallised and deformed blastoporphyritic augen gneiss intruding and interleaved with units of mafic to felsic granulite (Fig. 6B). Relic phenocrysts of very coarse-grained K-feldspar have survived the deformation, whereas the bulk of the phenocrysts have been corroded, flattened, and recrystallised into K-feldspar-plagioclase-quartz aggregates in medium-grained matrix. The strike of metamorphic banding and foliation varies mainly between east and east-northeast, dips being mostly steep to vertical. A northeast-plunging lineation defines the axes of tight mesoscopic folds. Joints strike mainly longitudinally. Marjoribanks (1975) regarded a large segment of Redbank Hill as an integral part of the Redbank fault zone. However, as discussed later, the high metamorphic grade of the bulk of the Redbank terrane contrasts with the retrogressed deformed nature of the RTZ as defined in this paper (compare Figs 6A with 6B, and 7A



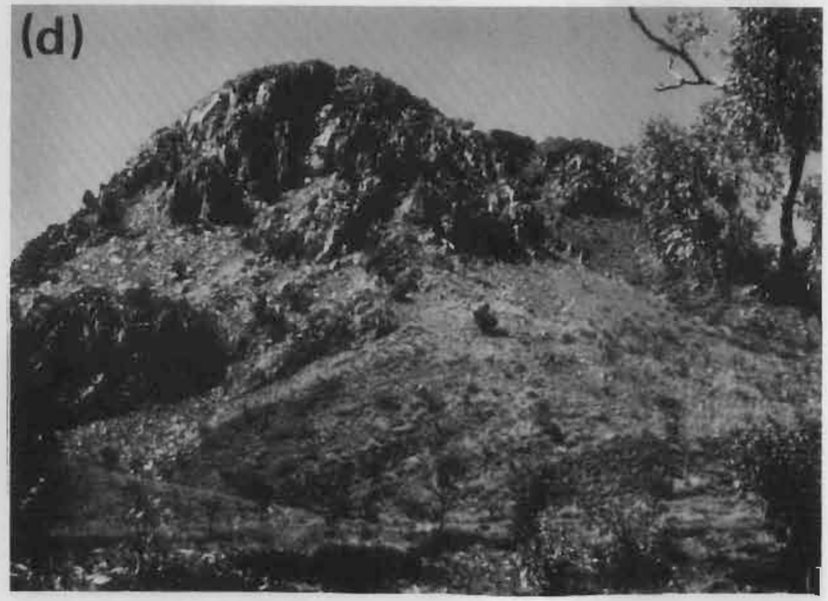


Figure 5. **(a)** Mount Heughlin (132⅞14'E, 23⅞2'S) viewed from the south, showing northward-dipping felsic granulite (upper cliffs) thrust over amphibolite facies gneiss (lower slopes). The RTZ constitutes a narrow zone at the base of the upper cliffs. **(b)** Aerial view of a part of the Mount Sonder–Mount Razorback thrust fault near Redbank Gorge (about 132°30'E, 23°34'S) (location S in Fig. 2), showing deformed Teapot area granite thrust over Heavitree Quartzite. **(c)** A basic granulite kernel (Black Hill) within mylonites and phyllonites of the RTZ (foreground) (132°40'E, 23°28'S) (Location R in Fig. 2). **(d)** A sliver of quartzite juxtaposed with the RTZ about 132°01'E, 23°16'S (Location H in Fig. 2). The lower slopes consist of deformed granulite facies gneiss.

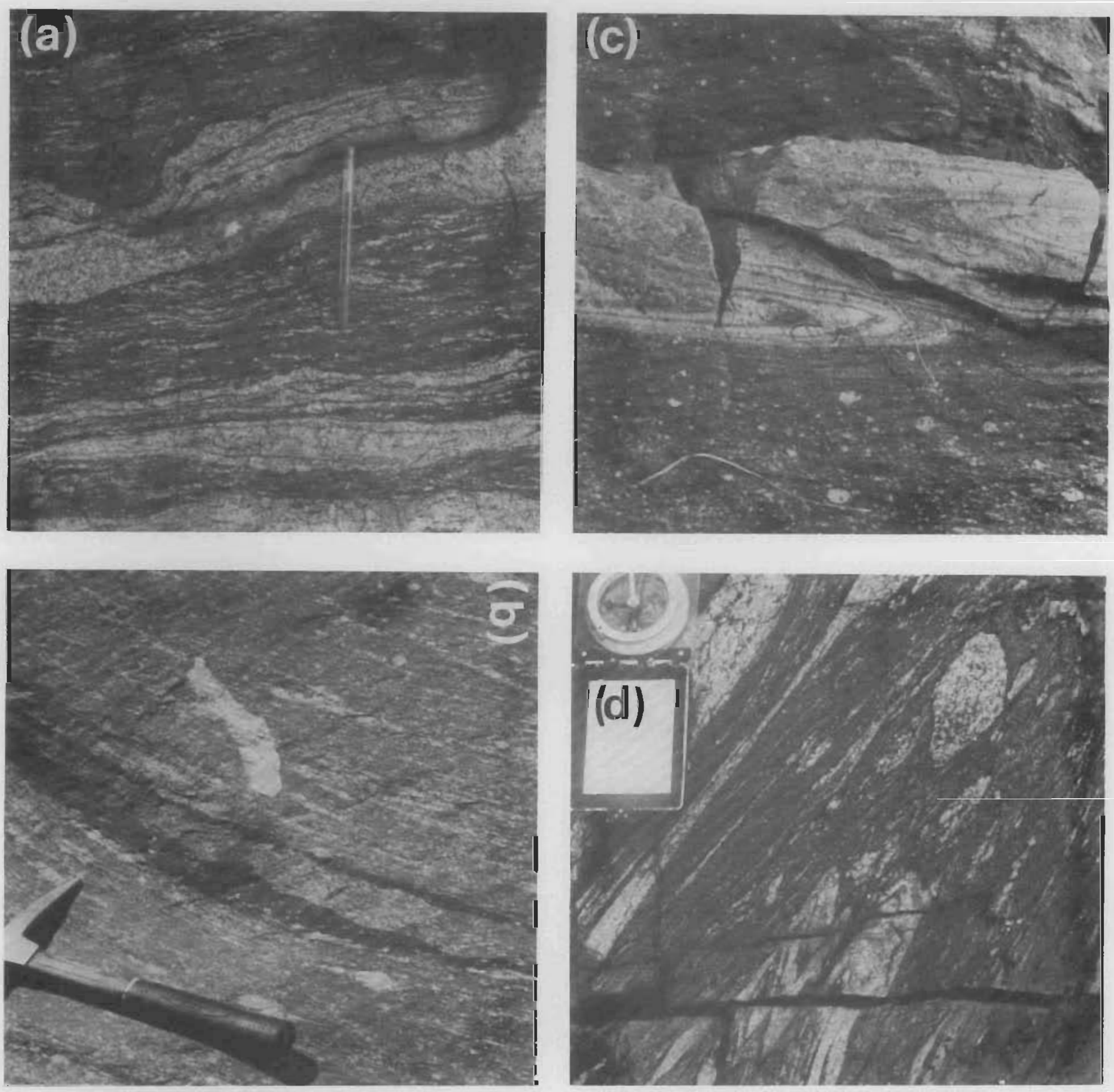


Figure 6A. Redbank–Mount Zeil thrust zone (RTZ).
(a) Banded ultramylonite (dark units) and protomylonite (light coloured units). **(b)** Relic rounded feldspar grains in mylonite. **(c)** Folded epidote-quartz mylonite (light coloured) and ultramylonite (dark bands). **(d)** Folded mylonite intruded by veins and segregations of quartz.

with 7B). At the same time, the massif is transected by numerous narrow mylonitic shears. Further, major faults may conceivably occur beneath the valleys separating the Mount Hay, Mount Chapple, and Redbank Hill massifs from one another, as suggested by mylonite outcrops along the northern rim of Redbank Hill. This possibility remains the subject of geophysical investigations.

Southern block

The paragneiss of the Derwent Creek area consists of well-layered and banded amphibolite facies metasediments and possible felsic metavolcanics, including orthogneiss and para-amphibolite and/or ortho-amphibolite cut by migmatite. Calc-silicate, metapelite, and quartzite may be present. The rocks may be contemporaneous with or older than the Chewings Range Group of Marjoribanks (1975), since both are intruded by granite of the Teapot area and related migmatite. Relic enclaves of paragneiss occur within the granite and migmatite. In the east, the paragneiss consists of a high proportion of pelitic schist, semipelitic gneiss, and quartzite—the last forming the Chewings Range (Figs 2,3). In the area under consideration the paragneiss is best exposed west of Derwent Creek, and is progressively migmatised between Derwent and Dashwood Creeks, grading eastward into migmatite. Difficulties in distinguishing between banded quartzofeldspathic paragneiss, migmatised equivalents, and intrusive migmatitic fractions result in uncertainties regarding the proportion of paragneiss within the migmatites. The quartzofeldspathic gneiss consists principally of garnet, biotite, muscovite, plagioclase, K-feldspar, and quartz. Deformed cataclastic to mylonitic derivatives related to RTZ deformation are common, displaying finely laminated epidote-rich bands and recrystallised quartz-feldspar mosaics.

The amphibolites are well banded on a centimetre scale, including amphibole-rich palaeosome and migmatitic neosome. They display tight isoclinal folding and are

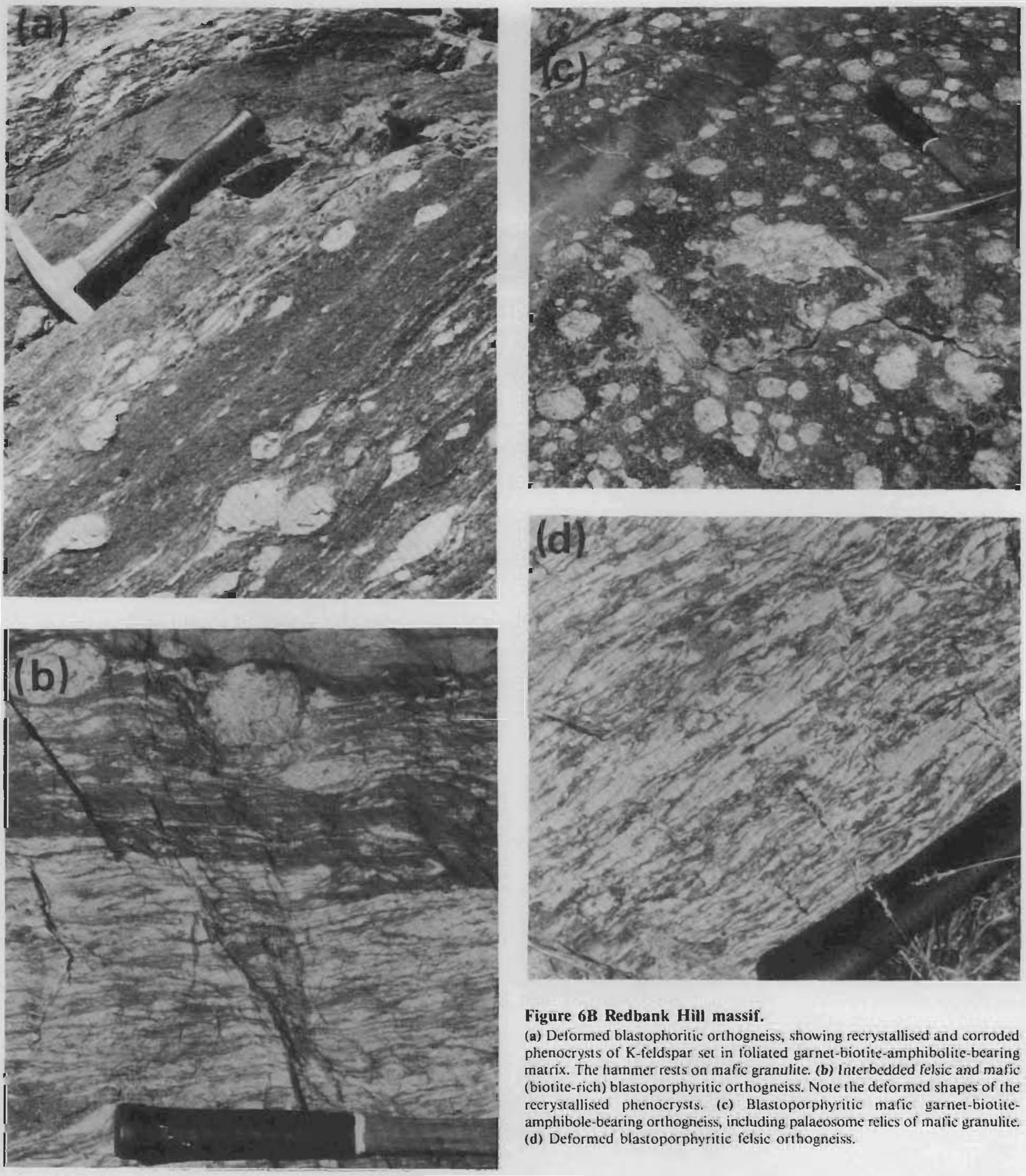


Figure 6B Redbank Hill massif.

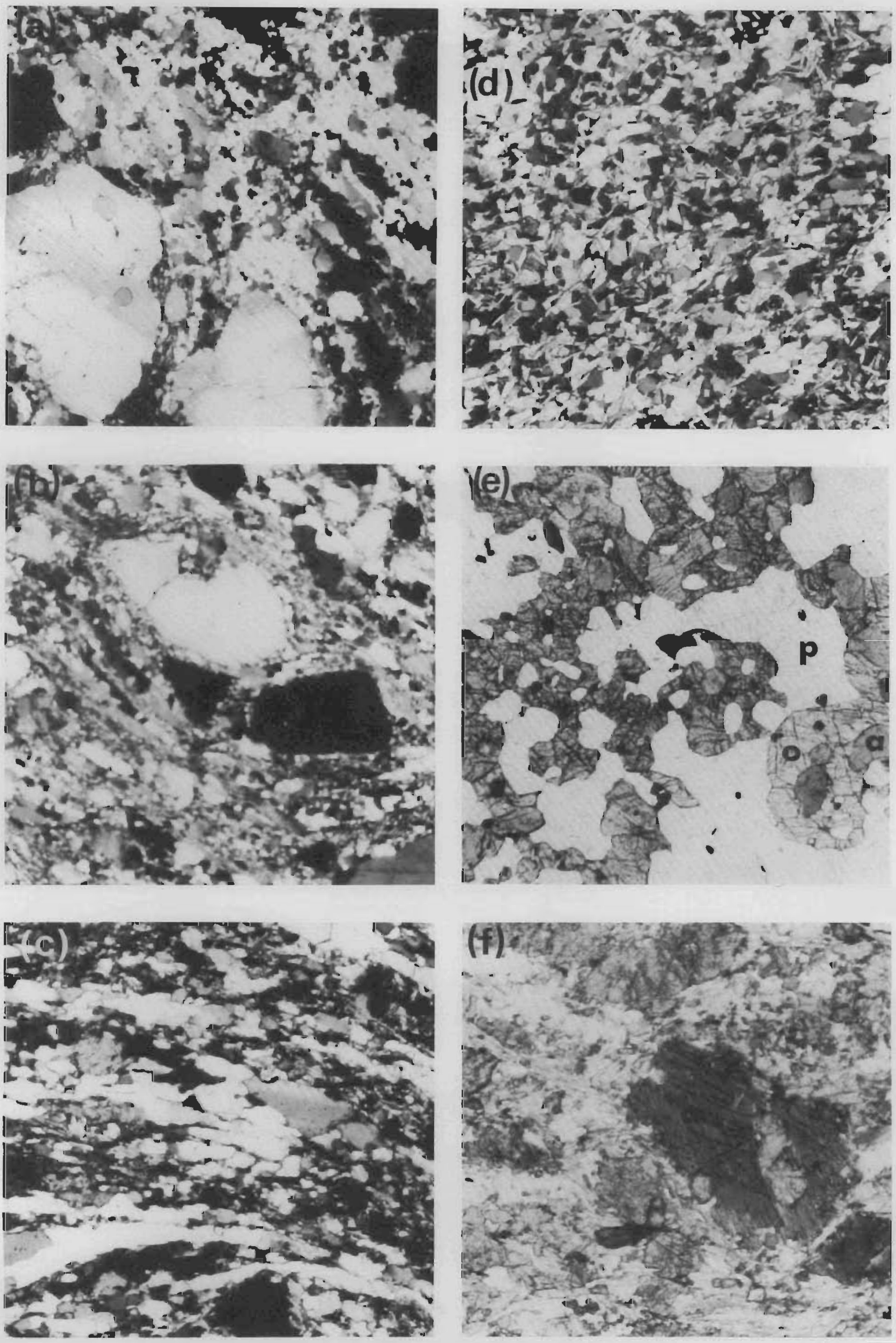
(a) Deformed blastophoritic orthogneiss, showing recrystallised and corroded phenocrysts of K-feldspar set in foliated garnet-biotite-amphibolite-bearing matrix. The hammer rests on mafic granulite. **(b)** Interbedded felsic and mafic (biotite-rich) blastoporphyritic orthogneiss. Note the deformed shapes of the recrystallised phenocrysts. **(c)** Blastoporphyritic mafic garnet-biotite-amphibole-bearing orthogneiss, including palaeosome relics of mafic granulite. **(d)** Deformed blastoporphyritic felsic orthogneiss.

pervasively intruded by amphibole-rich pegmatites. Where heavily migmatised, supracrustal relics occur as enclaves, streaks, and wisps of amphibolite and biotite engulfed by leucosome mobilisate. Owing to their location between the RTZ to the north and the Mount Sonder–Mount Razorback thrust to the south, they are commonly intensely deformed, exhibiting cataclastic to mylonitic textures and altered to epidote and sericite. The migmatite is flow folded at random orientations, showing no consistent axial trends, which suggests late magmatic rather than post-consolidation deformation, and is transected by numerous veins and dykes of fine-grained granite and pegmatite.

Granite of the Teapot area occupies approximately 200 km^2 in the southeast and southwest of Glen Helen and Narwietooma 1:100 000 Sheet areas, respectively, extending southward into Hermannsburg 1:100 000 Sheet area (Fig. 2). The granite forms the core of a wide zone of migmatite that intrudes paragneiss in the west and east. The Teapot granite is deformed along east–west faults and mylonitic shears that parallel the RTZ and Mount Sonder–Mount Razorback thrusts. These lineaments, and a meridional joint set, dissect the granitic terrane into rectangular blocks, a morphology that distinguishes the granite from adjacent migmatite and gneiss.

Basic intrusions associated with the RTZ

Basic intrusions have been recorded only south of the RTZ, and are classified here into three groups: (1) deformed, partly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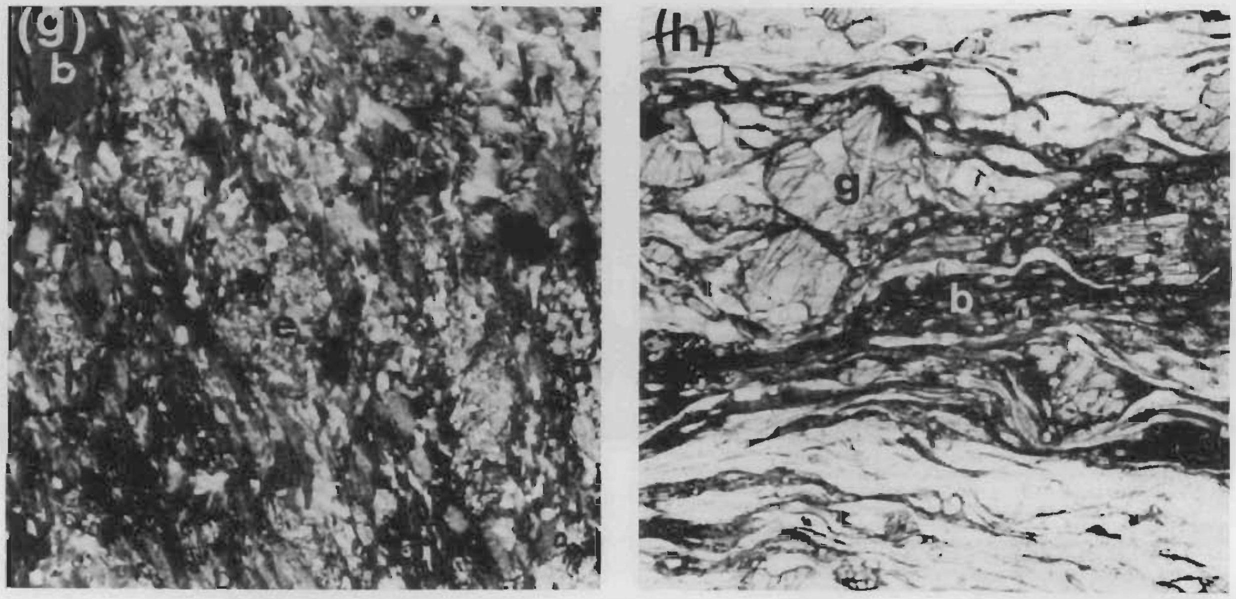


Figure 7A. Photomicrographs of RTZ rocks.
(a) Sphene-amphibole-biotite-K feldspar-plagioclase-quartz mylonite, showing deformed biotite and recrystallised quartz; 6.3 × 12; crossed nicols **(b)** Biotite-amphibole-plagioclase-feldspar-quartz mylonite, showing deformed biotite and corroded grains of feldspar in a flow matrix of foliated biotite and recrystallised quartz; 6.3 × 12; crossed nicols. **(c)** Ribbon quartz ultramylonite within the RTZ; about 13 × 12; crossed nicols. **(d)** Epidote-muscovite-quartz ultramylonite within the RTZ; 13 × 12; crossed nicols. **(e)** Relic mafic granulite within the RTZ; the photomicrograph shows fractured grains of orthopyroxene (o) with inclusions of amphibole (a) interspersed with plagioclase (p); 8 × 12; plane polarised light. **(f)** Sphene-bearing biotite-amphibole-plagioclase-quartz phyllonite, showing deformed fragments of amphibole in phyllonitic matrix; 21 × 12; plane polarised light. **(g)** Epidote-biotite-plagioclase-quartz phyllonite; 16 × 12; plane polarised light. **(h)** Deformed garnet-sillimanite-biotite paragneiss; 6.3 × 12; plane polarised light.

amphibolitised, gabbro stocks to the south of Mount Zeil; (2) deformed and altered basic dykes; (3) weakly deformed and little-altered basic dykes. Immediately south of Mount Zeil and the RTZ (about 23°24'S, 132°21'E) are a number of small bodies of altered gabbro and dolerite, including small basic dykes, which crop out over an area of about 20 km^2 and are surrounded by concentrically foliated K-feldspar-rich leucogneiss and by biotite gneiss (Fig. 4b). Three clusters of basic intrusions are outlined, each surrounded by a leucogneiss envelope. The two western clusters outline a folded sill-like body about 100–300 m thick. The eastern body is the largest: it has a thick gneiss envelope, including a 2.5 km long eastward-projecting tongue juxtaposed with the RTZ (Fig. 4b). Some of the gabbro samples retain primary orthopyroxene, clinopyroxene, and plagioclase, whereas other rocks are extensively amphibolitised. The leucocratic gniess-biotite gniess selvedges are interpreted in terms of local anatexis and remobilisation of migmatite country rocks, owing to heating by the intrusions. Biotite-rich zones within the gneiss envelopes may represent some assimilation of basic material by felsic partial melts. The juxtaposition of a leucogneiss envelope along the RTZ (Fig. 4b) suggests the intrusion of the gneiss was controlled and delimited by the overthrust Mount Zeil granulite and, thus, a post-RTZ age for the gabbro. The mineral replacement sequence: pyroxene-tremolite-hornblende-biotite in the metagabbro suggests middle-upper greenschist facies, possibly related to late-state reheating along the RTZ.

Dolerite dykes of the Stuart dyke swarm (897±9 Ma, Rb-Sr isochron age, Black & others, 1983) are widespread within the Teapot area granite, which they intrude mainly along east-west fractures. Deformed basic dykes occur in the western part of the granite and associated migmatite in the Dashwood Creek area, where the trend of the dykes is commonly northwest. Small dykes also intrude paragneiss west of Derwent Creek. No dykes are observed in the high-grade terrane north of the RTZ (except for deformed basic granulites possibly derived from early dykes) nor are dykes known to intersect the RTZ, the Mount Sonder-Mount Razorback thrust fault, or the unconformity at the base of the Heavitree Quartzite. These relations could suggest that the dykes predate the approximately 900 Ma old Heavitree Quartzite and the thrusting. However, this is not consistent with the only weakly deformed state of some dykes. Mild folding in places (e.g. 23°29'S, 132°19'E) suggests that the latest stages of deformation and fault reactivation postdated dyke emplacement.

Heavitree Quartzite

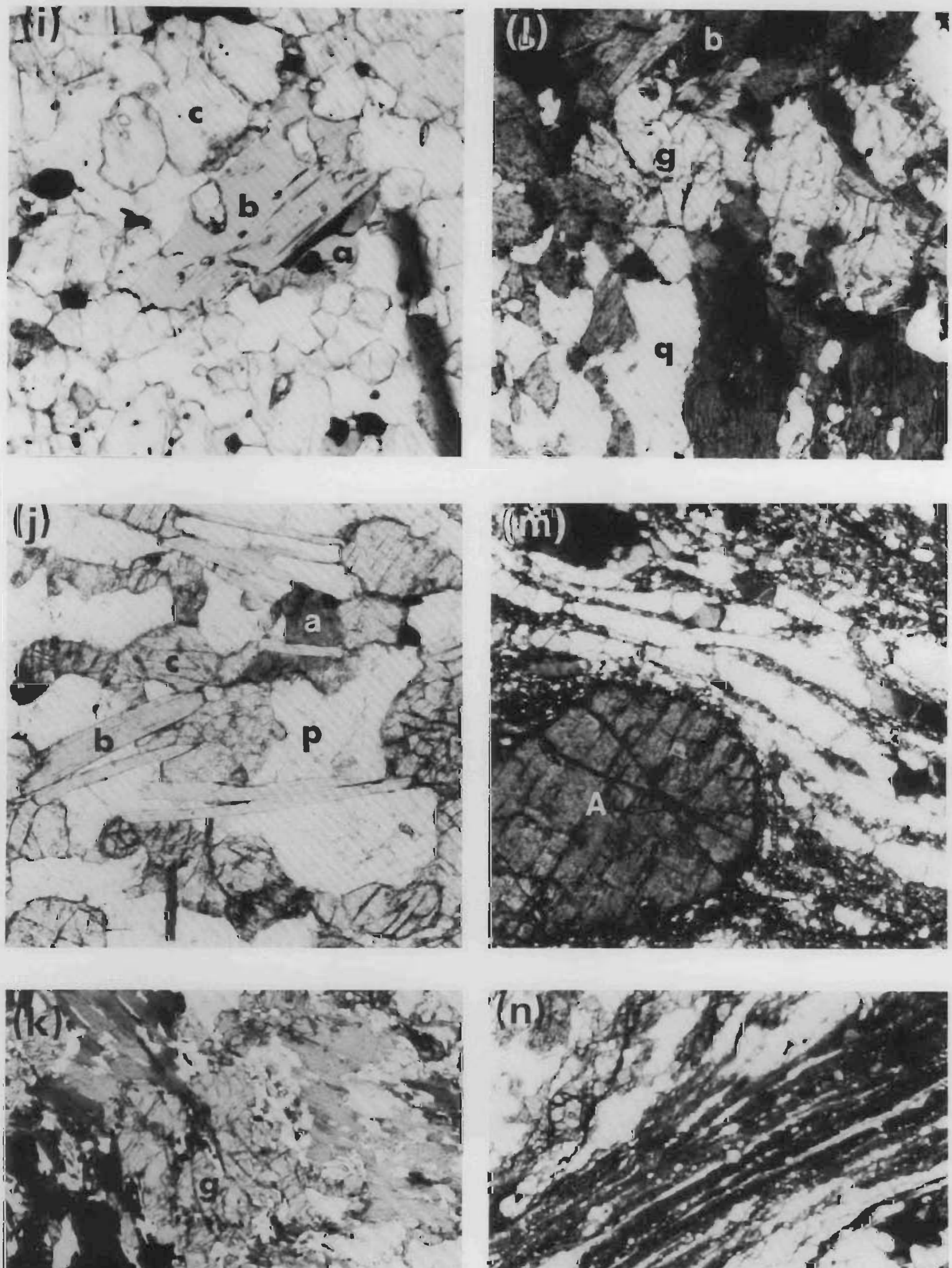
The area includes few outcrops of the Heavitree Quartzite—the basal unit of the late Proterozoic to Devonian Basin sequence (Wells & others, 1970):

(1) Ridge-forming quartzite unconformably overlying paragneiss in the Derwent Creek area along the Haast Bluff ridge.
(2) Quartzite outcrops striking northwest to west along the southwestern margin of Glen Helen 1:100 000 Sheet area.
(3) An isolated outcrop of quartzite juxtaposed with and located immediately north of the RTZ at about 23°16'S; 132°01'E (Fig. 5d).

Immediately south of Glen Helen and Narwietooma 1:100 000 Sheet areas, major ridge-forming outcrops of the Heavitree Quartzite form Mount Razorback and Mount Sonder, where the sediments are overthrust by deformed Teapot area granite (Fig. 5b). The significance of the Heavitree Quartzite in relation to the age of the RTZ is discussed below.

Age relations of the RTZ

The oldest ages recorded to date in the southwestern part of the Arunta Inlier are Sm-Nd model ages of about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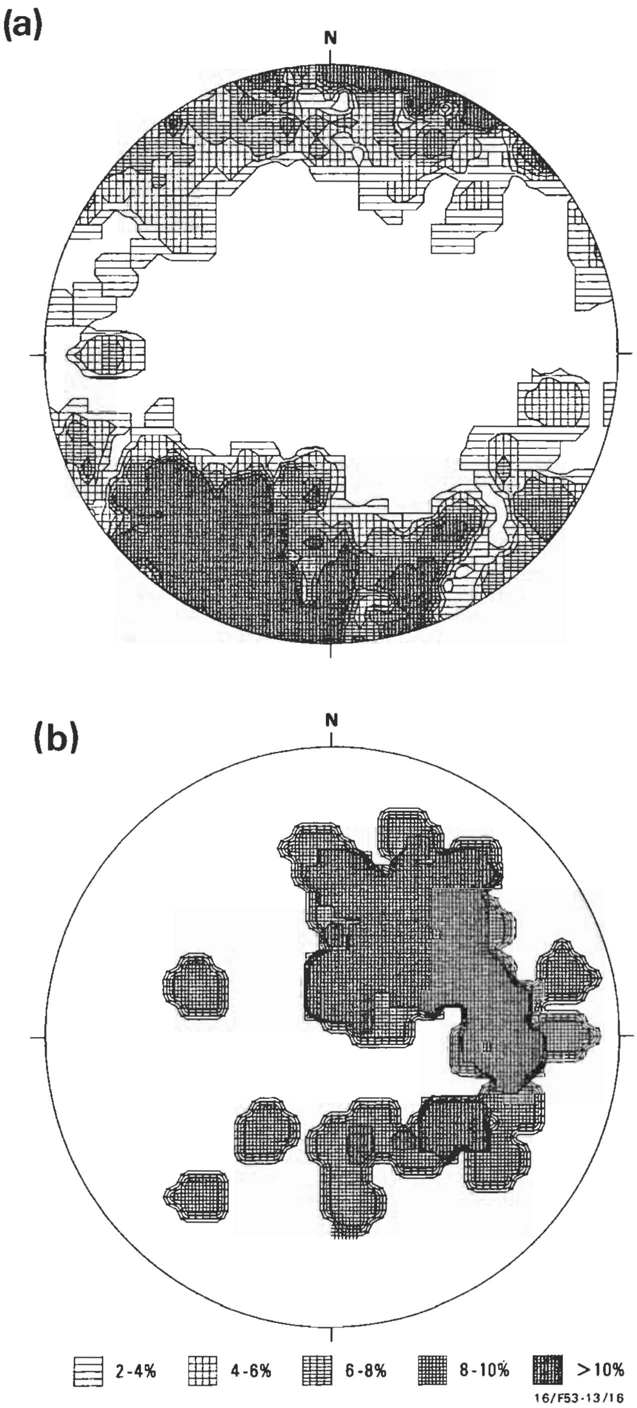

Figure 8. (A) Contoured poles to 229 metamorphic banding and foliation readings in the Anburla, Narwietooma and Glen Helen 1:100 000 Sheet areas. (B) Contoured projections of 61 lineation readings in the Anburla, Narwietooma and Glen Helen 1:100 000 Sheet areas.

2000–2400 Ma (Black & McCulloch, 1984), analogous to Sm-Nd isochron ages from the Strangways Range (Windrim & McCulloch, 1983). Marjoribanks & Black (1974) and Marjoribanks (1975) considered the RTZ to have predated the 1053±50 Ma age (Rb-Sr, total rock) of migmatite of the Ormiston Zone and the 893±97 Ma age (Rb-Sr, total rock-feldspar) of blastoporphyritic gneiss of Redbank Hill. This view is inherently related to a proposed correlation by these authors between migmatites south and north of the RTZ, and to their view of the southern part of Redbank Hill as an integral part of the RTZ. The present study, however, indicates that mylonite and phyllonite of the RTZ invariably transect the high-grade rock units and are nowhere affected by younger migmatisation. No confident correlations can be made between felsic igneous units north and south of the RTZ and their ages remain the subject of isotopic work. In so far as the approximate 1000 Ma and older Rb-Sr ages signify igneous events, they define older age limits for the thrusting. However, in view of the likely resetting of Rb-Sr ages by thermal rises along the RTZ, these ages may instead reflect movements along the thrust zone. The existence of an antecedent phase of the RTZ in pre-migmatite times thus remains a possibility.

A minimum age for vertical movements along the RTZ west of Derwent Creek is possibly furnished by outcrops of Heavitree Quartzite to the south and stratigraphically enigmatic quartzite to the north of the fault, at about 23°16′S, 132°01′E. In this area, a narrow 1500 m long sliver of quartzite with relic bedding striking at 320° is fault bounded within mafic granulite and gneiss juxtaposed with the RTZ (Fig. 5d). The quartzite could be derived from the Heavitree Quartzite or from an older metamorphosed quartzite, such as in the Chewings Range Group. In the former case, the similar structural level of the quartzite and the basal unconformity of the Heavitree Quartzite in the Haast Bluff ridge south of the RTZ would place limits on relative vertical movements in post-Heavitree Quartzite time. Such a consideration is consistent with the relatively little-deformed state of the Stuart dyke swarm (approx. 900 Ma), which suggests it was not affected by major deformation associated with the RTZ. It would follow that only limited reactivation of the RTZ has occurred after about 900 Ma ago. Such a conclusion, however, is difficult to reconcile with (1) major movements along the Mount Sonder-Mount Razorback thrust fault about 400 Ma ago (Alice Springs Orogeny; Black & others, 1983), and (2) the development of the Devonian Brewer Conglomerate, containing up to boulder-sized detritus derived from the north and signifying major uplift. The conglomerate contains granitic detritus, but is devoid of pebbles of granulite, implying still further uplift and denudation of the northern block in post-Devonian time. Thus, although the RTZ could have been active about 1000–900 Ma ago, major movements must have occurred during the Alice Springs Orogeny and younger times. This casts doubt on the significance of the quartzite correlation discussed above.

Owing to their separation by the RTZ, the temporal relations between the northern granulite block and the southern paragneiss-migmatite-orthogneiss block can be determined only by considerations based on isotopic methods and structure, as follows.

Northern block

The oldest deformation recognised in the Mount Hay and Mount Chapple mafic granulites predated lit-par-lit injection of felsic magma along a pre-existing foliation (S_1), including mesoscopic intrafolial folds (F_1), resulting in irregular

Figure 7B. Photomicrographs of Redbank Hill rocks.

(i) Biotite-amphibole-clinopyroxene-plagioclase gneiss; biotite replaces clinopyroxene, which replaces amphibole; 27 × 12; plane polarised light. **(j)** Biotite-amphibole-orthopyroxene-clinopyroxene-plagioclase granulite; note the cross-cutting relation of biotite; 132 × 12; plane polarised light. **(k)** Garnet-biotite-amphibole-orthopyroxene-plagioclase granulite; garnet replacing biotite replacing pyroxene replacing amphibole; 6.3 × 12; plane polarised light. **(l)** Garnet-biotite-amphibole mafic band in gneiss; 23 × 12; plane polarised light. **(m)** A rounded relic porphyroblast of amphibole in quartz ribbon ultramylonite; 32 × 12; plane polarised light. **(n)** A microscopic mylonite zone in biotite-amphibole-orthopyroxene-clinopyroxene-plagioclase granulite; 6.3 × 12; plane polarised light.

localised flow deformation and folding (F_2) associated with magmatic injection (D_2). The D_1 and D_2 fabrics were overprinted by deformation during the principal tectonic phase (D_3), which produced a gneissosity (S_3), a marked lineation (L_3) and reclined isoclinal folds (F_3). Rb-Sr ages measured on banded bimodal granulite from Mount Hay (1788±20 Ma, R_i = 0.7085; 1728±65 Ma, R_i = 0.706; Black & others, 1983) may represent the felsic anatectic/intrusive event or, alternatively, the waning of long-term metamorphism during 1800-1700 Ma ago. Prograde metamorphism is represented by reactions from amphibole-plagioclase to orthopyroxene-plagioclase to clinopyroxene-garnet-plagioclase assemblages. Biotite intersects all other minerals and shows little alignment, suggesting introduction of a K-bearing fluid phase, possibly in association with the felsic igneous activity and relaxation of regional stress.

The foliation of the granulite is deflected by mostly north-plunging flexures and open folds (F_4) representing deformation (D_4) of probable post-1800 Ma age. These folds predate penetrative ductile deformation (D_5) along the RTZ and its associated fault splays. Even younger drag flexures (F_5) are superimposed in the vicinity of the RTZ, resulting, in places, in deflection of the strike of mylonite.

Majoribanks (1975) suggested that the granulite facies metamorphism was related to early thrusting—an interpretation related to a view of the southeastern part of Redbank Hill as an integral part of the high-grade block, which extends about 70 km north of the RTZ. Except for grain size, there is little basis for distinguishing between amphibolite-facies deformed blastoporphyritic orthogneiss of Redbank Hill and amphibolite to granulite facies porphyroblastic orthogneiss of the Mount Chapple and Mount Zeil massifs.

Southern block

Majoribanks (1975) distinguished two principal divisions in the Hermannsburg 1:100 000 Sheet area: (1) the Chewings Range zone (CRZ)—quartzofeldspathic gneiss, pelitic to semipelitic gneiss, quartzite; and (2) the Ormiston zone (OZ)—migmatised felsic gneiss, mica schist, quartzite, amphibolite and mylonitic rocks. At the core of the migmatite are a number of granitic bodies, the largest of which is in the Teapot area (Fig. 2). Ormiston zone migmatite contains remnants of CRZ paragneiss. The minimum age of the CRZ is given by a Potrock gneiss total-rock (TR) Rb-Sr isochron age of 1586±69 (R_i = 0.729) (Marjoribanks & Black, 1974). A TR-mineral Rb-Sr age for these rocks gives an age similar to the OZ migmatite, where a TR-muscovite age of 1053±50 Ma is considered by Marjoribanks & Black (1974) to represent migmatisation postdating early development of the RTZ. Structural elements in the CRZ in part correlate with those in paragneiss of the Derwent Creek area. Marjoribanks (1975) distinguished the following episodes in the Ormiston Pound-Chewings Range area.

D_1—(Pre-Chewings Phase)—marked by rare F_1 intrafolial folds, which affect relic sedimentary layering (S_1), and are mainly retained in pelitic and quartzitic units.

D_2—(Chewings Phase)—marked by strong S_2 axial cleavage related to F_2 folds. The schistosity transposes and partly obliterates the S_1 layering. S_2-S_1 intersections (F_2 fold axes) define L_2 lineation.

D_3—(Ormiston Phase)—local east-northeast-trending folds (F_3) expressed as axial-plane cleavage (S_3) in quartzite in the Ormiston Pound area, and related to deflection induced by the Ormiston Pound granite and related migmatisation.

D_4—(Mount Giles Phase)—major east-trending asymmetric open folding (F_4) of the Chewings Range Quartzite, with little effect on gneiss to the north.

D_5—(Alice Springs Orogeny)—uplift of the Arunta basement along the northern margin of the Late Proterozoic-Devonian Amadeus Basin, represented by the Ormiston thrust fault, Mount Sonder-Mount Razorback thrust fault, thrust-nappe structures in the Heavitree Quartzite, and probably major movements along the RTZ. The involvement of Devonian sediments in the deformation and K-Ar ages of 400 Ma (Black & others, 1983) define a late Permian to Carboniferous age for these movements.

Geophysical anomalies associated with the RTZ

Comparison between geological features and radiometric, aeromagnetic and Bouguer anomaly maps indicates the following.

(1) The principal granulite massifs, including Mount Hay, Mount Chapple, Redbank Hill, and Mount Zeil, are closely matched by radiometric patterns (Fig. 9).

(2) Total radiometric counts reflect the felsic/mafic ratios in the rocks. Thus, circular lows of about 20 c/s (counts per second) occur over the mafic granulite of Mount Hay, 60-80 c/s correspond to bimodal and intermediate granulite of the Mount Chapple massif, 80-100 c/s correspond to intermediate to felsic granulite of the Redbank Hill massif, and 120-200 c/s correspond to felsic granulite and gneiss of Mount Zeil. Isolated higher values reflect K-rich felsic rock concentrations.

(3) The RTZ stands out on the radiometric map, owing to sharp contrast between granulite to the north (<200 c/s) and migmatite, granite, and gneiss to the south (>200 c/s).

(4) The southern block, including granite, migmatite, and paragneiss terranes, displays numerous circular highs to 600 c/s and smaller intermediate highs. These are strongest over the granite of the Teapot area, well developed over migmatite of the Dashwood Creek area, and only weak over paragneiss of the Derwent Creek area. These variations, reflecting K, U, and Th levels in the rocks, are consistent with the progressively decreasing role of granite and migmatite from east to west. The radiometric map provides an effective means of estimating the over-all abundance of K-rich and K-poor lithologies where mesoscopic interbanding makes distinction in the field difficult.

(5) The radiometric pattern over the alluvial cover of the Burt Plain consists of numerous lows of about 100-120 c/s. Strings of highs occur over a drainage area derived from the southern granite/migmatite terrane. Small highs (up to 300 c/s) coincide with isolated outcrops of orthopyroxene-bearing intermediate to felsic granulite and garnetiferous felsic gneiss (132°49′E-132°53′E, 23°02′S-23°08′S). These high counts (relative to low counts over Mount Chapple granulite) suggest a possible northward increase in the proportion of K-rich rocks.

Consideration of the Bouguer anomaly map (Fig. 10) in terms of principal geological features shows that the centre of the major Papunya gravity ridge (+500 $\mu m/s^2$) coincides with positive radiometric anomalies over isolated outcrops in the Burt Plain (described above) about 20 km north of the Mount Chapple ridge. A steep gravity gradient of over 30 $\mu m/s^2/km$ occurs from the maximum of 500 $\mu m/s^2$ southwards to a minimum of −1200 $\mu m/s^2$ over the Teapot area granite. The

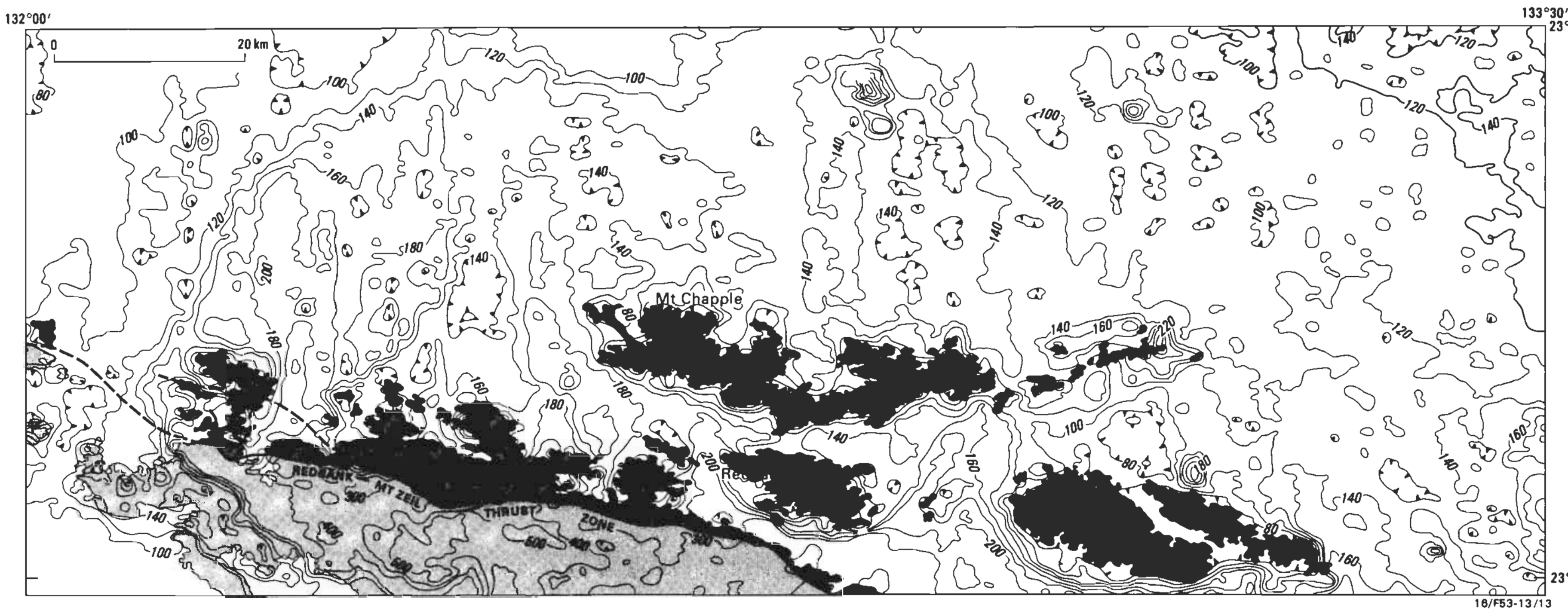

Figure 9. Simplified radiometric anomaly map of the northern part of Hermannsburg 1:250 000 Sheet area.
c/s—counts per second; dark areas—granulite-facies rocks; light areas—amphibolite facies and granitic terrane.

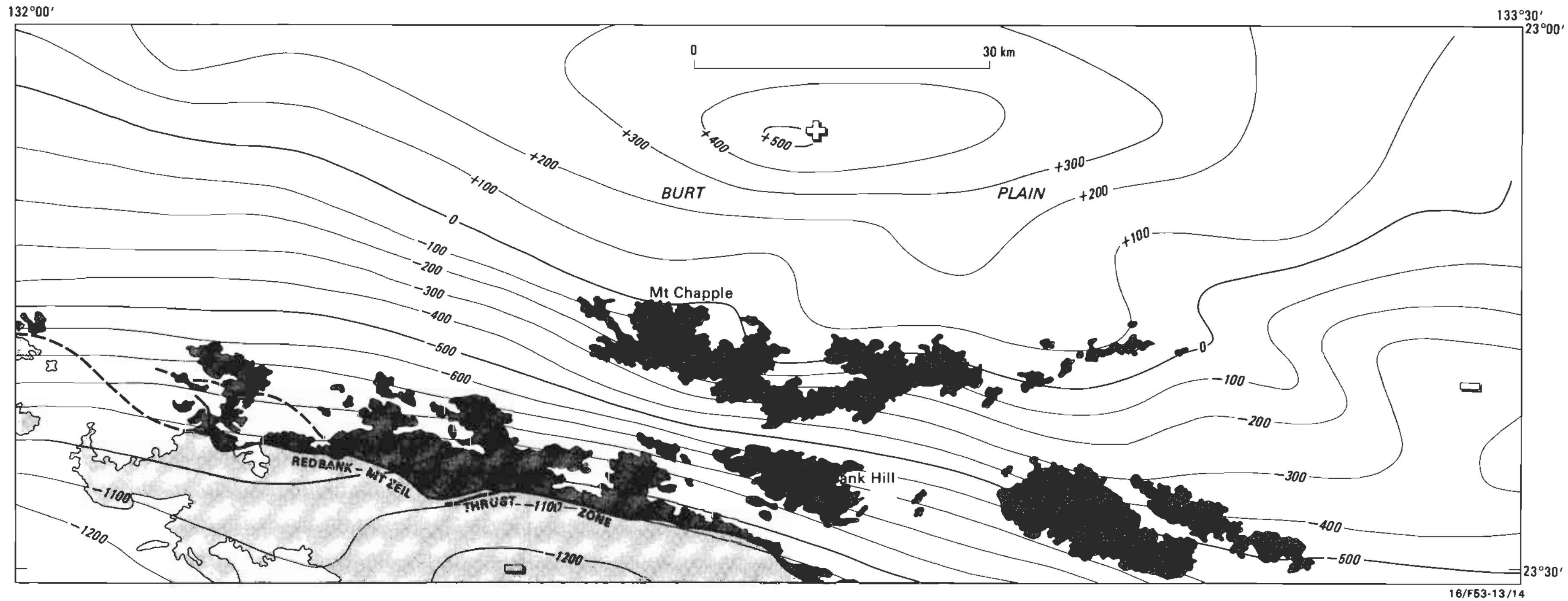

Figure 10. Simplified Bouguer gravity anomaly map of the northen part of Hermannsburg 1:250 000 Sheet area.
Units in $\mu m/s^2$.

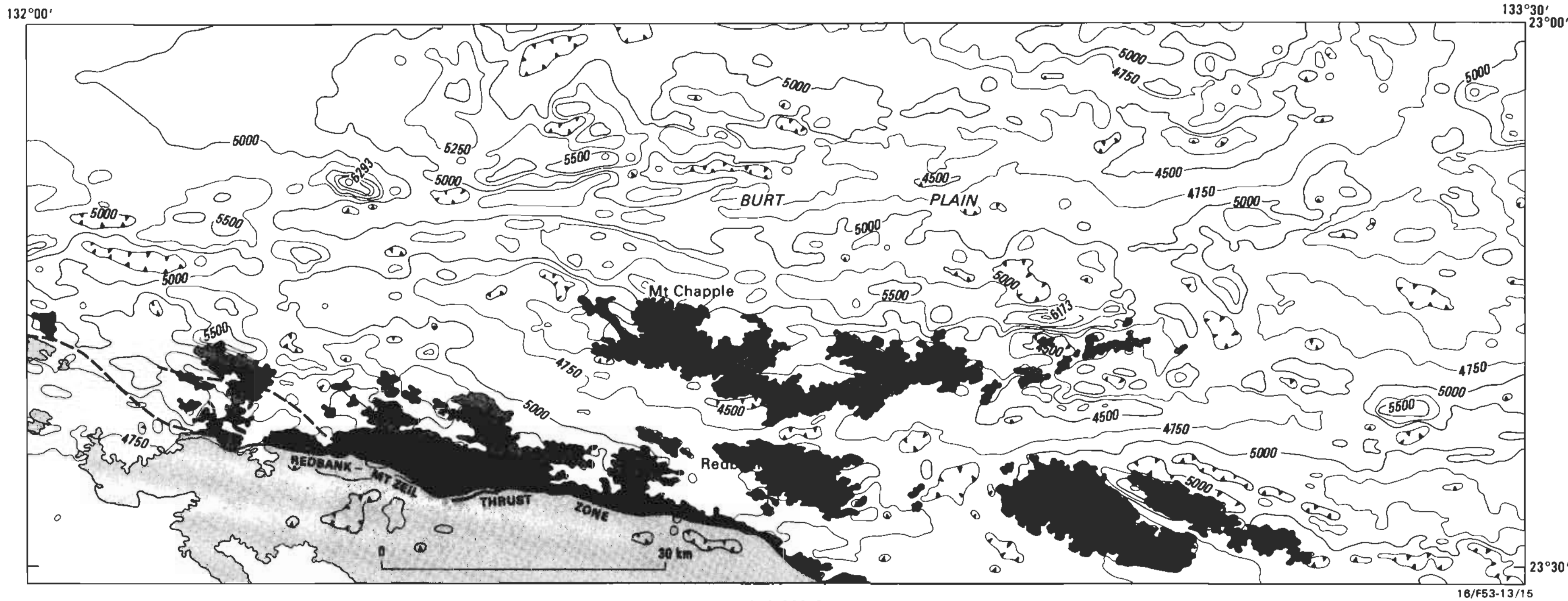

Figure 11. Simplified aeromagnetic anomaly map for the northen part of Hermannsburg 1:250 000 Sheet area.
Units in nT.

gravity contours and the RTZ are near-parallel and the -1100 $\mu m/s^2$ contour approximately coincides with the fault trace in the east. The gravity gradient may reflect a northward thickening of a wedge of overthrust granulite.

Aeromagnetic patterns (Fig. 11) also correlate with major lithological and structural features associated with the RTZ. The granulite terrane north of the RTZ is magnetically more disturbed than the granite and migmatite of the southern block, demarcating the thrust fault along most of its length. However, the patterns over paragneiss terrane are more strongly disturbed than over migmatite and granite, and thus the RTZ is poorly demarcated where granulites are thrust over paragneiss west of Dashwood Creek. Strong linear latitudinal anomalies characterise the northern block, and are typically juxtaposed with the northern margins of the main granulite massifs, i.e. Mount Hay, Mount Chapple, and Mount Zeil. Well-pronounced east-trending linear anomalies occur under the Burt Plain, displaying patterns suggestive of fold closures (D. Tucker, personal communication, 1984) and clearly reflecting basement structures. The lithological significance of these anomalies, however, is uncertain. The anorthosite-basic granulite ridge north of the Mount Hay has a strong positive magnetic anomaly (5961 nT), whereas the Mount Hay basic granulite ridge to the south is magnetically quiet. Interpretation of these patterns must await studies of relic magnetic properties in these rocks.

Implications for crystal structure

The significance of the major Bouguer anomalies in central Australia is the subject of an ongoing debate. Forman & Shaw (1973) and Mathur (1976) interpreted the Papunya gravity anomaly ($+500$ $\mu m/s^2$) in terms of upward dislocation of the Moho through thrusting or mantle doming. Anfiloff & Shaw (1973) modelled the gravity anomalies in terms of lateral lithological variation between dense granulite-dominated blocks and granite and sediment-dominated blocks. Wellman (1978) discussed the nature of the gravity anomalies in terms of crustal density contrasts, associated compensating masses, and variations in crustal thickness. Shaw & others (1984) attributed the large gravity highs to basic igneous activity in an early Proterozoic ensialic rift zone.

Many of the questions that arise from the study of the Redbank-Mount Zeil thrust zone remain unanswered pending seismic studies and isotopic age correlation between the northern and southern blocks. Such studies would provide an insight as to the nature of the deep crust prior to faulting. Possible models include the following.

Model 1—The northern block granulite is older than the southern block paragneiss. Such relation implies that either (a) the paragneiss overlies granulite similar to that of the northern block, conformably or unconformably, or (b) the paragneiss evolved in a distinct crustal sector laterally juxtaposed with the northern granulite block. If model (a) applies, it is possible that, in places, original contacts between granulite and gneiss or gradation of granulite into gneiss may have been preserved. Transition from granulite to amphibolite facies rocks also occurs along the eastern extremity of the RTZ, south of the Harry Creek Deformed Zone (Shaw & others, 1984). On the other hand, model (b) implies the existence of an antecedent phase of the RTZ during the evolution of the paragneiss.

Model 2—The northern block granulite and the southern block paragneiss are contemporaneous. In this model, vertical crustal transition from a granulite-facies bimodal meta-igneous suite upwards to metasediment is applicable. The Teapot area granite and its migmatite envelope are younger than the granulite, and their anatectic root zones are represented by the swarms of granulite to amphibolite facies, felsic gneiss stringers within the subjacent granulites.

It is pertinent to discuss the alternative models with reference to other parts of the Arunta Inlier. Shaw & Stewart (1975) and Shaw & others,(1984) proposed a three-fold stratigraphic division and a three-fold latitudinal tectonic division of the Arunta Inlier (Fig. 1) on the basis of differences in stratigraphic sequence, granitic component, isotopic ages, metamorphic grades, and structure. The stratigraphic divisions are (from oldest to youngest): Division 1—mainly bimodal mafic-felsic granulite; Division 2—mainly metasediment, paragneiss, and associated migmatite and orthogneiss; greenschist to granulite facies. Division 3—mainly greenschist to amphibolite facies metasediment, including quartzite, shale, and carbonate. The latitudinal tectonic provinces are: Northern province—includes division 2 and, to a lesser extent, division 1 and 3 rocks, extensively intruded by rapakivi granites and orthogneiss of the Anmatjira zone in the Reynolds Range area (Stewart & others, 1980). Central province—dominated by division 1 rocks, with minor division 2 and 3 components. Southern province—dominated by quartzo-feldspathic paragneiss; intruded by migmatite and orthogneiss; tentatively assigned to division 2, and locally overlain by division 3 metasediments.

Available isotopic data include mainly Rb-Sr isochron ages and K-Ar ages, whereas the primary igneous and sedimentary ages of the metamorphic suites remain uncertain (Black, 1975; Black & others, 1980, 1983). In the southwestern part of the Arunta Inlier, although it is possible that division 2 rocks (Derwent Creek area paragneiss, Chewing Range Group, Dashwood Creek area migmatite, Ormiston Zone migmatite) postdate division 1 granulite, contemporaneity of these divisions in a vertically zoned crust remains a possible model.

In its regional context, the southwestern part of the Arunta Inlier can be interpreted in terms of a series of major northward-tilted blocks separated by thrust faults. Anfiloff & Shaw (1973) interpreted the thrusting in terms of north-south compression of the Australian continent, possibly related to an incipient plate tectonic regime. If the RTZ originated in the late Proterozoic, it follows that a north-south stress field predated the Mesozoic-Cainozoic plate tectonic regime. A long-term compressional stress field in central Australia has been invoked by Lambeck (1984) to explain the successive development of thrust faults between uplifted basement domes and subsiding basins, leading to variations in crustal thickness between these domains. In this model, the crust is relatively thin beneath uplifted basement, as indicated by some gravity models (Mathur, 1976). A long-term compressional stress field would place temporal limits on rift-structure models (Warren, 1983; Shaw & others, 1984). Although it is possible that middle Proterozoic basins evolved under a tensional regime, to date no definitive evidence has been produced for this.

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Geology, petrology, and tectonic significance of Permian and Carboniferous igneous rocks of the western Georgetown Inlier, north Queensland

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Volcanic and intrusive rocks of Permian age, ranging from basalt and andesite through granodiorite and dacite to rhyolite, are sparsely but non-randomly distributed in the western Georgetown Inlier, including newly recognised areas in the Croydon region. The basaltic to andesitic rocks are typical intra-plate transitional alkaline rocks, apparently genetically unrelated to the granodiorite/dacite to rhyolite group, which are a suite of fractionated I-type (and possibly A-type) rocks, lower in alkalis, derived from evolved (old) crustal source rocks. The Permian magmatism appears to have been controlled by northwest-trending, and some north-trending, major fractures. Carboniferous igneous rocks in the same region, although only slightly different in chemistry, include a much greater proportion of felsic ignimbrites relative to more mafic extrusive rocks, and are related to north-south aligned and/or elongated sag-type cauldron structures. Total volumes, relative proportions of mafic and felsic rocks, and, to some extent, their compositions, appear to be related to tectonic style.

Introduction

The Croydon sub-province (Withnall & others, 1980) is the westernmost part of the largely Proterozoic Georgetown Inlier (Fig. 1). It is made up predominantly of felsic ignimbrites belonging to the Croydon Volcanic Group (Croydon Volcanics of Branch, 1966) and related granitoids, including the Esmeralda Granite (White, 1959; Branch, 1966). The sub-province is flanked to the east, with mostly faulted contacts, by the Early to Middle Proterozoic Etheridge and Langlovale Groups, which consist of metamorphosed shallow-marine to fluviatile, mostly pelitic to psammitic, clastic sediments (Withnall & Mackenzie, 1980, 1983; Draper & others, 1981). Volcanic rocks, dominantly felsic ignimbrites, of Carboniferous to early Permian age are widely distributed throughout the Georgetown Inlier; these include the Newcastle Range, Maureen, and Cumberland Range Volcanic Groups, and the Dismal Creek Dacite (Fig. 1). Branch (1966) considered that the Croydon Volcanics were also Carboniferous and therefore part of the late Palaeozoic northeastern Queensland cauldron-subsidence volcanic province. However, isotopic dating by Richards & others (1966) and Black (1973) showed that the Croydon Volcanics and Esmeralda Granite are Proterozoic, thus apparently placing the western limit of late Palaeozoic extension-related volcanism (Oversby & others, 1980; Mackenzie & Oversby, 1983) in the region of the Cumberland Range (Fig. 1).

Mackenzie & Oversby (1983) and Oversby (1983) argued that the dominantly felsic Carboniferous magmatism in the Georgetown Inlier was related to east-west tensional stress and north-south elongated sag-type cauldron structures (Oversby & others, 1980; Walker, 1984), while the much less voluminous, mafic-dominated, Permian magmatism was related to northeast-southwest tension and northwest-trending fractures. This paper presents new data on Permian igneous rocks in the western Georgetown Inlier and compares them with Permian and Carboniferous igneous rocks elsewhere in the Inlier. Its aim is to document geochemical differences between the Permian and Carboniferous rocks and to explain the origin of these differences and how they might relate to differences in tectonic setting.

Geology

Permian igneous rocks recently recognised in the western Georgetown Inlier include the Bullseye Rhyolite, Linley Rhyolite, Little Pocket Dacite, McFarlanes Andesite, and Awring Granodiorite, which crop out in two small areas within the Croydon Volcanic Group. The Carnes and Gongora Granodiorites, recently found to be also Permian, crop out farther to the southeast in the Etheridge Group (Fig. 1).

Bullseye Rhyolite

The Bullseye Rhyolite consists of welded rhyolitic ignimbrite and non-welded airfall tuff underlain in the west (localities 1-3, Fig. 2) by up to 20 m of fluviatile sedimentary rocks. It is preserved as a series of small, sub-parallel, horst-like fault blocks and tilted fault slices on the eastern margin of the Croydon Volcanic Group (Figs 1 & 2).

The sedimentary sequence consists mainly of a cobble to boulder conglomerate, with interbeds up to 40 cm thick of cross-laminated, quartzose sandstone and pebbly sandstone. The conglomerate is made up predominantly of rounded clasts of quartzite and a quartz-sand matrix derived from the Proterozoic Inorunie Group (Oversby & others, 1981, 1982; Mackenzie & others, 1985; Mackenzie, 1983).

Pieces of silicified tree trunks, up to 50 cm across and 60-70 cm long, preserved near the contact between the sediments and the overlying volcanics were identified by L.N. Morris (personal communication, 1981) as *Araucarioxylon* sp., similar to *Araucarioxylon arberi* (Seward) Beeston from the Baralaba Coal Measures near Theodore, Queensland, a species restricted to the Permian (Beeston, 1972).

The volcanic sequence consists of a discontinuous basal layer of fine, rhyolitic, air-fall tuff overlain by a series of fine to medium-coarse, crystal-rich welded rhyolitic ignimbrite sheets with minor intercalated tuff. The basal tuff layer is up to 3 m thick in the north of the area (localities 1, 5-7, Fig. 2) and grades laterally into variably reworked sediments at locality 3, but it is very thin or absent elsewhere. The ignimbrite sequence is up to 30 m thick in the west (localities 1-3) and thins to about 3-4 m in the east (locality 8); the degree of compaction and welding also decreases to the east. Basal cross-lamination is well developed at locality 5, suggesting base-surge deposition, and, at locality 7, several sheets of poorly welded ignimbrite, ranging from less than a metre to several metres thick, are intercalated with massive to finely laminated beds up to 3 m thick of fine, rhyolitic, air-fall ash tuff, and may be distal deposits. Most of the pyroclastic rocks are partly to completely silicified.

Fine-grained, sparsely porphyritic to aphyric, biotite rhyodacite and hornblende-biotite dacite lavas crop out at locality 3, and on the eastern bank of Olsens Waterhole (Fig. 2).

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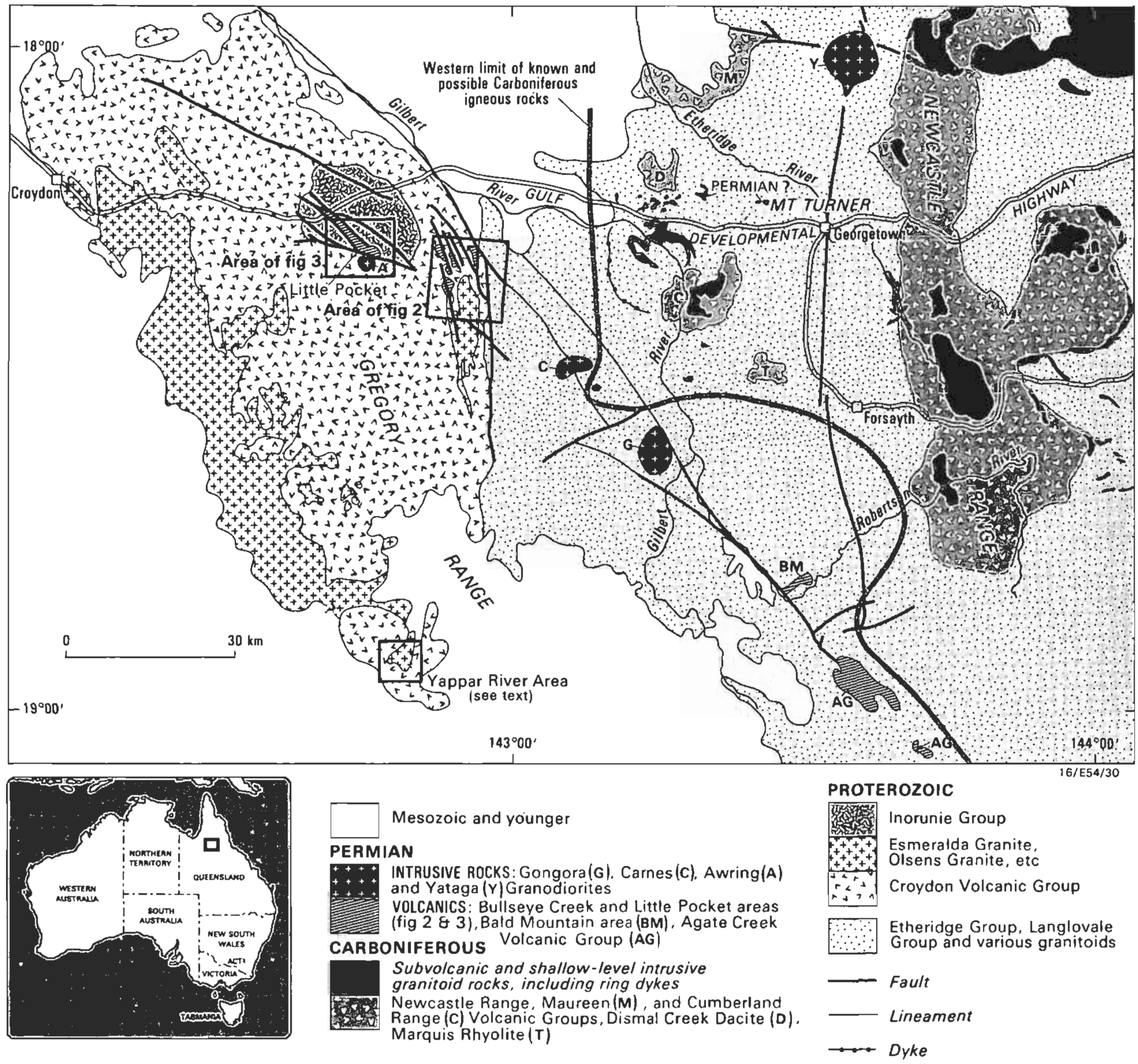

Figure 1. Generalised geology and locality map of the western Georgetown Inlier.

Goat Creek Andesite

Although the Croydon Volcanic Group contains basaltic to andesitic rocks that are agate-bearing in part, the age and relations of poorly exposed agate-bearing andesitic to basaltic rocks that constitute the Goat Creek Andesite in the Bullseye Creek area are uncertain. The andesite is mostly confined to graben-like depressions between the 'horsts' on which the Bullseye Rhyolite is preserved, and may be largely or entirely a correlative of the Permian McFarlanes Andesite.

Linley Rhyolite, Little Pocket Dacite, McFarlanes Andesite, and Awring Granodiorite

The Little Pocket area, 12 km south of the Gulf Developmental Highway on the Little River (Figs 1, 3), contains a variety of igneous and minor sedimentary rocks of Permian and possible Permian age and has lithological and structural similarities to the Bullseye Creek area. The McFarlanes Andesite, Little Pocket Dacite, and Linley Rhyolite are almost entirely confined to a fault-bounded, graben-like valley, which also contains a remnant of conglomerate similar to that at the base of the Bullseye Rhyolite. Outcrop, especially of the andesite and dacite, is very poor, and, because contacts are not exposed, relations are unclear. The Linley Rhyolite, which consists of moderately crystal-rich, welded rhyolitic ignimbrite and minor porphyritic rhyolite lava, appears to overlie the McFarlanes Andesite, a sparsely porphyritic, two-pyroxene or olivine-two-pyroxene basaltic andesite to andesite, which is agate-bearing in places. The conglomerate, made up predominantly of well-rounded clasts of quartzite from the Inorunie Group, appears to overlie the Little Pocket Dacite, which is made up of porphyritic hornblende-biotite dacite lava and minor lava breccia.

The Awring Granodiorite, an irregularly shaped pluton, 4 km x 3 km, consists mostly of porphyritic hornblende-biotite granodiorite to tonalite, intruded by small stocks of monzonite and microgranite. It intrudes the Croydon Volcanic Group, Inorunie Group, and, possibly, the Linley Rhyolite, which is strongly altered adjacent to the pluton. The pluton is the site of a minor copper prospect, 'Mount Little' (Branch, 1960), and has been explored for copper by Pickands Mather & Co. International (Munro & Smith, 1968; Smith, 1969), Central Coast Exploration (O'Rourke, 1978), and West Coast Holdings, later Queensland Metals Corporation N.L. (Fawckner, 1984). Isotopic dating produced minimum ages

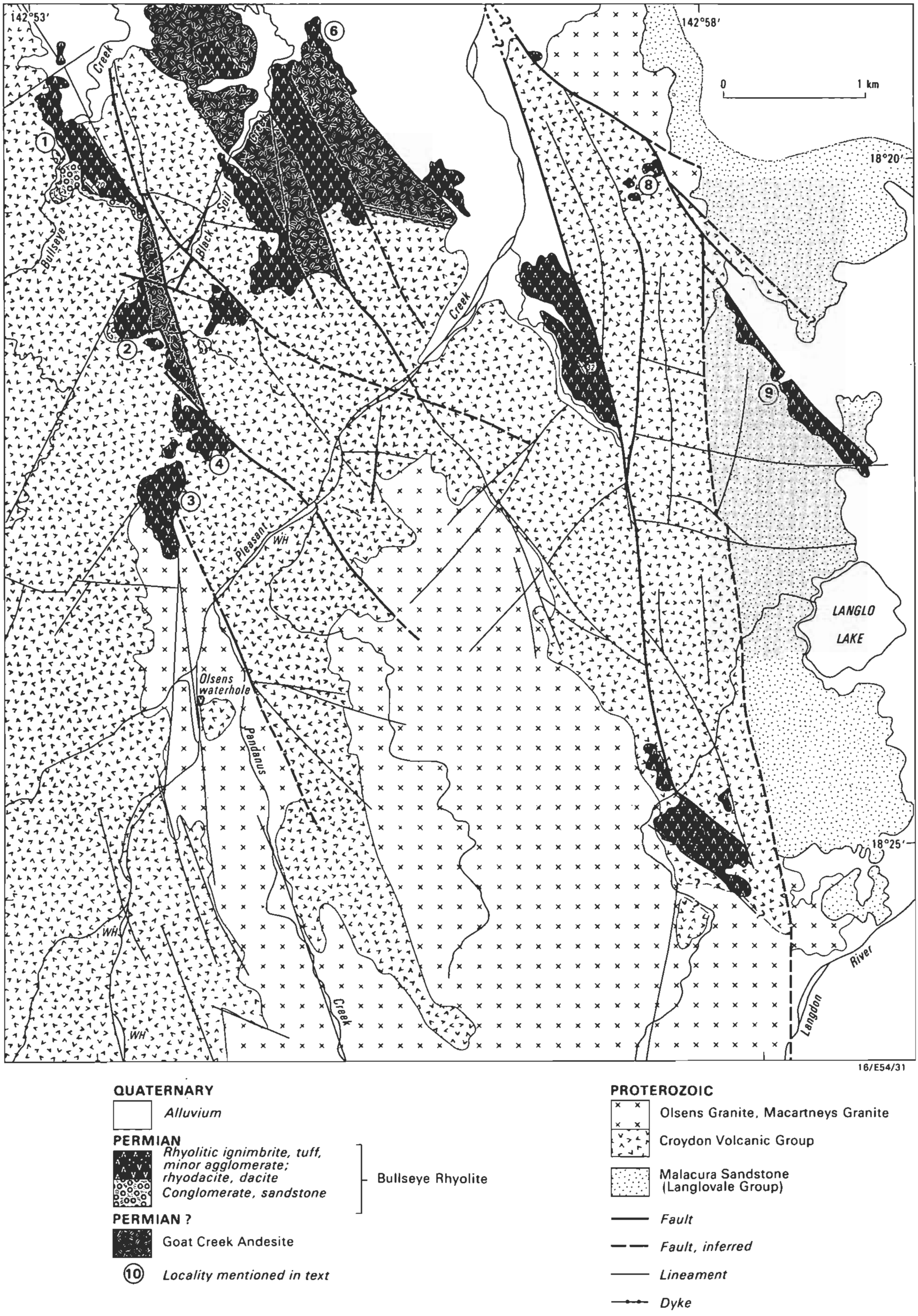

Figure 2. Geology of the Bullseye Creek area.

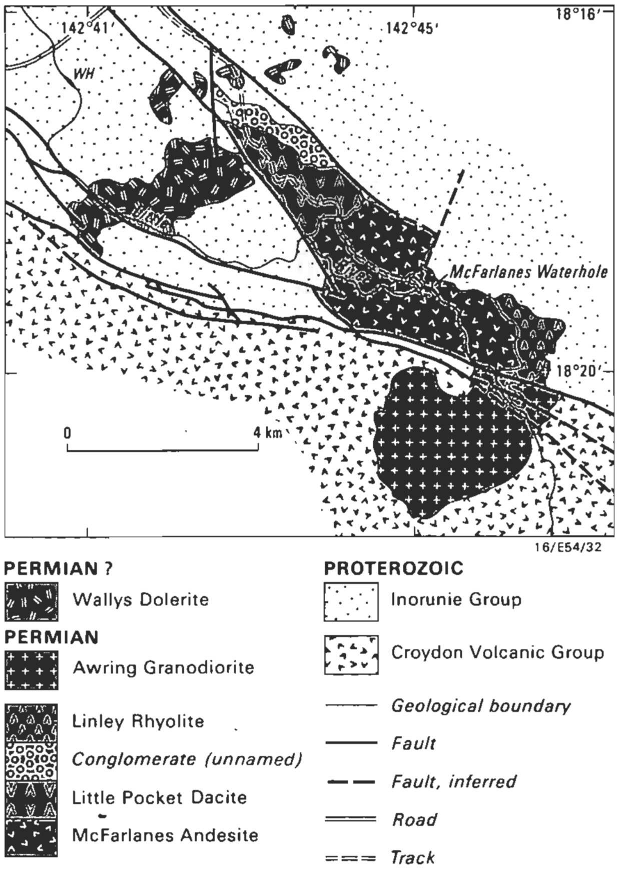

Figure 3. Geology of the Little Pocket area.

(see **Petrography** of about 275 Ma for the McFarlanes Andesite and about 280 Ma for the Awring Granodiorite (Table 1) (Australian Mineral Development Laboratories, unpublished report, GS 2558/83).

Wallys Dolerite

The Wallys Dolerite crops out as a number of small stocks, up to 3 km long and 1 km wide, intruding the Inorunie Group (but not the overlying Jurassic-Cretaceous sediments) in the Little Pocket area (Fig. 3); small dykes and stocks of identical dolerite crop out 75 km to the south, in the Yappar River area (Fig. 1), where they intrude the Croydon Volcanic Group and Esmeralda Granite. Isotopic dating has not been possible, because of uniformly very low K and Rb contents, but lack of deformation and metamorphism, distribution, and geological relations suggest that the Wallys Dolerite may be late Palaeozoic or early Mesozoic.

Carnes and Gongora Granodiorites

The Carnes and Gongora Granodiorites are sub-elliptical plutons emplaced into rocks of the Etheridge Group about 20 km and 40 km, respectively, southeast of the Bullseye Creek area (Fig. 1; Mackenzie, 1980). Both have contact-metamorphic aureoles about 200-250 m wide, and consist of medium, uneven-grained biotite granodiorite. The Gongora Granodiorite is richer in K-feldspar and slightly richer in biotite than the Carnes Granodiorite (which grades into tonalite), and is porphyritic in part. Both were considered to be of Proterozoic age by Mackenzie (1980), but recent Rb-Sr isotopic dating of the Gongora Granodiorite gave an age of 255 ± 11 Ma (Table 1).

Table 1. Isotopic age data
A. K-Ar

Sample	*K(wt%)*	*$^{40}Ar(\times 10^{-10} moles/g)$*	*$^{40}Ar^*/^{40}Ar_{total}$*	*Age($\times 10^6$yr) $\pm 1\sigma$*
McFarlanes Andesite				
80300800	2.480	12.788	0.959	275 ± 1
Awring Granodiorite				
80300811				
(biotite)	7.35 7.28	38.51	0.975	281 ± 3

Constants:
$^{40}K = 0.01167$ atom %; $\lambda_\beta = 4.962 \times 10^{-10} yr^{-1}$; $\lambda_\epsilon = 0.581 \times 10^{-10} yr^{-1}$

B. Rb/Sr

Sample	*Rb(ppm)*	*Sr(ppm)*	*Rb/Sr*	*$^{87}Rb/^{86}Sr$*	*$^{87}Sr/^{86}Sr$*
Awring Granodiorite					
80303070					
total rock	58	624	0.093	0.269	0.7154 ± 0.0001
biotite	723	14.2	50.89	150.7	0.9655 ± 0.0002
80300811					
total rock	80.6	590		0.3947	0.71676
biotite	341	14.0		72.19	0.9994
Gongora Granodiorite					
77300184					
total rock	85.8	444		0.5590	0.7163
biotite	459	9.39		148.8	1.2600
K-feldspar	259	274		2.735	0.7206
79300432					
total rock	75.2	465		0.4658	0.7162
biotite	446	13.0		102.9	1.0827

Constants:
$^{85}Rb/^{87}Rb = 2.600$; $^{87}Rb\lambda = 1.42 \times 10^{-11} yr^{-1}$; $^{88}Sr/^{86}Sr = 8.3752$

Ages: 80303070 is altered and gives a geologically unreasonable age.
80300811—total rock-biotite join gives an age of 276 ± 4 Ma.
77300184—total rock-biotite join gives an age of 258 Ma.
79300432—total rock-biotite join gives an age of 252 Ma.
Last two give Minimum Model 2 age of 255 ± 11 Ma, initial $^{87}Sr/^{86}Sr = 0.7144 \pm 0.0007$ for the Gongora Granodiorite.

* Source: AMDEL, Adelaide.

Petrography

Bullseye Rhyolite

The rhyolitic ignimbrite consists of 25-45 per cent crystals, mostly 0.5 to 4 mm across, of quartz, sanidine, plagioclase, and biotite (trace) in a very fine-grained, devitrified, originally glass shard-rich groundmass. Moderately abundant zircon and rare partly altered sphene are the principal accessory minerals. Pumice clasts are rare, but locally derived foreign rock clasts constitute up to 5 per cent of the rock in two outcrop areas (localities 7 & 10, Fig. 2). A 30-40 cm thick basal layer of the ignimbrite in one area (locality 2) is made up of 17 per cent crystals, up to 2 mm long, and rare clasts of quartzite, up to 1 cm across, in a very fine-grained, devitrified, originally glass shard-rich groundmass. Feldspar crystals, particularly plagioclase, and the groundmass of most rocks are partly to completely silicified, probably as a result of Tertiary deep weathering, which has produced widespread silcrete in the area (e.g. Smart & others, 1980).

The rhyodacite consists of sparse phenocrysts, up to 1.5 mm long, of plagioclase (An_{30})$\pm$biotite$\pm$rare quartz in a very fine-grained groundmass of sanidine, plagioclase, quartz, biotite (commonly chloritised), and opaque oxide. The dacite consists of scarce, (up to 1%) 1 mm long, altered hornblende phenocrysts in a very fine-grained groundmass of plagioclase, quartz, sanidine, chloritised biotite (7%), altered hornblende (1%), and opaque oxide; the hornblende has been altered to calcite and chlorite.

Goat Creek Andesite

The only specimens of Goat Creek Andesite sufficiently coherent to enable a thin section to be cut are fine-grained, aphanitic, highly altered (spilitised) basaltic andesite to basalt, containing interstitial glass, albitised plagioclase, chloritised pyroxene, 3-5 per cent quartz, and abundant secondary hematite and calcite.

Linley Rhyolite

The ignimbrite is moderately to poorly welded, and consists of 15-20 per cent crystals (0.5-4 mm) of quartz, sanidine, altered or silicified plagioclase, and minor biotite, in a fine-grained, devitrified and commonly silicified groundmass, originally composed mainly of glass shards. Sphene, much of which is partly altered, and zircon are abundant accessory minerals, commonly aggregated in rounded masses with quartz (after a mafic silicate mineral?) or with zircon crystals fringing a corroded sphene core. Locally derived foreign igneous rock clasts and pumice fragments constitute a few per cent of most specimens examined. At some localities, the ignimbrite is intensely altered, with bright green nontronite replacing glass and some feldspar, and partly silicifed.

The rhyolite contains about 25 per cent phenocrysts of quartz, sericitised feldspar, and chloritised biotite (1%) in a very fine-grained, sericitised groundmass.

Little Pocket Dacite

The Little Pocket Dacite consists of brownish-green to brown, moderately porphyritic hornblende-biotite dacite, made up of phenocrysts of plagioclase (7%, up to 6 mm), biotite (up to 2%, up to 2 mm), quartz (1%, 0.1-2 mm), and hornblende (trace, up to 2.5 mm) in a fine-grained groundmass containing up to 5 per cent chloritised biotite and abundant secondary hematite (after magnetite) and 'leucoxene', and a trace of calcite.

McFarlanes Andesite

The McFarlanes Andesite consists of sparse (up to 4%) phenocrysts (up to 6 mm) of plagioclase or orthopyroxene, or both and rare olivine in a very fine-grained groundmass of plagioclase, orthopyroxene and clinopyroxene, opaque oxides, and, in some rocks, up to 3 per cent quartz, 1-2 per cent sanidine, and a trace of biotite. Piemontite with quartz $\pm$ apatite $\pm$ chlorite and/or pumpellyite+alkali feldspar is present in one specimen, confined to relatively coarse-grained irregular patches, resembling incipient ocelli. Agate-filled amygdales are common in some areas, especially near McFarlanes Waterhole (Fig. 3).

Awring Granodiorite

The Awring Granodiorite consists mainly of abundantly porphyritic hornblende-biotite or biotite granodiorite to tonalite, made up of phenocrysts (up to 6-7 mm) of plagioclase, quartz, biotite, and scarce hornblende in a fine-grained groundmass of the same minerals plus K-feldspar, opaques (including up to 1% pyrite$\pm$up to 1% chalcopyrite$\pm$ rare arsenopyrite and maghemite in some specimens), and abundant accessory zircon and apatite. Feldspars are weakly to moderately sericitised, and biotite and hornblende are variably chloritised in most rocks; in others, biotite is strongly recrystallised, and fine-grained biotite$\pm$calcite forms pseudomorphs after hornblende.

A small plug of fine-grained porphyritic microadamellite or microgranodiorite near the centre of the pluton consists of phenocrysts of plagioclase (2-3%, up to 5 mm) and rare sanidine, and altered pyroxene (up to 3 mm) in a fine-grained groundmass of sanidine, plagioclase, quartz, hornblende (4%), biotite (3%),altered pyroxene (1%), opaque oxide (1%), and accessory zircon and apatite. Feldspars are partly sericitised, and the pyroxene—probably orthopyroxene—is replaced by chlorite or hornblende or both.

Wallys Dolerite

The Wallys Dolerite is fine to medium-grained, aphyric, and made up of partly sericitised plagioclase (An_{55-68}), augite (25%), pigeonite (10%), quartz (1-3%), magnetite (3-4%), up to 1 per cent of partly chloritised biotite fringing pyroxene grains, rare late-magmatic hornblende (after pyroxene), and accessory apatite.

Carnes and Gongora Granodiorites

The Carnes Granodiorite (to tonalite) contains about 60 per cent plagioclase, 25 per cent quartz, 6 per cent biotite, 4-8 per cent interstitial to poikilitic orthoclase, and trace amounts of secondary muscovite, chlorite, and sericite. The Gongora Granodiorite contains sparse plagioclase phenocrysts up to 8 mm long, 20-25 per cent orthoclase, 8-12 per cent biotite, and more abundant secondary chlorite and sericite, together with kaolinite and rare calcite and epidote.

Chemistry and chemical affinities

Major and trace-element, whole-rock analyses of selected specimens of the rock units described above are presented in Table 2.

The Awring Granodiorite has mineralogical and chemical characteristics typical of an I-type (Chappell & White, 1974) granitoid; it is similar to the Yataga Granodiorite, north-northeast of Georgetown (Fig. 1; R.D. Holmes, personal communication, 1984), and to the Bakerville Granodiorite near Herberton (Sheraton, 1974; Richards, 1980), both Permian I-types. The Little Pocket Dacite, which is mineralogically almost identical to the Awring Granodiorite,

Table 2. Chemical analyses of Permian igneous rocks.

Formation	*Wallys Dolerite*		*Goat Creek Andesite*		*McFarlanes Andesite*			*Little Pocket Dacite*	*Awring Granodiorite*	
Sample number	*80300186*	*80300166*	*80300810*	*80300809*	*80300808*	*80300801*	*80300800*	*79301019*	*80300806*	*80303070*
SiO_2	50.20	50.50	52.30	53.40	55.40	58.80	59.30	64.79	65.56	65.70
TiO_2	1.34	1.16	1.89	1.89	2.01	1.00	1.46	0.69	0.69	0.71
Al_2O_3	16.20	14.70	16.70	16.30	14.90	15.50	15.50	15.58	16.09	16.00
Fe_2O_3	1.21	0.99	3.64	4.91	2.43	1.06	3.87	3.15	0.55	1.17
FeO	9.39	9.19	5.14	4.01	6.66	5.38	3.25	0.76	3.21	3.01
MnO	0.17	0.17	0.16	0.12	0.14	0.15	0.13	0.05	0.03	0.05
MgO	5.85	7.85	3.67	4.13	4.22	4.27	2.82	2.10	1.65	1.66
CaO	11.10	11.40	2.88	2.73	6.23	6.15	5.53	3.03	3.66	4.54
Na_2O	2.14	1.84	2.98	2.21	3.01	3.55	3.16	3.52	3.39	4.00
K_2O	0.45	0.50	2.42	2.30	2.32	1.79	2.90	2.47	2.70	2.12
P_2O_5	0.09	0.07	0.77	0.73	0.82	0.14	0.54	0.18	0.20	0.18
H_2O+	1.18	1.19	3.83	3.95	0.83	1.27	0.78	1.49	0.93	0.79
H_2O-	0.16	< 0.01	2.89	3.53	1.02	0.49	0.70	0.83	0.16	0.13
CO_2	0.14	0.02	0.20	0.05	0.07	0.15	0.02	0.20	0.14	0.03
Rest	0.12	0.10	0.32	0.32	0.33	0.09	0.31	0.33	0.25	0.22
Total	99.74	99.68	99.79	100.58	100.39	99.79	100.27	99.17	99.21	100.31
Ba	90	120	1100	1200	1100	140	1050	1621	905	760
Li								9	12	
Rb	15	32	60	60	80	70	120	66	113	60
Sr	190	150	200	200	400	190	320	606	559	620
Pb		2	18	20	24	18	24	15	14	8
Th	4		14	16	14	8	20	8	7	8
U					4	4	4	2	3	4
Zr	80	65	620	600	540	120	490	167	158	170
Nb	12	8	34	32	32	12	28	7	6	12
Y	18	14	44	44	42	26	38	26	16	8
La			90	100	80		90	37	25	20
Ce		20	180	170	170	40	160	60	45	60
Nd		30	110	80	80	30	80	29	19	30
Sc	100	60	20	25	40	50	40	7	7	15
V	160	130	100	70	70		70	54	54	40
Cr								25	16	
Co								10	11	
Ni	20	20	40	35	25	25	10	3	2	
Cu	160	130	24	22	26	22	16	7	11	2
Zn								46	40	
Sn								<2	4	
W								<3	3	
Mo								<3	3	
Ga								22	23	
As								1	<1	
S	0.03	0.02	0.02		0.02	0.02	0.01	0.05	0.01	0.02

Analyses 80300186, 80300166, 80300810, 80300809, 80300808, 80300801, 80300800, and 80303070 by AMDEL, using X-ray fluorescence for all major elements except H_2O^+ H_2O^- and CO_2 (classical gravimetric methods), S, and all trace elements except Sc (spectrographic), V, Ni, and Cu (atomic absorption). All other analyses by J.G. Pyke and W. Pappas (BMR), using X-ray fluorescence for all major and trace elements except *loss on ignition (gravimetric), and Li, Cr, Co, Ni, Cu, and Zn (atomic absorption).

differs from it only in being more oxidised (higher Fe_2O_3/FeO), a little richer in MgO, and a little poorer in CaO. The Carnes and Gongora Granodiorites are also broadly similar in composition to the Awring Granodiorite, but are slightly more felsic (they lack hornblende), and slightly lower in La, Ce and Nd. Analyses of rocks from these four units plot in narrow, elongate clusters on major-element and some trace-element Harker variation diagrams (Figs 4 & 5), and, although the data are few, suggest that they may be genetically related to one another.

Rhyodacitic and dacitic lavas assigned to the Bullseye Rhyolite plot close to the 'trend' defined by the granodiorites and the Little Pocket Dacite, but they appear to be consistently and significantly lower in TiO_2, Fe_{total}, CaO, Sr, Zr, and Nb. Rhyolitic ignimbrites of the Bullseye Rhyolite and, to a lesser degree, the Linley Rhyolite have been variably enriched in K_2O and SiO_2, and depleted in Na_2O, CaO(?), Al_2O_3, and Sr by post-depositional surface processes. They retain a gross similarity to one another, but the data do not show a genetic link; rather, the trace-element data, particularly Zr and Nb, suggest that the ignimbrites are unrelated to one another. Both ignimbrites are, however, enriched in Ba, Rb, Zr, Nb, Y, La, Ce, and Nd. These characteristics and the high K_2O/Na_2O ratios distinguish the felsic ignimbrites from all the other Permian rocks, and strongly suggest that there is no direct genetic connection between them. Such chemical characteristics are similar to those of A-type rocks derived from sources depleted in low-temperature melting fraction (Loiselle & Wones, 1979; Collins & others, 1982).

The andesitic to basaltic rocks (50-60% SiO_2) show a broad range of composition, particularly in trace elements. On the Zr-SiO_2 plot, for example, the Goat Creek Andesite and two of the McFarlanes Andesite samples (0800, 0808) fall on the same trend, at much higher values than the Wallys Dolerite and Black Soil Andesite (discussed below). This separation is also evident with respect to several other elements, and indicates that, while the Goat Creek Andesite and McFarlanes Andesite (samples 0800, 0808) may be genetically related to one another, they are not related to the other mafic rocks. Figure 4 also indicates that the more mafic rocks are genetically unrelated to the more felsic ($SiO_2 > 64\%$) rocks: in particular, general trends of the two groups are completely separate on the Sr-SiO_2 plot. The Harker diagrams also show that one of the McFarlanes Andesite samples (0801) is consistently different to the other two (lower TiO_2, Fe_{total}, K_2O, P_2O_5, Ba, Rb, Sr, Zr, Nb, Y; higher MgO, CaO, Na_2O), and, therefore is probably not genetically related to them; an inconclusive K-Ar isotopic age of 191±1 Ma (Australian

Table 2. (continued)

Formation	*Awring Granodiorite*			*Gongora Granodiorite*	*Carnes Granodiorite*	*Bullseye Rhyolite*				*Linley Rhyolite*
Sample number	*80300034*	*80300789*	*80300038*	*77300432*	*77300001*	*79301026*	*80300065*	*80300061*	*80300053*	*80300040*
SiO_2	65.78	66.00	66.19	68.76	70.19	68.03	72.40	72.82	77.80	77.57
TiO_2	0.70	0.70	0.66	0.51	0.36	0.27	0.08	0.10	0.26	0.19
Al_2O_3	16.35	16.06	16.23	15.34	15.83	16.69	15.02	14.96	10.94	11.71
Fe_2O_3	1.79	0.45	0.60	0.31	0.18	0.62	0.52	0.54	0.11	0.71
FeO	1.81	2.70	2.87	2.17	1.95	1.12	0.10	0.09	0.09	0.15
MnO	0.02	0.01	0.03	0.02	0.02	0.01	<0.01	<0.01	<0.01	0.01
MgO	1.64	1.73	1.64	1.14	0.86	1.03	0.26	0.35	0.03	0.05
CaO	4.26	3.51	3.54	3.17	2.79	2.04	0.33	0.19	0.07	0.17
Na_2O	3.77	3.82	3.73	3.70	4.23	5.74	5.09	4.54	0.36	1.37
K_2O	2.32	2.58	2.55	2.98	2.48	2.23	3.31	3.07	8.58	5.86
P_2O_5	0.19	0.19	0.18	0.12	0.12	0.08	0.01	0.01	0.03	0.12
H_2O+	0.48	0.93	1.22	0.52	0.54	1.41	0.97	1.34	0.61	1.45
H_2O-	0.21	0.13	0.13	0.10	0.10	0.41	0.75	1.41	0.20	0.33
CO_2	0.02	0.13	0.03	0.07	0.11	0.07	0.14	0.04	0.02	0.05
Rest	0.22	0.24	0.24	0.21	0.18	0.17	0.17	0.13	0.24	0.46
Total	99.56	99.18	99.84	99.12	99.94	99.92	99.15	99.59	99.34	100.20
Ba	702	866	797	729	594	564	759	675	1036	1816
Li	13	14	10	11	12	31	23	10	11	14
Rb	62	68	81	87	74	82	162	112	289	178
Sr	634	621	615	526	477	423	304	149	38	41
Pb	11	11	13	11	17	20	15	21	10	32
Th	8	8	9	11	6	5	1	2	22	24
U	2	3	4	2	2	2	2	1	4	9
Zr	131	141	141	146	135	100	51	64	257	309
Nb	6	7	7	7	5	3	2	<2	12	16
Y	14	11	15	11	9	5	38	<1	47	136
La	30	27	28	23	20	9	<2	4	88	391
Ce	58	52	54	43	35	21	3	11	78	613
Nd	26	24	26	20	16	9	<3	3	90	278
Sc	7	7	6	6	5	3	<2	<2	4	<2
V	48	55	55	34	22	17	3	3	7	5
Cr	17	15	18	12	7	7	<2	<2	6	<2
Co	8	10	10	9	5	3	4	4	3	6
Ni	3	5	3	4	<2	<2	3	3	2	3
Cu	4	30	10	2	<2	6	3	<2	2	5
Zn	44	38	46	30	29	47	55	32	15	54
Sn	3	6	5	<2	<2	<2	<2	<2	5	<2
W	3	4	3	3	<3	4	<3	<3	10	9
Mo	<3	3	<3	<3	<3	<3	<3	<3	<3	<3
Ga	21	20	20	20	19	19	21	18	12	14
As	1	1	1	1	<1	1	1	<1	2	1
S	0.06	0.1	0.01	0.01					0.01	0.04

Mineral Development Laboratories, unpublished report GS2558/83) indicates that it may also be significantly younger, although field relations give no hint of them. The Goat Creek Andesite differs from the McFarlanes Andesite (samples 0800, 0808) in being relatively poorer in CaO and Sr, and richer in K/Rb and Rb/Sr. Most of the differences between the two may be accounted for by the more altered state of the former, and they may therefore be genetically related to one another. Both resemble fractionated magmas of the hawaiite–mugearite type derived from enriched mantle sources typical of many intraplate continental regions (e.g. Basaltic Volcanism Study Project, 1981).

The Wallys Dolerite is chemically quite distinct from the other mafic rocks; it has relatively higher MgO, and, in particular, CaO, lower Na_2O, and much lower K_2O and P_2O_5; it is also much higher in Sc, V, and Cu, and lower in Ba, Rb, Sr, Zr, Nb, and Y. It has the mineralogical and chemical characteristics of a continental tholeiite, and is comparable, for example, to some of the Tasmanian and Antarctic Jurassic dolerites (McDougall, 1962; Juckes, 1968; Faure & others, 1972), some Karoo basalts (e.g. Walker & Poldervaart, 1949; Cox & others, 1967; Cox, 1972), some of the Palisades dolerites (Walker, 1969), and some rift-related tholeiites from the continental margin of southeastern Brazil (Fodor & Vetter, 1984). Its age and relations to the other rocks in the area are unknown, and the writer is not aware of any similar rocks elsewhere in northeastern Queensland.

Comparisons with the Agate Creek Volcanic Group

Very few chemical analyses of the Permian volcanic rocks from the Agate Creek area (Fig. 1) are available. Those that are (Branch, 1966; Sheraton, 1974; B.S. Oversby, personal communication, 1984) suggest that the rocks are broadly comparable with those from the Bullseye Creek and Little Pocket areas. However, the Black Soil Andesite is significantly different in alkalis and most trace elements to the McFarlanes and Goat Creek Andesites and the Wallys Dolerite and, on these data, is genetically unrelated to them. The more felsic rocks (Big Surprise Tuff and Talaveras Rhyolite*) differ in composition from what would be expected if they were genetically related to the rhyodacitic to rhyolitic lavas of the Bullseye Rhyolite in a number of respects, including higher Zr, Nb, Y (Fig. 4), Rb, Ba, and K/Na, slightly higher TiO_2 (Fig. 4), and lower Na_2O. The Talaveras Rhyolite is, in addition, relatively high in Fe_{total}, Mg, Ca, and Sr.

Comparison with Carboniferous volcanic and intrusive rocks

Analyses of Carboniferous igneous rocks from the Newcastle Range Volcanic Group and Cumberland Range area (Branch, 1966; Sheraton, 1974; B.S. Oversby, personal communication,

* The Talaveras Rhyolite, along with an outlier of Black Soil Andesite, crops out in a small area 12 km southeast of the main Agate Creek area (Fig. 1).

Table 2. (continued)

		Agate Creek Group					
Formation	*Linley Rhyolite*	*Black Soil Andesite*			*Big Surprise Tuff*		*Talaveras Rhyolite*
Sample number	*79301022*	*81304556*	*81304555*	*68590027*	*81304553*	*81304554*	*81304552*
SiO_2	78.85	51.43	52.44	59.00	74.06	75.42	77.31
TiO_2	0.17	2.00	1.86	1.55	0.2	0.15	0.17
Al_2O_3	11.89	15.61	15.31	13.07	13.38	13.89	13.15
Fe_2O_3	0.06	3.02	3.06	7.56	0.78	0.41	1.82
FeO	0.12	6.86	6.48	0.56	0.10	0.12	0.10
MnO	0.01	0.15	0.15	0.06	0.01	0.02	0.03
MgO	0.02	5.23	4.02	3.14	0.17	0.10	0.66
CaO	0.19	8.10	7.47	1.05	0.37	0.37	0.71
Na_2O	1.86	3.33	3.53	0.23	1.33	2.24	1.90
K_2O	5.35	1.32	1.59	9.10	7.48	5.79	4.06
P_2O_5	0.02	0.37	0.38	0.53	0.03	0.02	0.04
H_2O+	1.32						
H_2O-	0.28	2.60*	3.68*	3.44*	1.49*	1.53*	3.62*
CO_2	0.04						
Rest	0.16	0.29	0.29	0.39	0.20	0.22	0.19
Total	100.33	100.31	100.26	99.68	99.60	100.28	103.76
Ba	448	625	692	2235	881	1147	949
Li	14	4	7	10	9	10	10
Rb	163	203	156	286	229	221	188
Sr	24	610	582	48	119	121	134
Pb	23	34	32	7	20	50	23
Th	28	21	29	10	38	31	29
U	4	5	<1		6	3	3
Zr	331	232	250	388	140	114	93
Nb	16	7	7		9	11	9
Y	33	22	10	32	35	17	32
La	56	42	46	56	39	26	29
Ce	104	86	95	106	75	46	47
Nd	46						
Sc	<2	25	26		6	3	<3
V	4	186	202		20	15	11
Cr	3	33	29		8	5	4
Co	2	36	32	24	6	5	5
Ni	2	28	25	44	4	3	2
Cu	4	14	15	9	5	5	3
Zn	10	92	89	98	43	25	30
Sn	<2	<2	<2		2	2	2
W	5	3	<3		3	4	<3
Mo	<3	3	3		<3	<3	<3
Ga	19	14	13	15	13	17	15
As	<1	3	10		<1	<1	1
S							

1984), and from the Maureen Volcanic Group (all shown in Fig. 1) are compared with those of the Permian igneous rocks in Figure 5.

The most immediately apparent difference between the Carboniferous and Permian is the much larger volume of dominantly felsic ignimbrites in the Carboniferous and the greater proportion of more mafic rocks in the Permian. Major-element compositions of the Carboniferous and Permian rocks are generally similar, but there are a number of significant differences in detail. Most of the intermediate to silicic Carboniferous rocks are lower in Al_2O_3 and higher in total Fe than the equivalent Permian rocks. Amongst these, a group of intermediate SiO_2 (61-67%) Carboniferous rocks also characterised by relatively high K_2O appears to be genetically related by crystal fractionation to lower-SiO_2 (53-59%) Carboniferous rocks, on the basis of linear trends on the K_2O, Rb, Y, and, in particular, the Zr Harker plots (Fig. 5). The Zr plot also highlights differences in the more mafic rocks (50-60% SiO_2), indicating that the Carboniferous rocks are genetically unrelated to the Permian rocks; similar differences are apparent in P_2O_5, Ba, and Sr contents (Table 2). A group of Carboniferous rocks with 67-71 per cent SiO_2 and distinctively low Fe_{total}, Zr, and Y contents is discussed below. The most felsic Carboniferous rocks ($SiO_2 > 71\%$) are poorer, for example, in K_2O, Rb, and Zr (and also richer in CaO; Table 2) than would be expected if they were fractionated from the more mafic Carboniferous rocks, to which they are probably genetically unrelated.

Analyses of intrusive rocks from the Cumberland Range area (Fig. 1; Sheraton, 1974; Sheraton & Labonne, 1978) plot on the Zr-SiO_2 diagram, and most other variation diagrams, close to the Permian granodiorites. In many plots, notably Zr-SiO_2 and Y-SiO_2, these analyses are well separated from those of all the other Carboniferous rocks considered here. The analysed Cumberland Range intrusive rocks include rocks assigned to the Mount Sircom Microgranodiorite (Mackenzie, 1980), and to the Mount Darcy Microgranodiorite (Mackenzie, 1980), one sample of which produced a Permian date (L.P. Black, personal communication, 1984). Dating of alteration related to petrographically similar rocks at Mount Turner, 15 km to the northeast (Fig. 1) also gave a Permian age (L.P. Black, personal communication 1984). The composition of the analysed rocks also suggests that they may be Permian rather than Carboniferous.

Initial $^{87}Sr/^{86}Sr$ ratios of the Carboniferous rhyolitic to dacitic rocks range between 0.710 and 0.726 (L.P. Black & R.D. Holmes, personal communication, 1984), and the few data available from the Permian granodiorites range from 0.7143 and 0.7153, indicating that both suites of rocks are derived largely from highly evolved (old) crustal rocks, such as the Proterozoic rocks that make up much of the Georgetown Inlier. Initial ratios from the Carboniferous mafic rocks (0.707-0.712) indicate that they could represent mantle-derived magmas variably affected by crustal

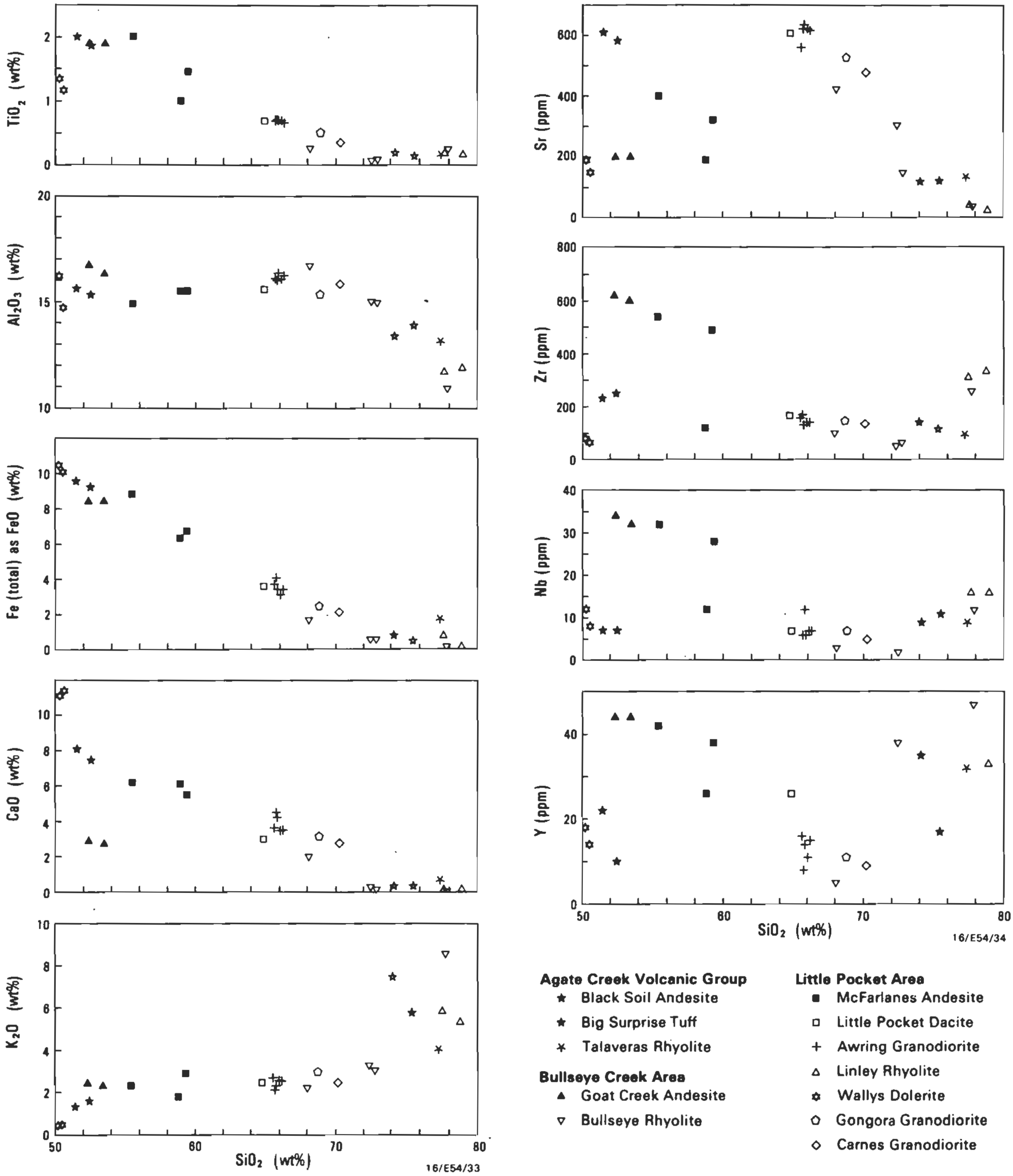

Figure 4. Harker variation diagrams for selected major (A) and trace (B) elements in the Permian igneous rocks.

contamination (L.P. Black & R.D. Holmes, personal communication 1984).

Discussion

Petrogenesis

On the basis of the data summarised above, the Permian igneous rocks of the western Georgetown Inlier, despite some gross similarities, appear to be as diverse in source composition as they are dispersed geographically. The basaltic to andesitic rocks (Goat Creek Andesite, McFarlanes Andesite, Black Soil Andesite) do not appear, from these data, to be directly genetically related to one another (with the possible exception of the first two) or to the more felsic rocks (Little Pocket Dacite, Awring Granodiorite, Linley Rhyolite, and Bullseye Rhyolite). There is also little evidence of a genetic link between the intermediate rocks (dacite, granodiorite, and rhyodacite) and the most felsic ignimbrites, and the two ignimbrites may be unrelated to one another.

A possible explanation for the unusual trace-element composition of the felsic ignimbrites is concentration of the accessory minerals zircon and sphene, which are abundant in these rocks, perhaps by winnowing during transport and deposition (Sparks & Walker, 1977); there is an inverse correlation between size/abundance of crystals, and content

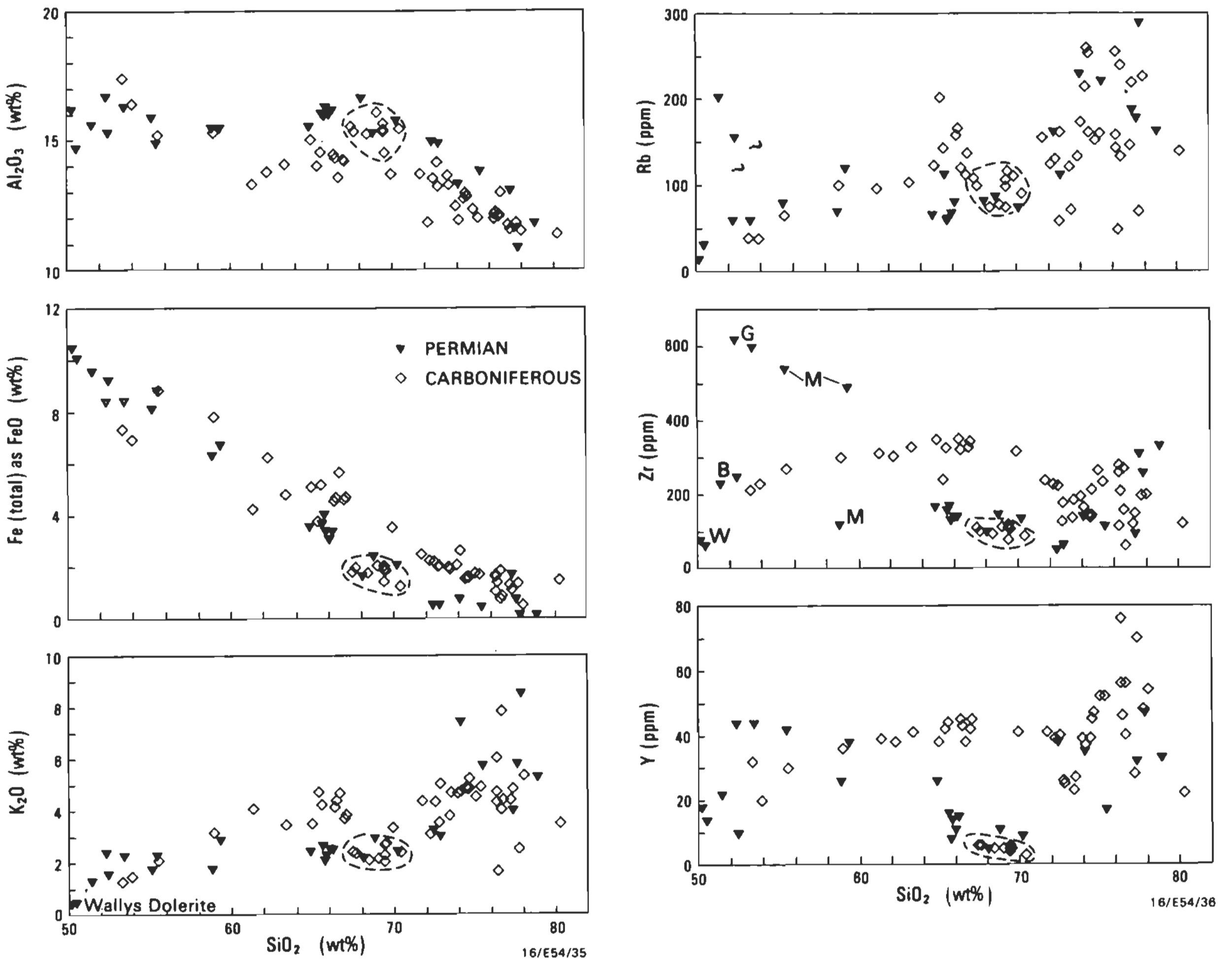

Figure 5. Harker variation diagrams for selected major (A) and trace (B) elements, comparing Permian with Carboniferous rocks. Broken line encloses intrusive rocks from the Cumberland Range area. On Zr plot, arrow indicates possible fractionation trend; and G—Goat Creek Andesite, M—McFarlanes Andesite, B—Black Soil andesite, W—Wallys Dolerite.

of Zr, Y, La, Ce, and Nd. Alternatively, the abundant zircon and sphene, and high contents of Zr, etc. may be primary features of a melt fraction derived from a crystallising magma with the composition of, say, the Awring Granodiorite. A third alternative is that the felsic ignimbrites were derived from a source different to that which produced the intermediate magmas, one with depleted, or A-type, characteristics. There are insufficient data to discriminate between these alternative explanations, and the first and last are not mutually exclusive.

The Wallys Dolerite is genetically unrelated to the igneous rocks of known Permian age in the Georgetown Inlier. Its composition is broadly similar to some high-volume continental tholeiites, but it also has features, such as relative depletion in incompatible elements, similar to some rocks classified as oceanic tholeiites; its origin, age, and tectonic significance remain conjectural.

The Carboniferous igneous rocks, although broadly similar in composition to the Permian rocks, differ from them in a number of details, implying that source compositions for (1) the basaltic andesites and dacites (53-67% SiO_2), (2) a group of intrusive rocks from the Cumberland Range area (67.5-70.5% SiO_2), and, possibly, (3) the felsic ignimbrites and rhyolites are different from one another and from their Permian equivalents. The Permian felsic ignimbrites are more enriched in Zr, Nb, and light rare earths than their Carboniferous counterparts, perhaps reflecting sampling bias, or, more likely, derivation of the Permian magmas from sources relatively more depleted in a low-temperature melting fraction (A-type). It is suggested that, in both the Carboniferous and the Permian, the most mafic rocks may have been derived from basaltic magmas of mantle origin that underplated the crust in this region and provided the heat source for partial melting of a variety of crustal rocks to produce the intermediate to felsic magmas. The present data provide evidence of fractionation of the Carboniferous rocks to dacitic compositions, but little or no conclusive evidence of mixing between these magmas and the more felsic, anatectic magmas.

Tectonic significance

The Carnes and Gongora Granodiorites and the Agate Creek Volcanic Group crop out along a major northwest-trending fault structure that incorporates the Robertson Fault and also passes through the Bullseye Creek area (Fig. 1); the Little Pocket area is to the west of this structure, but is also cut by several northwest-trending faults (Figs 1 & 3). Rhyolitic volcanic and intrusive rocks of the Bald Mountain area (Fig. 1) are also located on the fault structure, but isotopic age and geochemical data were not available at the time of writing. The fault structure is a long-lived feature, active in the late Palaeozoic and the locus of substantial but variable vertical movements in the late Mesozoic, but its full extent to the northwest and southeast is unknown.

The reason for such a concentration of Permian magmatism along this northwest-trending structure is uncertain, but it is consistent with the hypothesis that the more voluminous, felsic ignimbrite-dominated Carboniferous magmatism in the Georgetown Inlier is related to east-west tensional stress and major north-south-oriented sag-type cauldron structures fractures, and dykes, while the less voluminous, more mafic and diffuse Permian magmatism is related to northwest-trending dykes and fractures, and possible northeast-southwest tension (Mackenzie & Oversby, 1983; Oversby, 1983). The Permian Yataga Granodiorite is located at the intersection of the north-trending Delaney Fault and an east-west fault system that also partly controlled Carboniferous volcanism in the Maureen area (Fig. 1). The Agate Creek volcanics are also located at the intersection of two major fault systems (Delaney and Robertson Faults), and the Bullseye Rhyolite is located near the intersection of the northwest-trending structure and a major north-south fault system of unknown age that forms the eastern boundary of the Croydon Volcanic Group. However, the north-trending faults, like the east-west Maureen fault, are pre-Permian structures that were probably reactivated and/or intruded by magma in the Permian. It is also significant that the rocks discussed here are the westernmost known expressions of both Permian and Carboniferous magmatism in the region and, therefore, any differences between the two groups cannot be attributed to one being sampled from nearer its province margin than the other.

The foregoing observations suggest that tectonic style and the nature of Permian and Carboniferous magmatism in the region are strongly interrelated. This relationship may have operated in the following manner. In the Permian, brittle deformation in response to northeast-southwest tension produced widely spaced, penetrative faults, and was accompanied by relatively small-scale emplacement into the crust of mantle-derived mafic magmas, which found relatively easy access to the surface via the faults. This might be expected to have limited the opportunity for crustal anatexis and production of intermediate to felsic magmas. Magmatism in the Carboniferous was much more extensive and voluminous, reflecting a relatively much larger volume of mantle-derived mafic magma emplaced into (or underplating) the lower crust. The consequent greater heat input might have led to deformation in response to the prevailing east-west tension being more ductile in style in the deeper crust, resulting in numerous, shallow faults with a predominant north-south trend, and less opportunity for mafic magmas to penetrate the upper crust. Under such circumstances, deeper crustal melting to produce anatectic magmas should have been much more extensive than in the Permian, and the resulting larger(?) plutons, along with any overlying sag-type cauldron-collapse structures, would have tended to be north--south elongated or aligned and accompanied by further shallow fractures and dykes. The greater heat flux might also have caused partial melting of a greater volume of shallower level, more hydrous rocks, less likely to have been depleted in low-temperature melting fraction than in the Permian episode, and resulting in more voluminous explosive felsic volcanism.

Current interpretations of the broad-scale tectonic evolution of eastern Australia (e.g. Evans & Roberts, 1979; Powell, 1984) hinge on north-south compression during the Carboniferous and Permian; Evans & Roberts' (1979) interpretation includes north-south tensional fractures in the Late Carboniferous and northwest-trending strike-slip faults in the Early Permian. The model outlined above does not appear to conflict with these interpretations or with interpretations of the regional tectonic-magmatic history (e.g. Oversby & others, 1980; Mackenzie & Oversby, 1983). However, the model remains speculative and is based on preliminary work; further work is in progress or planned, to test and develop it.

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Coronation Hill U-Au mine, South Alligator Valley, Northern Territory: an epigenetic sandstone-type deposit hosted by debris-flow conglomerate

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Host rocks to the Coronation Hill U-Au mine have long been regarded as agglomerate occupying a volcanic vent, and, as such, the deposit has been regarded as volcanogenic and radically different from the other U-Au stratabound, unconformity-related deposits of the South Alligator Valley district. The 'agglomerate' is reinterpreted as a polymictic debris-flow conglomerate, consisting of rounded to angular clasts of quartz, quartzite, sandstone, carbonaceous shale, rhyolite, and volcaniclastics in a greywacke matrix. Its development was unrelated to volcanism. The deposit lies on the flank of a basinal conglomerate-sandstone-volcanic succession (Coronation Sandstone of the late Early Proterozoic El Sherana Group) that is unconformable on carbonaceous shale (Early Proterozoic Koolpin Formation). The ore surrounds an intensely faulted wedge-shaped area of conglomerate, altered volcanics, and carbonaceous schist. Uranium mineralisation is classified as epigenetic sandstone type, with uranium-enriched felsic volcanics as the source rock, sandstone beds as conduit rocks, and the carbonaceous schist, either as fault wedges or as clasts in the conglomerate, acting as reductant. In other deposits of the region, precipitation took place within in-situ carbonaceous shale faulted against the conduit sandstone. Intense chlorite alteration in the volcanics is unrelated to uranium mineralisation, but may be related to the gold mineralisation, which in places forms ore shoots that are separate from uranium ore and pass into the altered volcanics.

Introduction

The Coronation Hill mine is one of thirteen uranium-gold mines of the South Alligator Valley district, about 220 km southeast of Darwin in the Northern Territory (Fig. 1; Crohn, 1968; Crick & others, 1980). The deposits were discovered and operated from the mid 1950s to early 1960s. The ore consisted mainly of massive, vein-like, and disseminated pitchblende in carbonaceous shale and chert-banded siltstone in Early Proterozoic sediments (Koolpin Formation) of the Pine Creek Geosyncline. Lesser secondary uranium mineralisation occurred in sandstone and minor rhyolite and tuff (Coronation Sandstone, Pul Pul Rhyolite) of the late Early Proterozoic sequence, which is dominated by felsic volcanics and volcaniclastics (Needham & Stuart-Smith, 1985). This sequence separates deformed and metamorphosed metasediments of the Pine Creek Geosyncline from undeformed platform cover sediments (mainly sandstones) of the Middle Proterozoic McArthur Basin sequence further east, and is itself only mildly deformed.

The orebodies are mainly located on or near faulted contacts between Koolpin Formation and Coronation Sandstone or Pul Pul Rhyolite. Most workers favour ore genesis models that involve leaching of uranium from the felsic volcanics, movement of the uraniferous fluid along faults, and precipitation of uranium in carbonaceous and/or pyritic shale (Ayres & Eadington, 1975; Foy, 1975; Donnelly & Ferguson, 1980; Crick & others, 1980). However, the setting of the Coronation Hill mine is unlike that of the other deposits. It has been described by many workers as a volcanic vent, which would demand a significantly different model of ore genesis to that accepted for the other deposits of the district. This, and the rarity of uranium concentration in volcanic vents generally, led us to re-examine the geology of the Coronation Hill mine.

The study was conducted mostly before the discovery of the disseminated fine gold and platinum group elements (PGE) deposit in 1985 by a joint venture involving BHP Minerals, Noranda Australia and EZ, and therefore does not incorporate any data from that work. An outline of the geology of the gold body is given in the Noranda Pacific Ltd prospectus dated 27 June 1985. The gold is non-visible and finely disseminated in altered (quartz-sericite-minor chlorite) felsic volcanics of the Coronation Sandstone immediately east of the uranium-gold mine open cut.

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Previous investigations

Early development of the Coronation Hill mine was described by Allen (1954) & Gardner (1955). They described the host sequence as east-southeast-trending, generally south-dipping, altered volcanics, volcaniclastics, sandstone, and a polymictic sandstone-matrix conglomerate. Following mining in 1961-1962, Shepherd (1967) mapped the pit and outlined an area of 'highly fragmental agglomerate' occupying a 'volcanic fissure' about 20 m wide, trending roughly northeast across the east-southeast-trending sequence, and which hosted most of the ore. Subsequently, many authors of review papers of the district have unquestioningly described the host rock as volcanic breccia, and have embraced the volcanic vent concept, so that, by implication, a magmatic origin for the deposit has generally become the preferred model. Walpole & others (1968) nominated Pul Pul Hill and a site about 6.5 km east-southeast of Coronation Hill as additional volcanic vents. In 1976, a 201 m inclined hole was drilled beneath the mine workings by Noranda Australia Ltd to test for extensions of uranium mineralisation at depth (Coronation Hill diamond-drillhole CH3).

Whilst mapping the South Alligator Valley district as part of a 1:100 000-scale mapping project (Stuart-Smith & others, 1983), we paid particular attention to areas of suggested volcanic eruption, but could find no firm evidence that any of these sites were volcanic centres. Pul Pul Hill, like Coronation Hill, consists in part of rhyolite and polymictic conglomeratic breccia. The site 6.5 km east-southeast of Coronation Hill lies within granite; the location intended by Walpole & others is probably 1.4 km east of Coronation Hill, as shown on the 1 inch to 1 mile 'Geological map of the South Alligator River Valley' which accompanies their report. Here, rhyolite crops out, similar to that at Coronation Hill and Pul Pul Hill.

The only other evidence besides 'volcanic breccia' cited for volcanic vents in the district is from Shepherd (1960), who described 'horizontally disposed columnar jointing at Coronation Hill and Pul Pul . . . suggesting that vertical fissures in these two localities may have been the centres for lava extrusion'.

Geology of the Coronation Hill area

The area around the Coronation Hill mine (Fig. 2) consists of gently folded interbedded volcanics and sediments of the Coronation Sandstone (late Early Proterozoic El Sherana Group) resting unconformably upon tightly folded carbonaceous and ferruginous chert-banded siltstone and

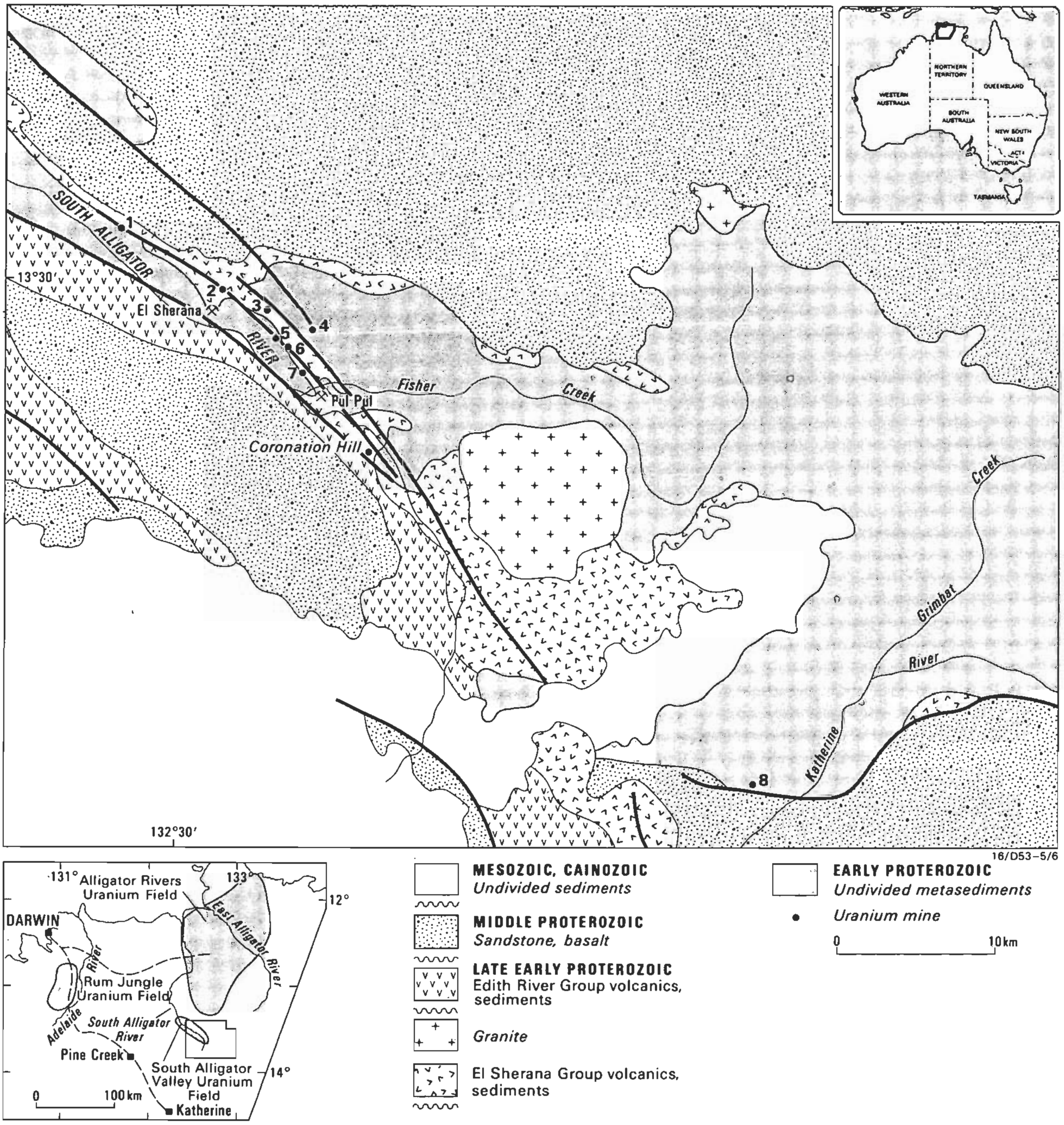

Figure 1. Coronation Hill mine location and regional geology.
1—Rockhole mine; 2—El Sherana, El Sherana West mines; 3—Koolpin mine; 4—Scinto VI mine; 5—Scinto V mine; 6—Palette, Skull mines; 7—Saddle Ridge mine; 8—Sleisbeck mine.

shale of the Koolpin Formation (Early Proterozoic South Alligator Group). During the hiatus which separated the Koolpin Formation and the Coronation Sandstone, a hematitic siliceous regolithic breccia was developed on and near exposed interbeds of stromatolitic carbonate within the Koolpin Formation. The top of Coronation Hill consists of this breccia (Scinto Breccia, El Sherana Group), which has partly slumped to rest in places on the younger Coronation Sandstone.

Units of the Coronation Sandstone define a basinal structure around Coronation Hill. The lowest unit (poorly sorted pebbly arkosic sandstone exposed near the banks of the South Alligator River) forms lenses up to about 70 m thick. Interbedded volcanics and volcaniclastics, including rhyolite, tuff, argillite, and shale, constitute the middle unit and overlie the sandstone apparently conformably. Dips are commonly erratic, suggesting syndepositional slumping, and flow layering in the autobrecciated, pale pink, finely porphyritic and commonly massive rhyolite is similarly unpredictable. Locally, south of the mine, this unit can be divided into an upper sequence about 50 m thick of rhyolite and minor tuff above about 100 m of interbedded tuff, argillite, siltstone, and rhyolite. Unpublished maps by United Uranium N.L. dated 1970 (geologist J. Harrison) suggest the presence of a distinctive green argillite about 50 m thick with minor tuff at the top of the interbedded sequence.

Black, highly chloritised, carbonate and quartz-veined massive rock with chloritised lath-shaped phenocrysts, probably of mafic composition originally, is present in mullock around the portal of the 900′ level adit. It may

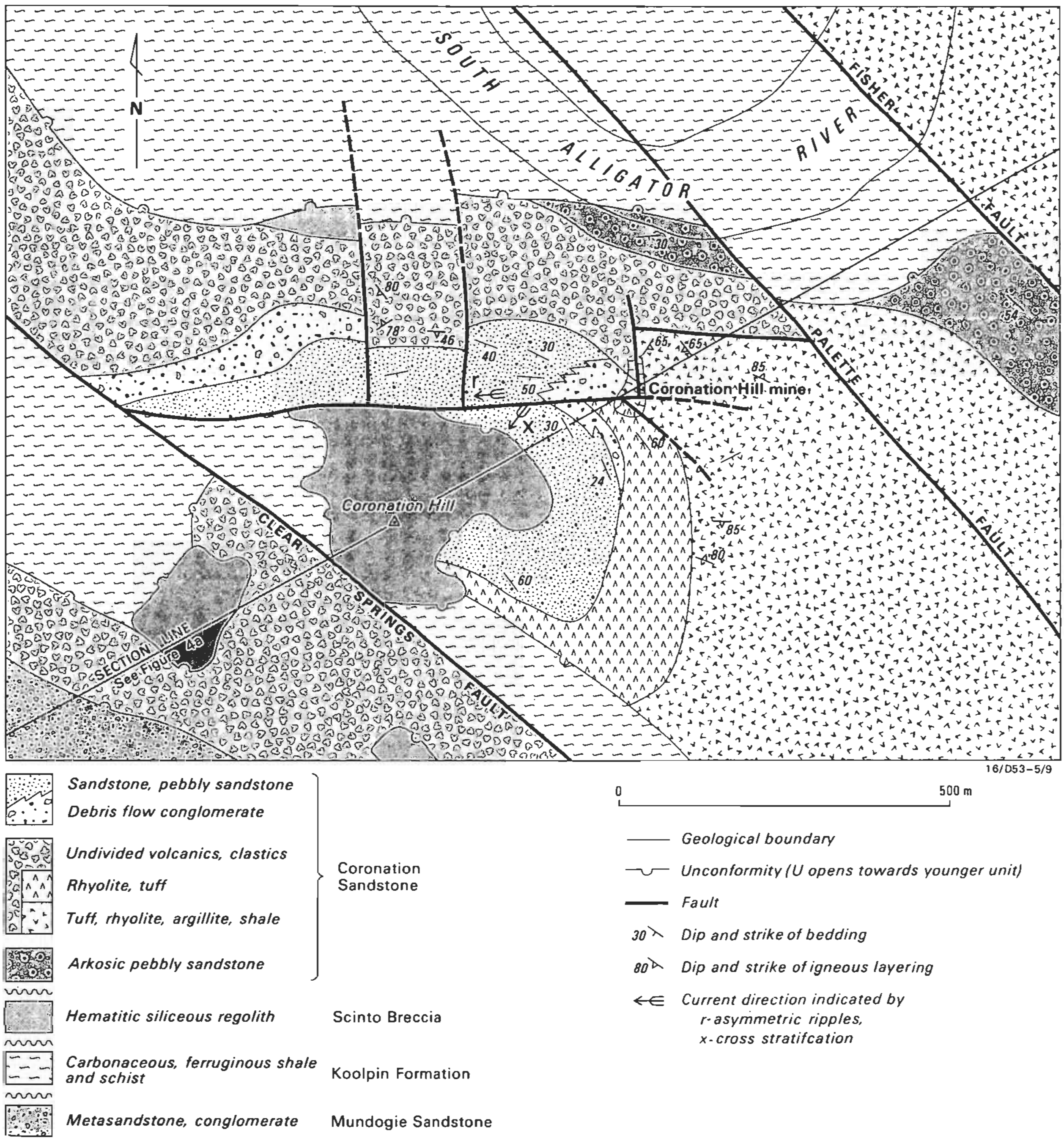

Figure 2. Geology of the area around Coronation Hill.
For explanation of symbols see Figure 9.

represent volcanics more mafic than the rhyolite, and is probably the same rock as that referred to as dacite (a 5 m body within tuff in the adit about 100 m from the portal) on unpublished plans of the mine workings prepared by D. Zimmerman & others of United Uranium N.L. in 1969.

The volcanic sequence is overlain apparently conformably by about 120 m of medium to coarse, ill-sorted, red-brown to purple sandstone, exposed mainly as cliffs. The sandstone is commonly pebbly with angular to subrounded vein quartz clasts: it is generally well bedded and in places cut by clastic dykes of disoriented angular bedded sandstone clasts in a sandstone matrix (Fig. 3). Minor asymmetric ripples indicate a west to southwest current direction. Polymictic conglomerate near the base grades laterally and upwards into quartz cobble conglomerate and sandstone. The polymictic conglomerate is similar to the vent breccia of the open cut, containing clasts mainly of vein quartz, silicified pale grey ill-sorted medium to very coarse lithic sandstone, ferruginous carbonaceous shale, and massive pink or cream rhyolite.

Many steep faults cross the area. The curvilinear faults of the open cut are splays from easterly and northerly trending fault sets that form a conjugate set between major northwest-striking faults, which dominate the structure of the South Alligator Valley district. A schematic section showing the setting of the Coronation Hill deposit within the basinal structure locally defined by the Coronation Sandstone is shown in Figure 4.

Description of the 'vent breccia'

The polymictic rock at Coronation Hill and Pul Pul Hill, described variously as conglomerate, breccia, and agglomerate

Figure 3. Clastic dyke in bedded pebbly sandstone of Coronation Sandstone, 400 m west of open cut.
Wallaby droppings 2 cm diameter.

by earlier workers, is a light grey, weathering buff or white, very poorly sorted, clast-supported melange of angular to well-rounded granules, pebbles, cobbles, and boulders of a range of volcanic and sedimentary lithologies in a variable matrix. The matrix is dominantly a pale grey coarse sand with minor medium to fine sand-grade pale grey to green-grey quartzose (and in places micaceous) greywacke (size grades are from Pettijohn & others, 1973). We examined material from the Coronation Hill open cut and from Noranda's drillhole.

Texture

Grainsize ranges from about 0.005 mm in the clay fraction to a maximum observed clast size of 1.32 m (greatest dimension). The size frequency distribution of grains defines three populations (determined by integration of microscopic point counting, visual estimates of crushed samples, grid analysis of outcrop photographs, and direct measurement of clasts in outcrop) (Fig. 5a): a matrix of medium sand to clay grade—about 10 per cent of the total rock (population A), a dominantly very coarse sand to granule population—about 40 per cent (population B); and a pebble to boulder population—about 50 per cent (population C).

Roundness of grains is related to the polymodal grain size (Fig. 5b). The matrix is typified by angular to subangular grains (at least in the determinable fraction coarser than about 0.03 mm), whereas the coarser populations (B, C) range from angular to rounded; a high proportion of well-rounded grains is present in population C.

Grain shape is difficult to determine for the whole range of size fractions, owing to the consolidated nature of the rock. However, pebble, cobble and boulder shapes were estimated on irregular outcrop surfaces, and by observation of sections cut through drill core; crushed matrix samples were also examined. Equant grains occur throughout the range, as do oblate or tabular grains except for the coarsest (>1024 mm) and intermodal pebble (916–32 mm) fractions. Prolate grains were observed only in the more dominant (over 8% of total rock) size fractions in B and C populations.

Composition

The composition of clasts indicates a heterogeneous provenance containing metamorphosed and unmetamorphosed sediments, and felsic volcanic rocks. About 48 per cent of clasts are non-volcanic.

Quartz, quartzite, and quartz sandstone are present as clasts in much the same amounts in both B and C populations (Fig. 5a). The clasts are generally rounded to well-rounded, and equant tending to prolate. The quartzite is highly strained with a strong planar fabric, indicating a metamorphic origin. Quartz grains in the sandstone are medium to coarse, unstrained, sub-rounded, and moderately to well-sorted, indicating derivation from a mature, unmetamorphosed source rock. Quartz in the matrix is generally highly angular and commonly tabular, but some larger grains are equant

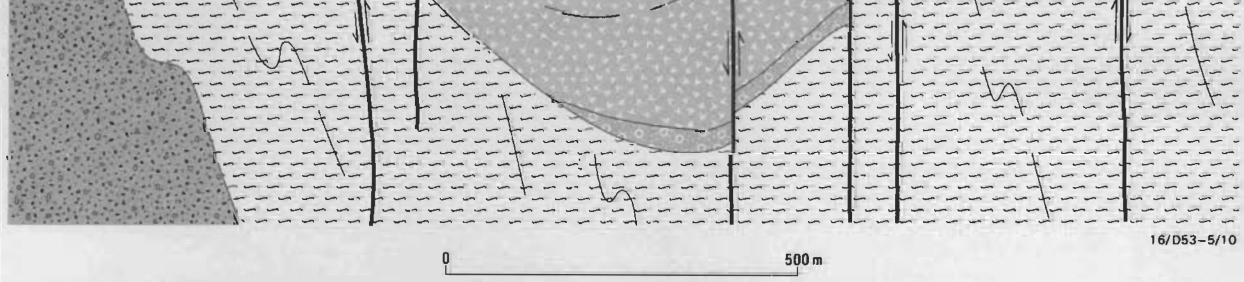

Figure 4. Schematic section through Coronation Hill area.
Vertical exaggeration about 1.5. Figure 2 shows section line and stratigraphic legend.

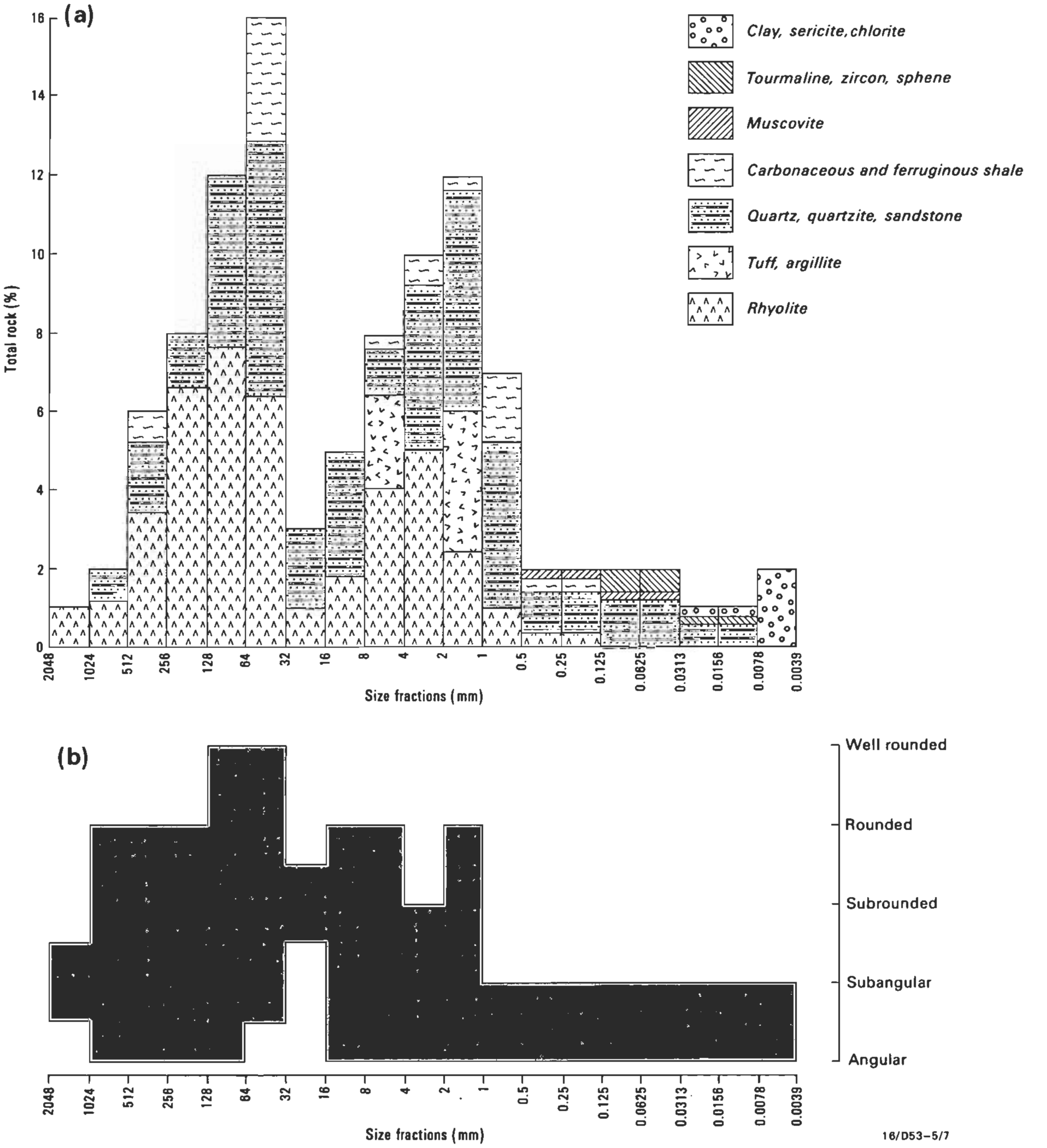

Figure 5. Mechanical composition of the debris-flow conglomerate. (a) frequency distribution of size fractions and lithological components of each size fraction; (b) clast shape variation by size fraction.

with subangular to subrounded shapes reminiscent of the euhedral quartz phenocrysts within many of the volcanic clasts. Syntaxial overgrowths are common on these and other larger, mainly rounded quartz grains.

Variation in the amount of volcanic clasts almost entirely accounts for the rock's pronounced polymodal character (Fig. 5a). The clasts are mainly pink or grey very fine rhyolite, composed almost entirely of interlocked quartz with scattered quartz phenocrysts up to 2 mm long. The rhyolite is commonly finely brecciated and weakly and irregularly altered to chlorite. Other volcanic rock types are dark grey massive to banded tuff and green/grey massive argillite. The volcanic clasts are with rare exception angular or subangular; equant shapes are most common, but tabular forms are widespread and prolate forms are evident in both populations B and C. Tuff and argillite are confined to the finer of these two populations, reflecting their less competent character.

Alteration and brecciation

All clast lithologies and the matrix display pervasive alteration to sericite and very pale green chlorite. About 25 per cent of the matrix clay fraction from 0.007 to 0.03 mm and all of it in finer grades is composed of these alteration minerals, which are interpreted to have developed from primary depositional clay particles. In volcanic clasts, mafic minerals are replaced by chlorite aggregates and feldspar phenocrysts are totally sericitised, and there is patchy Fe oxide, carbonate, quartz, and sphene (or leucoxene?) alteration. In places, sericite cuts across the chlorite aggregates. The sandstone clasts contain sericite completely replacing feldspar and radiating clusters of pale green chlorite after quartz. Fe oxides are restricted to near-surface, where they are formed by oxidation of chlorite.

Minor veinlets of quartz cut clasts and matrix and are commonly lined by thin selvages of dark green chlorite aggregates. Patches of dark green chlorite also occur in the rock near the quartz veins. The probable paragenetic sequence is: pervasive sericite + pale chlorite → remobilised sericite → quartz + dark chlorite

Nearby exposures of rocks from which the clasts may have been derived are much less altered, and feldspar and mafic minerals are commonly preserved, suggesting that even the early sericite-chlorite is post-depositional. Weak alignment of matrix sericite may have been induced by crystallisation during diagenetic compaction.

All the rhyolite clasts show fine brecciation, evident in hand specimen as fine irregular fractures commonly tinted pale green. The fractures are pre-alteration, and do not extend into the matrix or clasts of other compositions. They are thus pre-depositional and probably a result of autobrecciation.

Carbonaceous or ferruginous shale fragments are entirely angular or subangular and tabular, and are similar in size distribution to the volcanics, although in each fraction they represent only a small proportion of the whole rock.

Detrital euhedral to subhedral grains of muscovite up to 0.5 mm long, and zircon, tourmaline, and sphene up to 0.1 mm are scattered through the matrix. Clay-like minerals form a fine felted groundmass in the matrix.

Sedimentary structure

The rock is essentially structureless, with random fabric orientation and no gross sorting or grading of clasts (Figs 6–7). However, at 3 localities in the pit exposure, single beds, 8-10 cm thick, of graded sandy granular to silt-grade matrix are present (Fig. 8). Within them, structure is restricted to crude lamination parallel to bedding in the silt grade. Both clasts and matrix range from coarser nearer the base to finer near the top. The tops of the beds are sharp and overlain by massive conglomerate, which, within 50 cm stratigraphic interval, contains clasts up to 16 mm across.

Geometry

Owing to poor exposure and faulting, the geometry of the 'vent breccia' is difficult to reconstruct. Shepherd (1967) indicated a north-northeast-trending, steeply dipping body, about 10–15 m wide, on the west side of the Coronation Hill mine open cut. Our work indicates a stratigraphic thickness of at least 20 m and possibly more than 40 m, thickest in the open cut or immediately west of it, and rapidly thinning to the west and southeast. The upper contact is gradational into overlying sandstone of the Coronation Sandstone, and the lower contact—unexposed except at faulted contacts—is apparently conformable on volcanics of the same formation. The 'vent breccia' appears to form a channel-like body roughly perpendicular to the present northwest strike of the Coronation Sandstone near the mine, and sedimentary structures in the overlying sandstone suggest current directions from the northeast (Fig. 2).

Interpretation

The 'vent breccia' displays few of the characteristics of a pyroclastic rock. The only volcanic rock to contain such a high proportion of non-volcanic clasts is hydrothermal explosion breccia, but the absence of intense hydrothermal

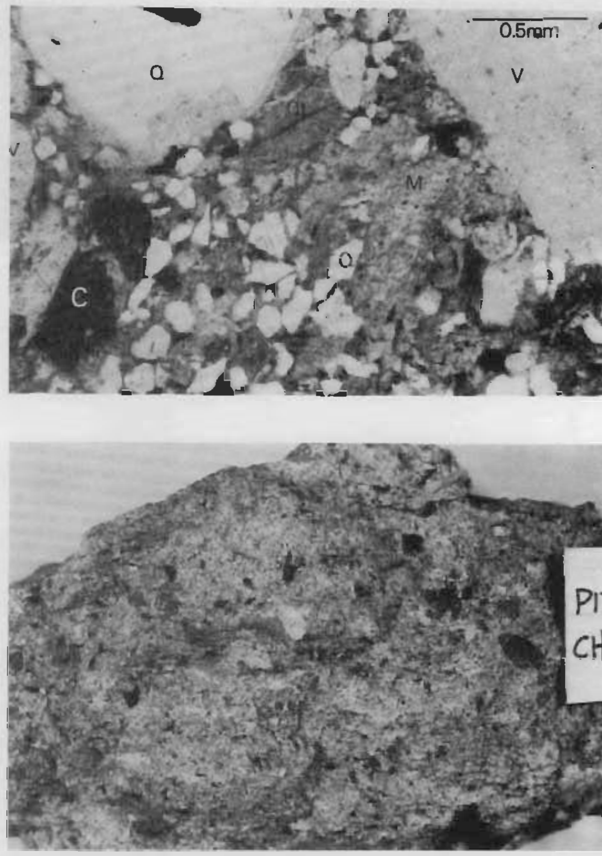

Figure 6. (upper) Photomicrograph of the polymictic debris-flow conglomerate:

Q—quartz, Qt—quartzite, V—felsic volcanic, C—carbonaceous shale, M—chlorite-sericite matrix flecked with equant iron-rich, and elongate carbonaceous, opaques. Note angular to subangular quartz grains, large embayed quartz grain derived from phenocryst with rhyolitic groundmass attached, scattered foliated pelite and quartzite clasts.

(Lower) angular carbonaceous slate fragments in ill-sorted coarse to pebbly greywacke matrix of the debris-flow conglomerate. Card is 2 mm high.

alteration precludes this origin (Nairn & Wiradiradja, 1980). The lithological character of clasts and matrix and the presence of indisputable sedimentary structures, such as graded beds, indicate the rock to be a polymodal epiclastic sedimentary rock. The matrix is fine to medium-grained, lithic, angular, poorly sorted quartz-dominant greywacke. The range in lithology, size, roundness, and shape of clasts indicates an extraformational origin. Minor interludes when current waned to low energies are indicated by rare graded beds as fine as silt grade, and the rapid return to pebble-grade clasts above the graded beds suggests rapid energy fluctuations. Such unsorted, massive sedimentary deposits are common in both alluvial and deep-sea fan environments, and are interpreted as debris-flow deposits (e.g. Bull, 1972; Heward, 1978).

The clast-supported, clast size and sandy matrix characteristics indicate a laminar grain flow transport mechanism with grains supported by dispersive pressure, and deposition by 'frictional freezing' as a consequence of frictional grain resistance (Lowe, 1982). Sediments of this type, deposited from cohesionless flows (also termed 'density modified grain flows'; Lowe, 1976) typically consist of clast-supported pebbles and cobbles set in a poorly sorted sand, silt and clay matrix in beds of >0.4 m (Lowe, 1982).

The absence of grading or inverse grading indicates relatively low dispersive pressures during sedimentation. The two

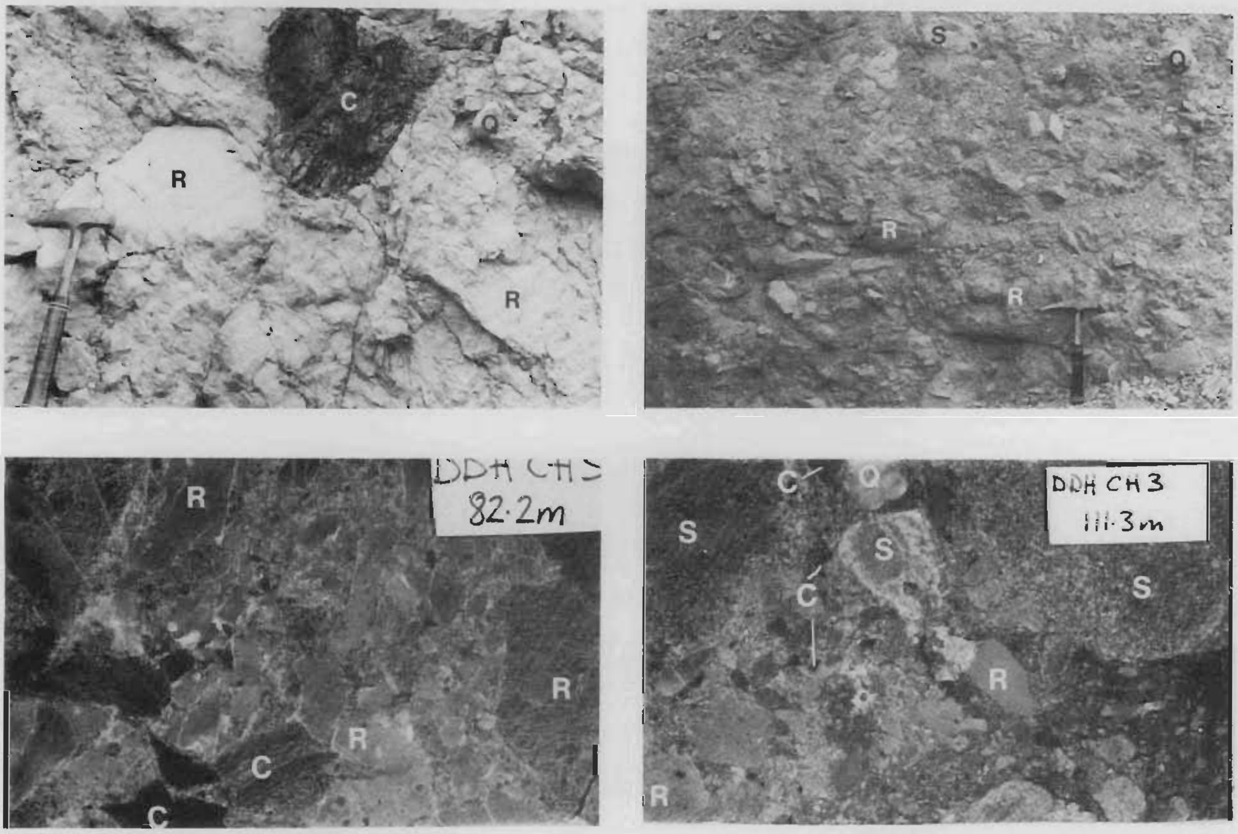

Figure 7. (Upper 2 photographs) Clasts of rhyolite (R), quartzite (Q), sandstone (S), and carbonaceous schist (C) in the polymictic debris-flow conglomerate. West wall of pit adit. (Lower 2 photographs) Polymictic debris-flow conglomerate from diamond-drill hole CH3, core 5 cm wide.

Figure 8. Graded bed (5 cm thick) interbedded with polymictic debris-flow conglomerate.

graded beds indicate the presence of at least three flows in the roughly 20 m thick sequence exposed in the mine workings. The association with sub-aerial felsic volcanics and related valley-fill volcanolithic sediments indicates a fluvial, high-energy environment of deposition.

Owing to the mixture of rounded, sub-rounded, and sub-angular clasts with angular clasts, the term 'conglomerate' is preferred over 'breccia', which may be readily confused with the earlier interpreted origin of the rock as a cognate volcanic breccia. The recommended name is 'debris-flow conglomerate'.

Geology of the Coronation Hill open cut

Our mapping of the open cut (Fig. 9) has revealed 2 previously unrecorded major structures and determined the outcrop area of the debris-flow conglomerate. The new structures are an east-southeast subvertical fault, which throws the conglomerate against volcanics on the south side, and a shear zone trending east-northeast across conglomerate and volcanics with no apparent offset.

Only the walls of the pit contain outcrop, as the floor is entirely covered by rubble. The pit consists of an open adit about 10 m wide by 65 m long driven horizontally southwards into a rising hillside with an original gradient of about 1 in 3, to a 33 × 24 m hole that originally was connected to underground workings by underground stopes. The hole is now about 10 m deep and much of the eastern part is concealed by a scree slope. Therefore, all observations were restricted to wall areas. Geology of the pit floor is adapted from an unpublished plan by United Uranium N.L. dated 1969 with geology by D. Zimmerman. Our mapping was controlled by tape and compass.

The conglomerate extends along three-quarters of the western wall of the pit and entrance, and is truncated by subvertical faults against purple, green and grey, commonly sheared volcanics in the west corner of the pit and along the eastern wall. Graded beds in the conglomerate indicate dips of 42° to 90° to the west.

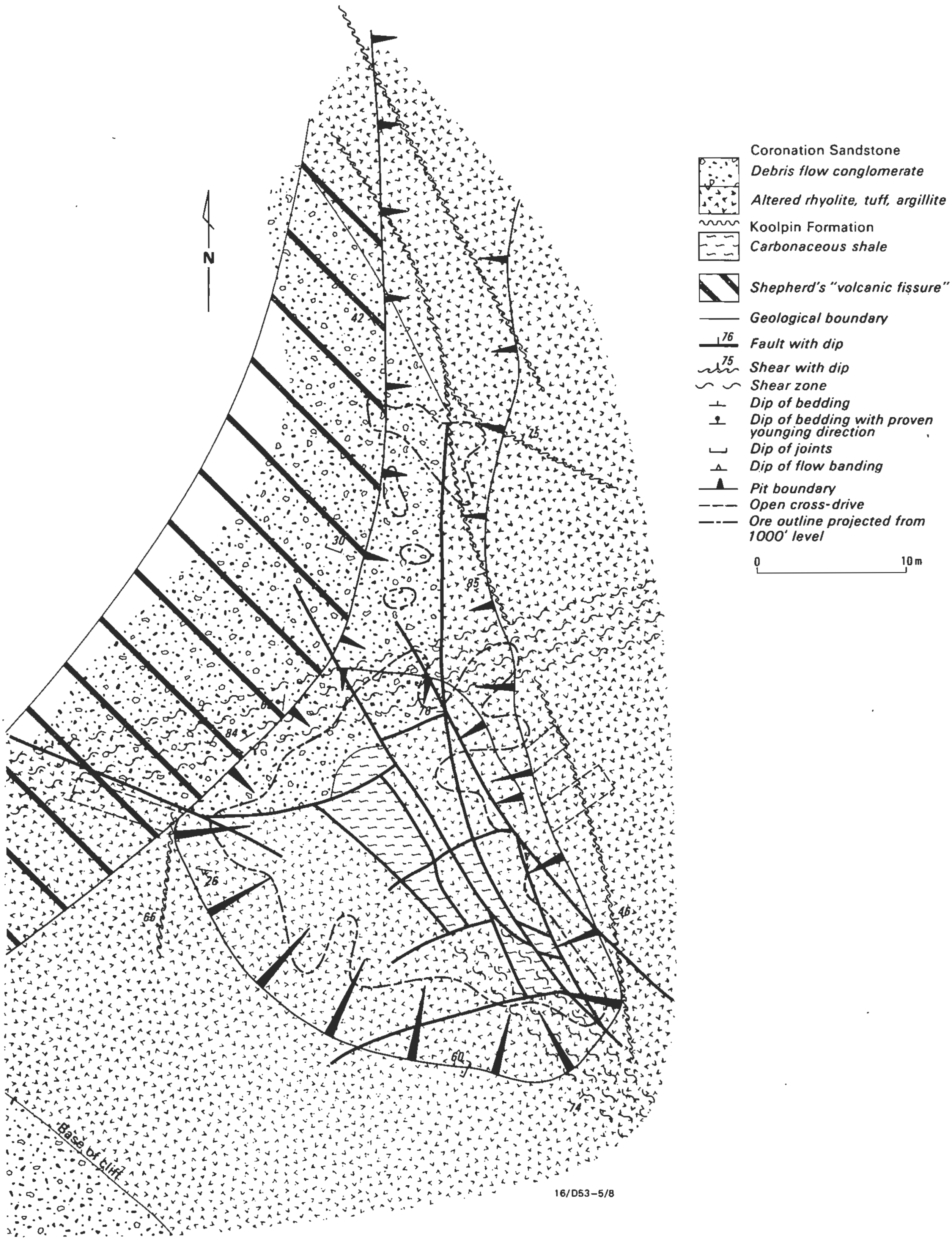

Figure 9. Geology of Coronation Hill mine pit, showing outline of ore and Shepherd's (1967) 'volcanic fissure'.

The volcanics are massive, fine, and extensively sheared, jointed, and stained. Their original lithology is obscure, but may have been interbedded rhyolite, argillite, and tuff, by analogy with rock types mapped on the surface east of the pit by J. Harrison (unpublished data, United Uranium N.L., 1970) and described below surface by Allen (1954) and G. Pietsch (unpublished data, Noranda Australia Ltd, 1977). They are now mainly schistose chloritic rocks, comprising about 75 per cent quartz, 20 per cent chlorite and 5 per cent iron oxides. Locally, cherty siltstone bands may represent bedding. The rock is extensively sheared and jointed, but in places a fine arenaceous texture is preserved. Fine brecciation is common, and in places the rock is laced with fine quartz veinlets. Strong hematite staining and, in places, massive hematite replacement accompanies some major fractures, and a zone of strong bleaching up to 7 m wide accompanies the east-northeast shear zone where it cuts the volcanics.

Unpublished plans of United Uranium N.L. dated December 1970 (geologist J. Harrison) show a carbonaceous shale lens within volcanics in the south wall of the pit, which we were unable to verify. Alternatively, it is highly chloritic schist derived by alteration of the volcanics, or it may be a faulted wedge of carbonaceous shale from a deeper stratigraphic level, which has been subsequently concealed by scree.

An interpretative cross-section based on our mapping, geological logs of drillholes BMR1 and BMR2 by Allen (1953), and our own logging of Noranda's drillhole CH3, is shown in Figure 10. We interpret the open cut area as a prism of Coronation Sandstone conglomerate, originally continuous with sandstone and conglomerate forming the cliffs above the pit, and now downfaulted into stratigraphically lower felsic volcanics of the same formation. Narrow fault wedges of carbonaceous shale lie within the prism of conglomerate and at depth may be isolated from their Koolpin Formation source.

Uranium-gold mineralisation was concentrated in carbonaceous clast-rich portions of the prism around and above the shale wedges, but extended into the shale wedge in places, and elsewhere as oxidised ore, into the felsic volcanics. The largest uranium ore shoot was in a steeply plunging triangular zone of intense faulting south of the east-northeast shear zone (Fig. 9). Gold mineralisation formed both veinlets, which cut the pitchblende ore, and disseminations. Gold also formed separate ore shoots in places, so it appears that the controls to uranium and gold mineralisation were unrelated. Shepherd's (1967) 'volcanic fissure' lay west of this triangular zone and was portrayed as a northeast-trending 20 m × 100 m body impinging on the west wall of the pit and continuing southwest to the main escarpment of Coronation Hill.

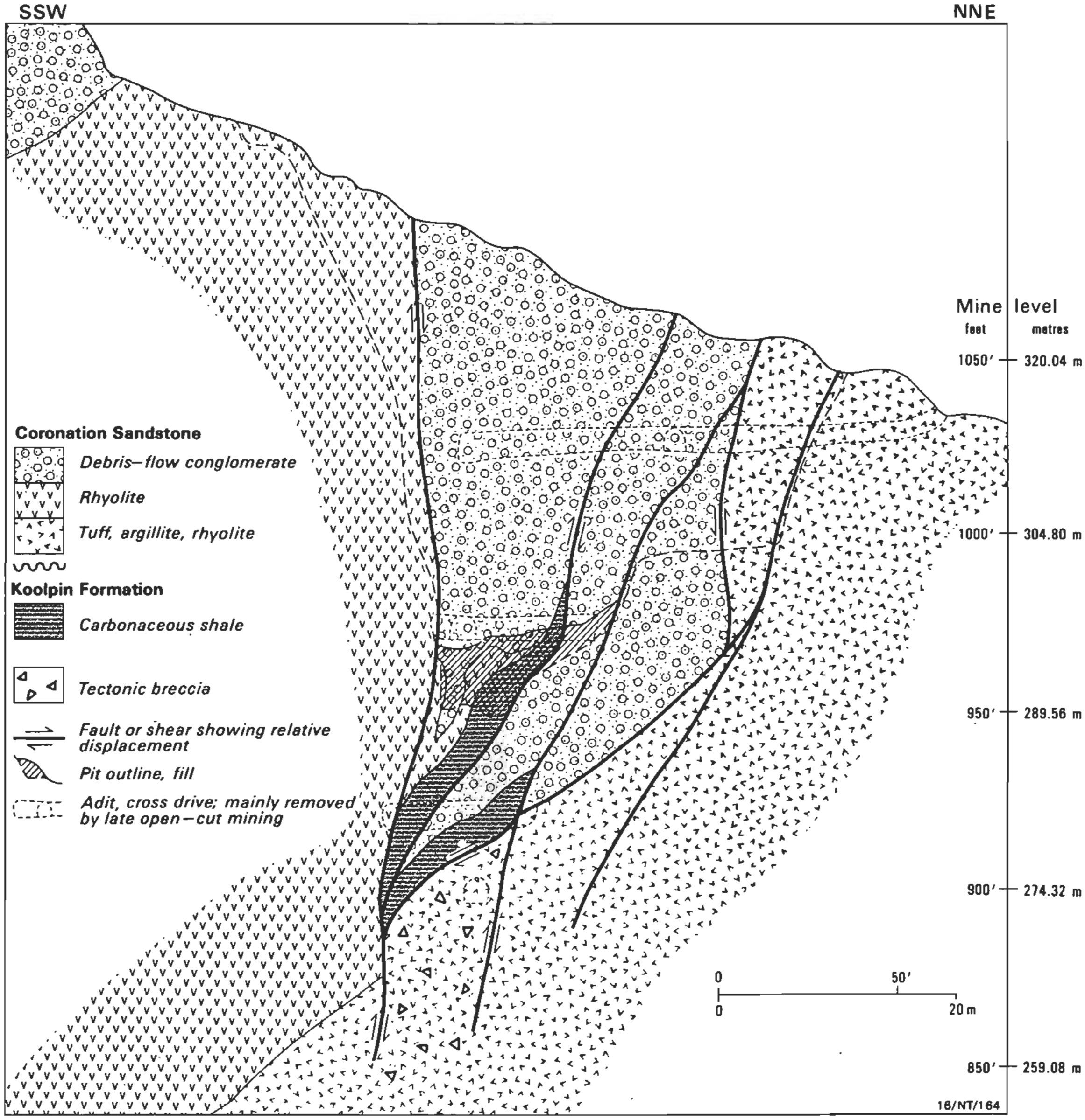

Figure 10. Interpretative cross-section of the Coronation Hill U-Au mine, based on drillhole logs of Allen (1954), our log of the 1976 Noranda drillhole, and recent mapping.

Relation to other U-Au deposits of the district

The other deposits of the district (El Sherana, El Sherana West, Rockhole, Palette, Saddle Ridge, Scinto V, Scinto VI, Koolpin Creek, Skull, and Sleisbeck) all lie on or close to the major northwest-trending faults or related conjugate faults within 400 m of a major fault (Needham, 1985). Primary mineralisation is hosted by carbonaceous and ferruginous shale of the Koolpin Formation, which is commonly in faulted contact with sandstone or volcanics of the Coronation Sandstone. The sandstone and volcanics commonly host secondary uranium minerals, reflecting the oxidising environment. The U-enriched Pul Pul Rhyolite and rhyolite of the Coronation Sandstone are the probable metal source (Ayres & Eadington, 1975), and the common juxtaposition of Koolpin Formation and sandstone of the Coronation Sandstone strongly suggests that the sandstone provided a conduit for mineralising fluids from the volcanics to the carbonaceous shale.

Misidentification of the host rocks of the Coronation Hill deposit as a volcanic vent has made this deposit difficult to fit into models advanced for the genesis of the other deposits of the district, which were reviewed by Crick & others (1980). Our interpretation makes the host rocks at Coronation Hill essentially the same as those in the other deposits, so that the same genetic model may apply to all the U-Au deposits of the area.

At Coronation Hill, volcanics (uranium source rocks) and sandstone (conduit bodies) of Coronation Sandstone are in faulted contact with Koolpin Formation carbonaceous and ferruginous shales (reductant rocks), in an area crossed by both northwest-trending faults and conjugate faults. In this case, precipitation of uranium took place partly in the conduit body, as large clasts of carbonaceous shale within the debris-flow conglomerate provided a sufficiently reduced environment.

Conclusions, uranium ore genesis model

The host rock at the Coronation Hill U-Au mine is a debris-flow conglomerate, developed in a high-energy fluvial environment during deposition of the Coronation Sandstone of the El Sherana Group. The landscape was rugged, consisting of ridges of shale and valley infills of sandstone, pyroclastics, and felsic volcanics. High-energy fluvial surges reworked the sandstone (clastic dykes, sandstone clasts of the Coronation Sandstone), ripped up and transported boulders of shale (Koolpin Formation), volcanics and volcaniclastics (Coronation Sandstone volcanic valley-fill), and reworked older mature pebbly arenites (the pre-Koolpin Formation Mundogie Sandstone). These clasts were dumped in a matrix of quartz-rich angular grains derived mainly from the valley-fill volcanics.

Several debris flows were interspersed with normal fluvial transport of sand and silt, and graded beds developed as currents waned. The landscape rapidly matured, so that the debris flows were overlain by relatively mature pebbly sands. Later, faulting juxtaposed the Coronation Sandstone sequence with Koolpin Formation, and groundwater circulation was induced by tectonic disturbance of groundwater gradients. The age of faulting is demonstrated as post 1650 Ma, as the same faults displace Middle Proterozoic sandstone of this age in the same district (Page & others, 1980). Thus, mineralisation took place by movement of low-temperature fluids from the U-enriched volcanics into the conduit sandstone and eventually into the reduced debris-flow conglomerate and carbonaceous shale.

All the uranium deposits of the South Alligator Valley district are epigenetic and have similar origins. However, on the basis of the minor component of in-situ carbonaceous and ferruginous shale (the major host of all the other deposits), the Coronation Hill deposit can be classified as 'epigenetic sandstone type', reflecting the coarse clastic nature of the host rock.

An aspect of the Coronation Hill deposit, and the other uranium deposits of the district that carried gold, is the apparent lack of relation between the extensive chlorite/hematite alteration associated with all these deposits and the gold mineralisation. As both gold veins and 'dark chlorite + quartz' are late events, they could possibly be genetically related.

The very finely disseminated nature of gold in the recently discovered deposit east of the old workings may indicate an early, possibly deuteric, mineralisation, distinct from the obviously late remobilised gold veins that cut uraninite ore in the U-Au orebody. Two distinct mineralising episodes are indicated with common or similar localising mechanisms. Thus, those other gold-bearing uranium deposits of the region indicate likely sites of low-grade gold-PGE mineralisation in nearby altered felsic volcanics.

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BMR Journal of Australian Geology & Geophysics, 10, 133-137

Temporal variation in seismicity of the Southwest Seismic Zone, Western Australia: implications for earthquake risk assessment

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In the area 30-33°S, 116-118°E of the Southwest Seismic Zone of Western Australia, ML ≥ 4.0 earthquakes for the period 1960-1983 do not fit a Poisson model. However, when foreshocks and aftershocks are excluded, the hypothesis of a Poisson distribution cannot be rejected for the resulting series of main shocks. A similar result holds for the subset of ML ≥ 5.0 events for the period 1949-1983. Consequently, when earthquake risk is being assessed by methods that assume a Poisson distribution, foreshocks and aftershocks should be excluded. However, the consequent apparent reduction of risk caused by removing these potentially damaging earthquakes should be pointed out. Although records of seismicity are probably incomplete for the early part of this century, there appears to have been an increase in numbers of ML ≥ 4.0 events, starting around 1949. Although, the data are too uncertain to test the increase in the ML ≥ 4.0 main shocks statistically, there has been an approximate five-fold increase in the mean yearly number of ML ≥ 4.5 main shocks during the period 1949 to 1983, compared with the period 1923 to 1948. This is clearly larger than would be expected from a Poisson process. Consequently, the apparent increase in the number of ML ≥ 4.0 events is probably also real and not an artefact of a Poisson process. Also, there were no ML ≥ 5.0 events during the period 1923 to 1948, and the only two ML ≥ 6.0 earthquakes this century took place in 1968 and 1979. This increase in seismicity since the late 1940s should be taken into account in the interpretation of earthquake risk calculations.

Introduction

That part of Western Australia's Southwest Seismic Zone which lies in the area 30 to 33°S, 116 to 118°E is one of the most seismically active regions of Australia and the largest contributor to the earthquake risk at Perth (Fig. 1). If one assumes that seismic events are independent and the earthquake process is stationary, then the process will probably be a Poisson process. Many computations of earthquake risk assume this to be true (Lomnitz, 1974).

The Mundaring Geophysical Observatory was established in 1959, so it is assumed that data on ML ≥ 4.0 earthquakes are complete from 1960. Consequently, detailed investigation of the occurrence in time of these events has been carried out only for the period 1960-1983. However, Everingham (1968) has tabulated Western Australian earthquake reports back to 1904, and Everingham & Tilbury (1971) examined the Milne-Shaw seismograph records and intensity data from the Perth Observatory for the period 1923-1961 and determined some epicentres and magnitudes. The earliest event they located occurred in 1940. Everingham & Tilbury (1972) noted that seismic activity in the Southwest Seismic Zone appeared to have increased markedly since about 1940. From their examination of Perth seismograms, they stated that there were no earthquakes in that area with ML ≥ 4.5 during the period 1923-1939, and that felt reports suggested that there were probably none during 1900-1922. (By contrast, there were 12 events with ML ≥ 4.5 during the period 1940-1967.) Because of this, I assume that the data on ML ≥ 5.0 earthquakes are probably complete back to 1923, and possibly even to 1904.

By examining the reports in Everingham (1968) I have tabulated main shocks that may have had ML ≥ 4.0 during 1904-1939 (Table 1). I assumed that reports of Modified Mercalli intensity IV or greater in Everingham (1968) indicated an event with ML ≥ 4.0. There were none in Everingham (1968) to add to the post 1939 data from the BMR Earthquake Data File and Everingham & Tilbury (1971) (Tables 1 & 2). This is a very rough method and probably results in the inclusion of smaller magnitude events, but it should give some indication of whether the level of seismicity has changed appreciably with time. I have excluded ML ≥ 4.0 foreshocks and aftershocks for the earlier period, as information on the numbers of these is too vague. There was one ML ≥ 5.0 aftershock prior to 1960. It occurred on 29 August 1955 at 06hr 09min GMT. Its epicentre was at 30.7°S, 116.4°E and its Richter magnitude was 5.3.

Earthquakes with ML ≥ 4.0, 1960–1983

The yearly number of events is plotted in Figure 2. With foreshocks and aftershocks included, the events appear to be strongly clustered, particularly in 1968 and 1979, the years of the ML 6.9 Meckering and ML 6.2 Cadoux earthquakes respectively.

For a pure Poisson process, the ratio of the variance to the mean is unity. (Variance/mean) xdf has a χ^2 distribution with df degrees of freedom, where df = N-2, and N is the number of observations. ($\chi^2 = \Sigma[(O-E)^2/E]$, where O is the observed value and E is the expected value). I used the variance/mean test because it is a very quick easy test to apply. If $\chi^2 >$ 95th percentile, the null hypothesis of a Poisson distribution may be rejected. If not, then it is worth doing a more sophisticated test.

For the ML ≥ 4.0 earthquake data, the variance is 11.77 and the mean 1.875, giving a ratio of the variance to the mean of 6.275 and (variance/mean) xdf of 138.05. For a χ^2 distribution with 22 degrees of freedom, the 99.95 percentile is 42.80, so the null hypothesis of a Poisson distribution can be rejected at the 0.0005 level of significance. Consequently, the ML ≥ 4.0 earthquake data with foreshocks and aftershocks included cannot possibly be described by a Poisson distribution. This is not surprising, because foreshocks and aftershocks are not independent events, so their inclusion contravenes one of the basic assumptions of a Poisson process. Therefore, earthquake risk analyses that include foreshocks and aftershocks, but assume a Poisson distribution, should be regarded with reservation.

Figure 2 also shows the yearly number of ML ≥ 4.0 main shocks only. Foreshocks and aftershocks occurring within 30 km of a main shock and within one month of each other or of a main shock have been excluded. The data from 1960 to 1983 have a ratio of variance to mean of 1.124 or (variance/mean) xdf of 24.73. The 95th percentile of the χ^2 distribution is 33.92, and the possibility of a Poisson distribution cannot be rejected. It requires further investigation.

For a Poisson process, the time intervals, T, between events follow a negative exponential distribution: $f(T) = \lambda e^{-\lambda T}$, where the mean of T is λ^{-1} (Lomnitz, 1974). From Table 3,

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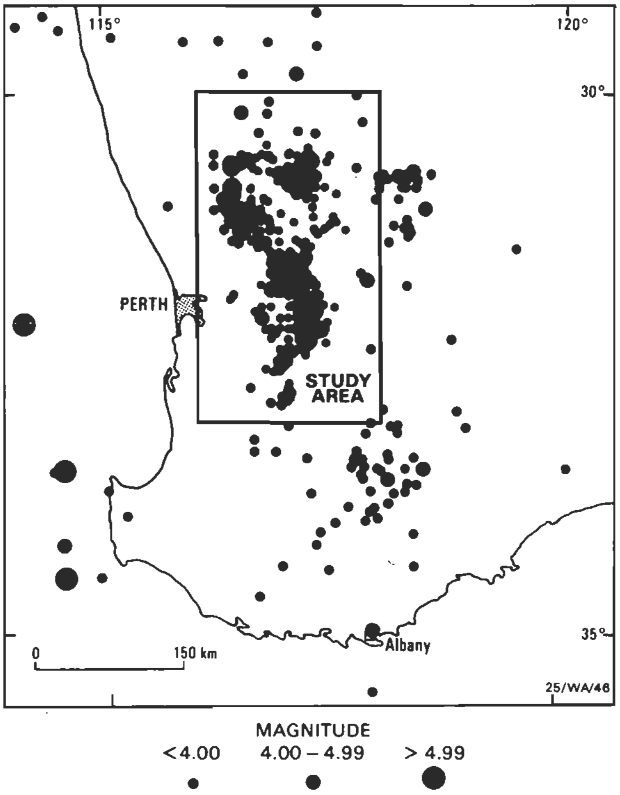

Figure 1. The Southwest Seismic Zone of Western Australia. The rectangle shows the area 30–33°S, 116–118°E, which is the subject of this study.

the maximum likelihood estimate for λ is 394 (days). Table 4 shows the observed and expected distribution of time intervals using λ = 394. The negative exponential distribution provides a good fit to the observed data. Consequently, for the occurrence of $ML \geq 4.0$ main shocks from 1960–1983, we are not in a position to reject the null hypothesis of a Poisson distribution.

Earthquakes with $ML \geq 5.0$, 1949–1983

The yearly number of $ML \geq 5.0$ earthquakes is plotted in Figure 2. As there were no events prior to 1949, I decided initially to see whether the earthquakes from 1949 to 1983 fitted a Poisson distribution.

For the data with foreshocks and aftershocks included, df is 33, the ratio of the variance to the mean is 2.088 and (variance/mean) xdf is 68.90. The 99.95 percentile of the χ^2 distribution for 33 degrees of freedom is 66.66, and the hypothesis of a Poisson distribution can be rejected at the 0.0005 level. Consequently, there is no way in which the data with foreshocks and aftershocks included can be described by a Poisson distribution.

For the same period, with foreshocks and aftershocks excluded, the ratio of variance to mean becomes 0.994, and (variance/mean) xdf is 32.80. The 95th percentile of the χ^2 distribution is 47.52, and the probability of a Poisson distribution requires further investigation.

The time intervals between the main shocks are shown in Table 5. As there are only eight of them, there are insufficient data to test for a negative exponential distribution and, hence, for the fit of the earthquake process to a Poisson distribution. However, the variance/mean test gives no reason to reject the null hypothesis of a Poisson process. Also, the $ML \geq 5.0$ main shocks are a subset of the $ML \geq 4.0$ main shocks, for which the hypothesis of a Poisson distribution was not able to be rejected.

Possible increase in seismicity

$ML \geq 5.0$ earthquakes

The occurrence of main shocks of $ML \geq 5.0$ during the period 1904–1983 is shown in Figure 2. The data may be complete back to 1904, but, to be conservative, I assume that they are complete back to 1923.

There appears to have been an increase in seismicity starting in 1949, but, with only nine main shocks, the data are too few to test this.

However, for $ML \geq 4.5$ main shocks (Tables 1 and 2) there are more data, complete back to 1923 (Everingham & Tilbury, 1972). It appears that the Perth seismograph would have covered about 50 per cent of the study area. There was only one $ML \geq 4.5$ main shock during the period 1923–1948, a

Table 1. Probable $ML \geq 4.0$ earthquakes, 1904–1959, excluding foreshocks and aftershocks

ID no.	*Date* *y*	*m*	*d*	*Origin time* *h*	*m*	*Locality*	*Richter magnitude*	*Richter magnitude from intensity data (Everingham & Tilbury, 1971)*
	11	08	19			Quellington & York		
	16	06	02			Quellington		
	16	12	01			Meckering		
	17	06	03			York & surrounding districts		
	32	03	15			Muresk		
	32	11	02			Northam		
	36	08	18			48 km ENE of Katanning, & Brookton		
	37	03-05				48 km NE of Katanning		
	40	12	18	21	45	32.2°S, 117.2°E	4.2	
	41	04	15			Northam		
	46	05	07			Yallingup		
	46	09	17	15	12	32.5°S, 116.9°E	4.5	
(-4)	49	05	02	10	00	30.9°S, 116.4°E	5.1	
(-3)	52	03	11	06	09	31.3°S, 116.5°E	5.1	4.6
(-2)	55	04	29	09	14	30.9°S, 116.4°E	4.7	5.1
(-1)	55	08	30	13	52	30.7°S, 116.4°E	5.8	5.5
	56	02	24	06	27	30.9°S, 116.4°E	4.5	
	56	04	05	23	13	30.9°S, 116.4°E	4.5	
(0)	58	03	20	03	03	32.3°S, 117.2°E	4.8	5.2

Table 2. ML ≥ 4.0 earthquakes, 1960–1983

ID no.	*Classification*	*Date*				*Origin time*		*Latitude*	*Longitude*	*Richter*
		y	*m*	*d*	*h*	*m*	*s*	*°S*	*°E*	*magnitude*
(1)	M	61	06	25	17	59	18.1	32.200	117.200	4.4
(2)	M	63	01	18	05	49	16.8	32.250	117.170	4.9
(3)	M	63	11	19	17	52	05.1	31.000	116.300	4.2
(4)	M	68	02	22	04	40	10.5	30.800	117.300	4.0
(5)	M	68	04	08	01	44	53.8	30.800	117.250	4.4
	F	68	10	03	03	55	33.4	31.590	116.980	4.2
(6)	M	68	10	14	02	58	50.6	31.620	116.980	6.9
	A	68	10	14	03	15	21.4	31.600	117.000	4.0
	A	68	10	14	03	57	47.7	31.660	116.990	4.0
	A	68	10	14	04	09	07.5	31.600	117.010	4.6
	A	68	10	14	06	47	50.4	31.690	116.980	4.2
	A	68	10	15	03	30	07.0	31.680	117.030	5.7
	A	68	10	16	00	55	10.2	31.660	117.020	4.2
	A	68	10	18	10	31	47.9	31.760	117.070	4.1
	A	68	10	21	15	32	59.2	31.610	117.090	4.6
	A	68	10	22	01	04	04.9	31.580	117.010	4.1
	A	68	10	31	00	58	48.9	31.780	116.980	4.1
	A	68	11	28	14	17	31.5	31.640	117.000	4.0
(7)	M	69	02	01	03	29	57.7	31.960	117.150	4.0
(8)	M	69	07	27	09	20	47.3	30.950	117.100	4.2
(9)	M	70	03	10	17	15	11.2	31.110	116.470	5.9
(10)	M	70	12	26	18	25	51.0	31.080	116.310	4.0
(11)	M	71	07	16	12	32	24.4	31.640	117.080	4.0
(12)	M	74	07	09	10	46	47.4	31.650	117.000	4.3
(13)	M	74	09	04	23	17	42.4	30.790	116.970	4.5
(14)	M	74	11	19	09	30	22.6	31.630	117.030	4.0
(15)	M	76	10	29	06	04	48.2	31.640	117.000	4.7
	F	79	06	01	21	54	02.9	30.830	117.170	5.2
(16)	M	79	06	02	09	48	01.0	30.830	117.150	6.2
	A	79	06	02	11	04	57.2	30.800	117.210	4.1
	A	79	06	03	07	45	34.5	30.770	117.170	5.3
	A	79	06	07	06	45	16.1	30.810	117.160	5.5
	A	79	06	07	22	33	30.4	30.730	117.160	4.0
	A	79	06	10	18	24	52.6	30.780	117.190	4.3
(17)	M	79	10	11	04	04	11.7	30.790	117.150	4.8
(18)	M	80	12	10	04	35	05.6	30.730	117.150	5.0
(19)	M	81	04	07	20	15	55.8	30.744	117.164	4.5
	F	82	01	24	04	06	20.0	30.900	117.120	4.3
	F	82	01	25	23	26	58.7	30.910	117.130	4.4
(20)	M	82	02	06	15	24	39.5	30.880	117.150	4.9
	A	82	02	06	15	30	36.7	30.870	117.100	4.6
	A	82	02	07	13	07	31.4	30.890	117.090	4.1
	A	82	02	08	04	39	34.5	30.890	117.100	4.1
(21)	M	83	01	26	06	16	15.4	30.730	117.130	4.8

F—foreshock; M—main shock; A—aftershock.

mean of 0.04 events per year. During the period 1948-1983, there were 18 such events, a mean of 0.51 events per year. Therefore, there appears to have been a more than ten-fold increase in the mean yearly number of ML ≥ 4.5 main shocks during the period 1949-1983. Even if one assumes that some of the increase was because only about 50 per cent of the study area was covered in the earlier period, there would still be approximately a five-fold increase in seismicity if ML ≥ 4.5 main shocks are considered. This is clearly larger than would be expected from a Poisson process. Consequently, it is highly likely that the increase in the subset of ML ≥ 5.0 main shocks is also real and not an artefact of a Poisson process.

ML ≥ 4.0 earthquakes

The number of ML ≥ 4.0 main shocks also appears to have increased at around the same time, although not as obviously as for the ML ≥ 5.0 subset (Fig. 2). The mean annual number of events during the period 1904-1948 is 0.27. However, Table 6 shows that the mean number per year drops for the period before 1929, suggesting less complete reporting before then. This is probably because the wheat belt expanded geographically (Encyclopaedia Britannica, 1963) between 1905 and 1930, so that by the late 1920s the population in the area was enough for reasonably complete reporting. The mean annual number for the period 1929-1948 is 0.40, compared with 0.67 for the period 1949-1957. This indicates a 167 per cent increase in seismicity. These two periods are comparable, as both are earlier than the operation of a short-period vertical seismograph at Watheroo (31 March 1958 to 12 January 1959), which was superseded by the establishment of Mundaring Geophysical Observatory in 1959 (Everingham, 1968). The mean annual number of ML ≥ 4.0 main shocks during the period 1949-1983 is 0.80, compared with 0.40 for the period 1929-1948. This appears

Table 3. ML ≥ 4.0 main shocks: time intervals between events

Earthquake ID nos.	*Interval between earthquakes (d)*
1,2	571
2,3	306
3,4	1555
4,5	45.9
5,6	189
6,7	110
7,8	176
8,9	226
9,10	291
10,11	202
11,12	1089
12,13	57.5
13,14	75.4
14,15	710
15,16	946
16,17	131
17,18	426
18,19	119
19,20	305
20,21	354
	Mean = 394 days

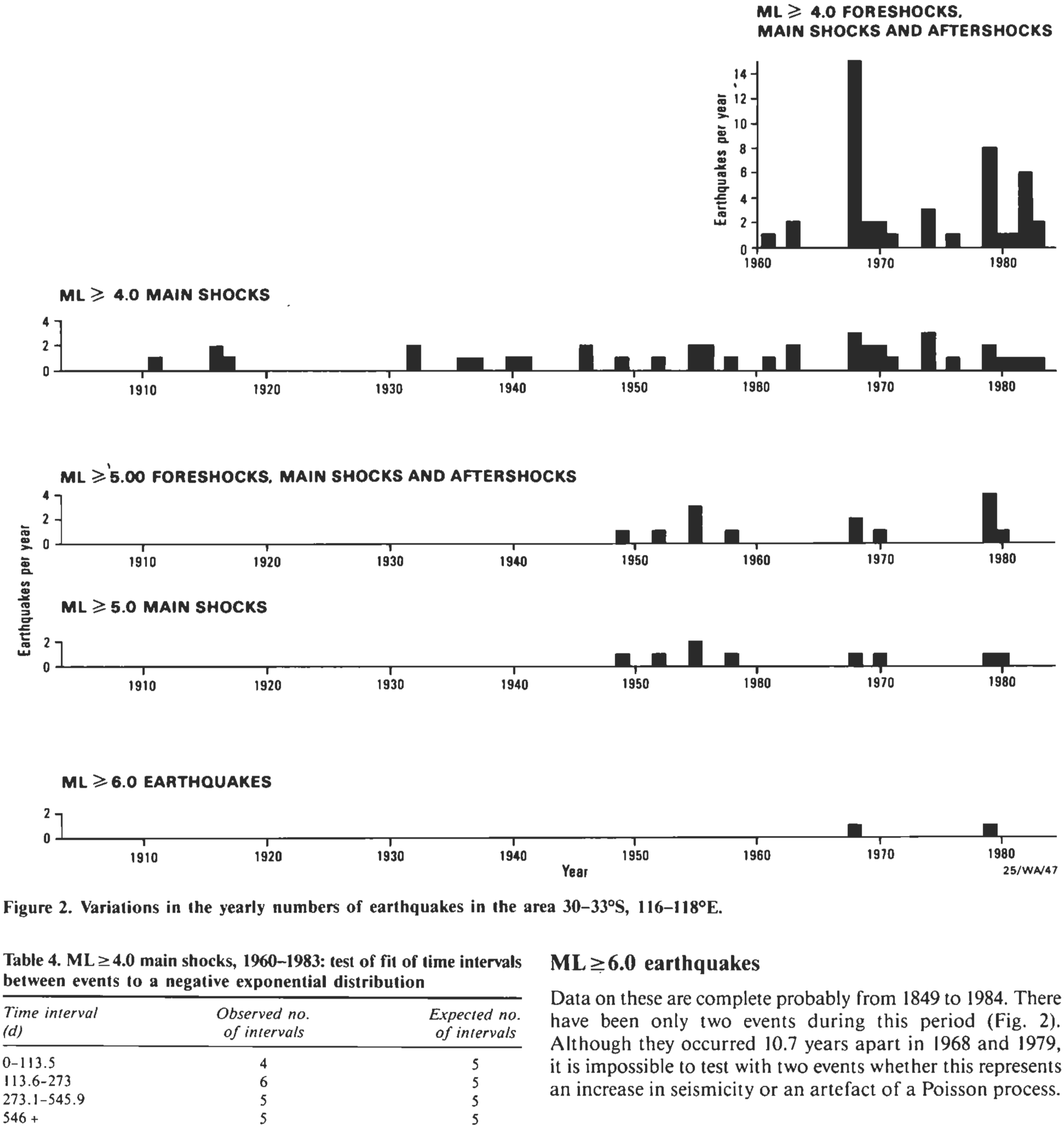

Figure 2. Variations in the yearly numbers of earthquakes in the area 30–33°S, 116–118°E.

Table 4. ML ≥ 4.0 main shocks, 1960–1983: test of fit of time intervals between events to a negative exponential distribution

Time interval (d)	*Observed no. of intervals*	*Expected no. of intervals*
0–113.5	4	5
113.6–273	6	5
273.1–545.9	5	5
546 +	5	5

df = 4.2 = 2, χ^2 = 0.4
The 10th and 25th percentiles are 0.21 and 0.58 respectively.
Therefore, χ^2 lies between the 10th and 25th percentiles.

Table 5. ML ≥ 5.0 main shocks: time intervals between events.

Earthquake ID nos.	*Interval between earthquakes (d)*
− 4, − 3	1044
− 3, − 2	1144
− 2, − 1	123
− 1,0	933
0,6	3861
6,9	512
9,16	3371
16,18	557
	Mean = 1443 days

to be a doubling of seismicity since 1949, but the data prior to 1958 are too uncertain to test this. However, the very large increase in the number of ML ≥ 4.5 main shocks (mentioned in the previous section) strongly suggests that the increase in ML ≥ 4.0 main shocks is also real.

ML ≥ 6.0 earthquakes

Data on these are complete probably from 1849 to 1984. There have been only two events during this period (Fig. 2). Although they occurred 10.7 years apart in 1968 and 1979, it is impossible to test with two events whether this represents an increase in seismicity or an artefact of a Poisson process.

Conclusions and implications for earthquake risk assessment

ML ≥ 4.0 earthquake data for the period 1960–1983, and ML ≥ 5.0 data for the period 1949–1983, do not fit a Poisson distribution if foreshocks and aftershocks are included.

However, if foreshocks and aftershocks occurring within one month of each other or of a main shock are excluded, there is no reason to reject the null hypothesis that the remaining sequence of main shocks can be represented by a Poisson distribution. Consequently, methods of earthquake risk assessment that rely on the assumption of a Poisson distribution should *not* be applied to the raw data.

The sequence of ML ≥ 5.0 main shocks from 1949 to 1983 and ML ≥ 4.0 main shocks from 1960 to 1983 appears to fulfil the criteria of completeness and having a Poisson distribution, necessary for most earthquake risk computations. However, it must be remembered that ML ≥ 4.0 foreshocks and aftershocks are potentially damaging

Table 6. Check on relative completeness of ML ≥ 4.0 earthquake data, 1904–1948.

Period	*No. of years*	*No. of events*	*Mean no. of events/year*
1944–1948	5	2	0.400
1939–1948	10	4	0.400
1934–1948	15	6	0.400
1929–1948	20	8	0.400
1924–1948	25	8	0.320
1919–1948	30	8	0.267
1914–1948	35	11	0.314
1909–1948	40	12	0.300
1904–1948	45	12	0.267

earthquakes that will have been omitted from the analysis. This should be clearly pointed out to users of the earthquake risk assessment (B.A. Gaull, BMR, personal communication).

Another property of the earthquake process that may not fulfil assumptions for earthquake risk calculations is that it does not appear to be stationary. Drawing conclusions from few data and probably incomplete historic reports for main shocks of ML ≥ 4.0 is risky, but the evidence for an increase in the numbers from about 1949 onwards merits serious consideration. It should be tested when more and better data become available. The increase in numbers of ML ≥ 4.5 and ML ≥ 5.0 main shocks during this period appears to be real.

If there has been an increase in seismicity, but only short-term, then using earthquake data from 1949 onwards will give conservative estimates of earthquake risk. However, if the increase is long-term, then assuming only two ML ≥ 6.0 events are likely to occur in 136 years or more may well underestimate the risk of these earthquakes.

Acknowledgements

I would like to thank Brian Gaull for helpful discussions before and during the course of this work, and Phil McFadden, Kevin McCue, and Brian Gaull for critically reading the manuscript and for their suggestions to improve it. Phil McFadden spent considerable time helping me to improve my application and interpretation of the statistics, and I greatly appreciate his help. I would also like to thank Peter Gregson and an anonymous referee for comments that enabled me to improve the paper further. The figures were drafted by Rex Bates.

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The Lithgow earthquake of 13 February 1985: macroseismic effects

Marion O. Michael-Leiba[1] & David Denham[1]

The Lithgow earthquake of magnitude ML 4.3, which took place on 13 February 1985, was the largest earthquake to have occurred in the Blue Mountains region of New South Wales since the Kurrajong earthquake of 1919. It caused minor damage in Lithgow and Wallerawang and was felt as far away as Parkes and Dubbo, 200 km from the epicentre. The total damage was estimated at approximately $65 000. Macroseismic and instrumental evidence suggests that, for this earthquake, the attenuation to the northeast in and under the Sydney Basin was much greater than the attenuation to the southwest through the Lachlan Fold Belt.

Hypocentral parameters

On 13 February 1985 at 08 h 01 min 23 s UT (BMR solution) an earthquake of magnitude ML 4.3 occurred beneath Lithgow, New South Wales. This was the largest event to have occurred in the Blue Mountains region since the ML 4.6 Kurrajong earthquake on 15 August 1919 (Cotton, 1921; Everingham & others, 1982). Although the Kurrajong event was larger, the Lithgow earthquake was felt with greater intensity in the epicentral region.

Using Herrin travel-time tables (Herrin & others, 1968) and an earthquake location program written by B.A. Bolt and modified by M. Landisman and L. Sykes, the epicentre was determined from 30 P-wave arrivals as being at 33.49° S, 150.18° E. Because no seismograph stations were operating close (<20 km) to the epicentre, it was not possible to estimate the depth from the travel-times. However, from the relationship $I_0 - I = 3 \log(1 + h^2/r^2)$ Båth, 1979, p.127), where I_0 is the maximum intensity and I the intensity at radius r, the depth, h, was calculated to be 7 km. If this depth is a reasonable estimate, the hypocentre was situated beneath the Sydney Basin, which is about 0.7 km thick at Lithgow (Bembrick, 1980).

The Richter magnitude (ML) was determined using Richter's standard distance factors extended by Eiby & Muir (1961). Distance corrections (Drake, 1974) were applied to compensate for the difference between the attenuation in southern California and southeastern Australia. Where measurement was made on a vertical component record, 0.15 was added to the ML values, because Richter's attenuation factors were derived for horizontal seismographs, which record larger amplitudes than equivalent vertical instruments. Table 1 shows the values of ML obtained for six stations. The scatter is discussed in another section. The mean value of ML is 4.3 ± 0.2, where the error term is the standard error of the mean.

Table 1. Magnitude of Lithgow earthquake

Station	Distance (degrees)	Azimuth (degrees)	ML
COO	3.2	27.1	3.8
RIV	0.9	113.0	3.9
STK	7.4	280.1	4.2
CMS	4.2	297.3	4.3
TOO	5.6	221.8	4.7
BFD	7.2	237.3	4.7
			Mean 4.30 ± 0.2

Macroseismic effects

The isoseismal map shown in Figure 1 is based on 129 reports (65 felt and 64 not felt) from questionnaires, verbal reports, and photographs of damage in Lithgow (Figs. 2, 3, 4). Included in this data set are 36 replies to questionnaires distributed by the Sydney Metropolitan Water, Sewerage and Drainage Board (L. McQueen and A. Preston, personal communication).

Sheryl Taylor of television station Channel 9 (Sydney) inspected the damage in Lithgow the day after the earthquake. She saw several partly demolished chimneys and broken windows, a shop in which beams 25 cm thick had shifted, a house in which the footings and front step had moved, and fresh cracks in walls and the widening of existing cracks in some buildings. Don Kipp of the *Lithgow Mercury* said that the earthquake had been felt severely all over Lithgow, bringing people running out into the streets. Objects fell off shelves in many parts of the city. The intensity was less in the underground mines than on the surface, because the amplitudes of both body and surface waves are greater at a free surface.

In a well-built wooden single-storey house on compact ground in Wallerawang (7 km northwest of Lithgow), about the lower 60 cm of the walls were made of brick on concrete footings (Mr. Lang, personal communication). The earthquake produced a vertical crack, approximately 1 mm wide, that passed through eight courses of bricks and mortar of the lower wall, one brick length from a corner of the house. In another single-storey house on compact level ground, the earthquake caused narrow vertical cracks each running through two or three bricks and the intervening mortar of the lower wall, which was of poor quality brickwork. Fibro walls in other houses suffered 1 cm wide cracks running from the ceiling to half way down the wall at an angle of about 30° to the vertical (Mrs Bird, personal communication).

In Wallerawang power station, the earthquake caused new cracks in a previously cracked wall on the first floor. The new cracks were in a part of the wall that was not already cracked (John Forest, personal communication). Both vertical and diagonal cracking occurred (Figs. 5, 6). A diagonal crack also occurred in the well-built brick external wall of the power station at ground floor level. The crack is 2.5-3.0 m long and decreases from about 1.5 mm wide at the top to approximately 0.5 mm at the lower end, petering out about 1.3 m above ground level. It generally follows the mortar, but passes diagonally through several bricks. The main generator at the power station tripped, owing to physical shaking of the float-type switch (Bucholtz relay) on the transformer.

The maximum intensity was assessed as VII on the Modified Mercalli scale, 1956 version (Richter, 1958), at both Lithgow and Wallerawang.

Several reports of anomalous damage (Fig. 1) were received from Bathurst some time after the earthquake. These were attributed to the February 13 event. One claim of moderate damage to brick and plaster in all rooms of a single storey, well-built brick house on compact level ground was paid by an insurance company (Joan Renshaw, personal communication). The apparently high intensities in some

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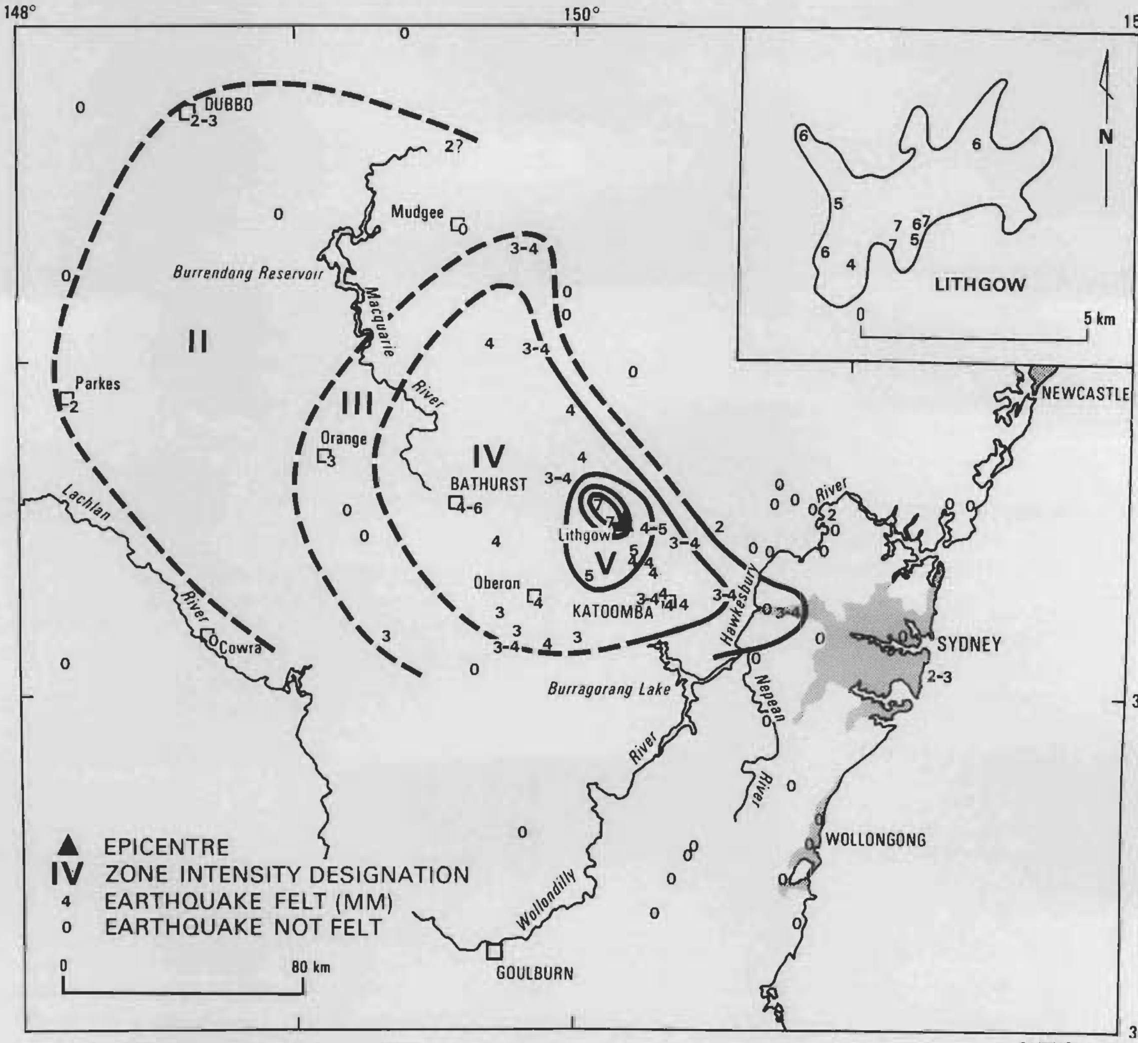

Figure 1. Isoseismal map of the Lithgow earthquake of 13 February 1985.
Intensities were determined with reference to the Modified Mercalli scale, 1956 version (Richter, 1958). The inset shows an enlargement of the Lithgow urban area.

Figure 2. Chimney in Lithgow, collapsed at the roofline because of the earthquake.
It used to be the same height as the chimney in the background (A. Churchill—personal communication). Photograph by A. Churchill, Rembrandt Photographics, Lithgow—commissioned by BMR.

Figure 3. Earthquake-damaged chimney in Lithgow.
Photograph by A. Churchill, Rembrandt Photographics, Lithgow—commissioned by BMR.

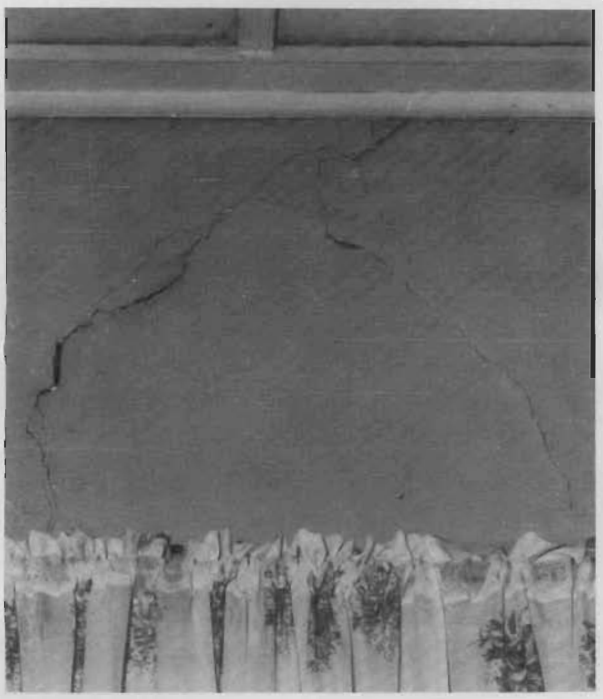

Figure 4. Cracking in a wall of a house in Lithgow.
The crack on the left was caused by the earthquake; the one on the right was slightly re-opened (A. Churchill—personal communication). Photograph by A. Churchill, Rembrandt Photographs, Lithgow—commissioned by BMR.

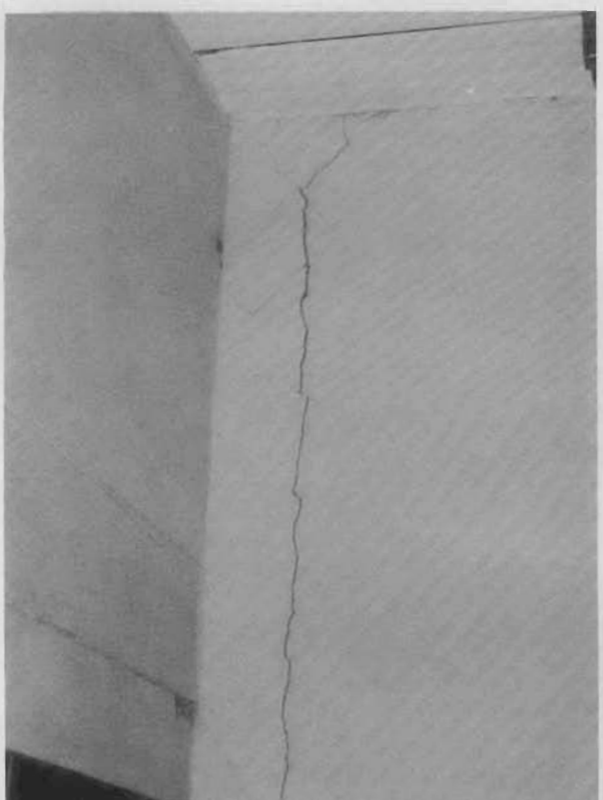

Figure 5. Vertical and diagonal cracking on the first floor of Wallerawang Power Station.
The 'X' crack near the top of the picture is caused by failure in tension along both diagonals during horizontal oscillations. Photograph by J. Forest, Wallerawang Power Station.

parts of Bathurst are difficult to explain. However, the earthquake was felt as far away as Parkes and Dubbo, 200 km from the epicentre.

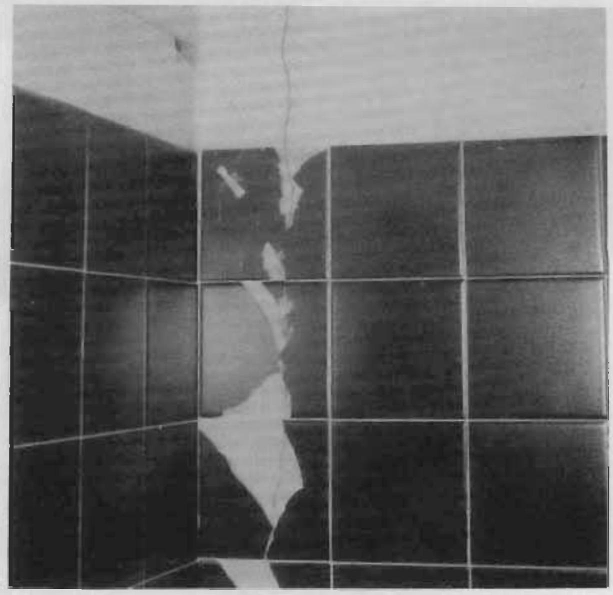

Figure 6. The vertical crack in Figure 5 continues down into the tiles in the lower part of the wall.
Photograph by J. Forest, Wallerawang Power Station.

The earthquake is estimated to have caused about $65 000 worth of damage. (This was deduced from information provided by the major insurance companies, and allowing for the excess and for the fact that not all houses were insured with these companies).

Anisotropy of attenuation

The isoseismals of the Lithgow earthquake are very asymmetrical, suggesting that the attenuation east of the epicentre is much greater than to the west. Figure 7 shows the positions of the Sydney Basin and the Lachlan Fold Belt and indicates that, for this earthquake, the attenuation of ground shaking was much greater in and under the Sydney Basin than through the Lachlan Fold Belt.

Figure 8 shows a comparison of the attenuation in intensity along segments QP and QR of line PQR in Figure 7. This line was chosen because it provides the best coverage of intensity data for the Sydney Basin and Lachlan Fold Belt (see Fig. 1). Nevertheless, there is a great deal of uncertainty about the positions of some of the isoseismals. This is indicated by error bars in Figure 8. Despite the uncertainty, the attenuation is clearly greater along section QR to the east than along QP to the west. If the position of the epicentre on the isoseismal map (Cotton, 1921) of the Kurrajong earthquake is correct, the rather meagre data from that event suggest that a similar, though less pronounced trend may have been observed.

The scatter of magnitudes in Table 1 also suggests anistropy of attenuation. There appears to be relatively high attenuation in and under the Sydney Basin (relatively low values of ML at RIV and COO) compared to the west (CMS and STK) and southwest (TOO and BFD). The attenuation to the southwest appears to be particularly low. Part of the differences in the attenuation may be due to the radiation pattern caused by the faulting mechanism. However, as this is unknown, it cannot be allowed for.

Acknowledgements

We are very grateful to L. McQueen and A. Preston for supplying us with replies to questionnaires concerning felt

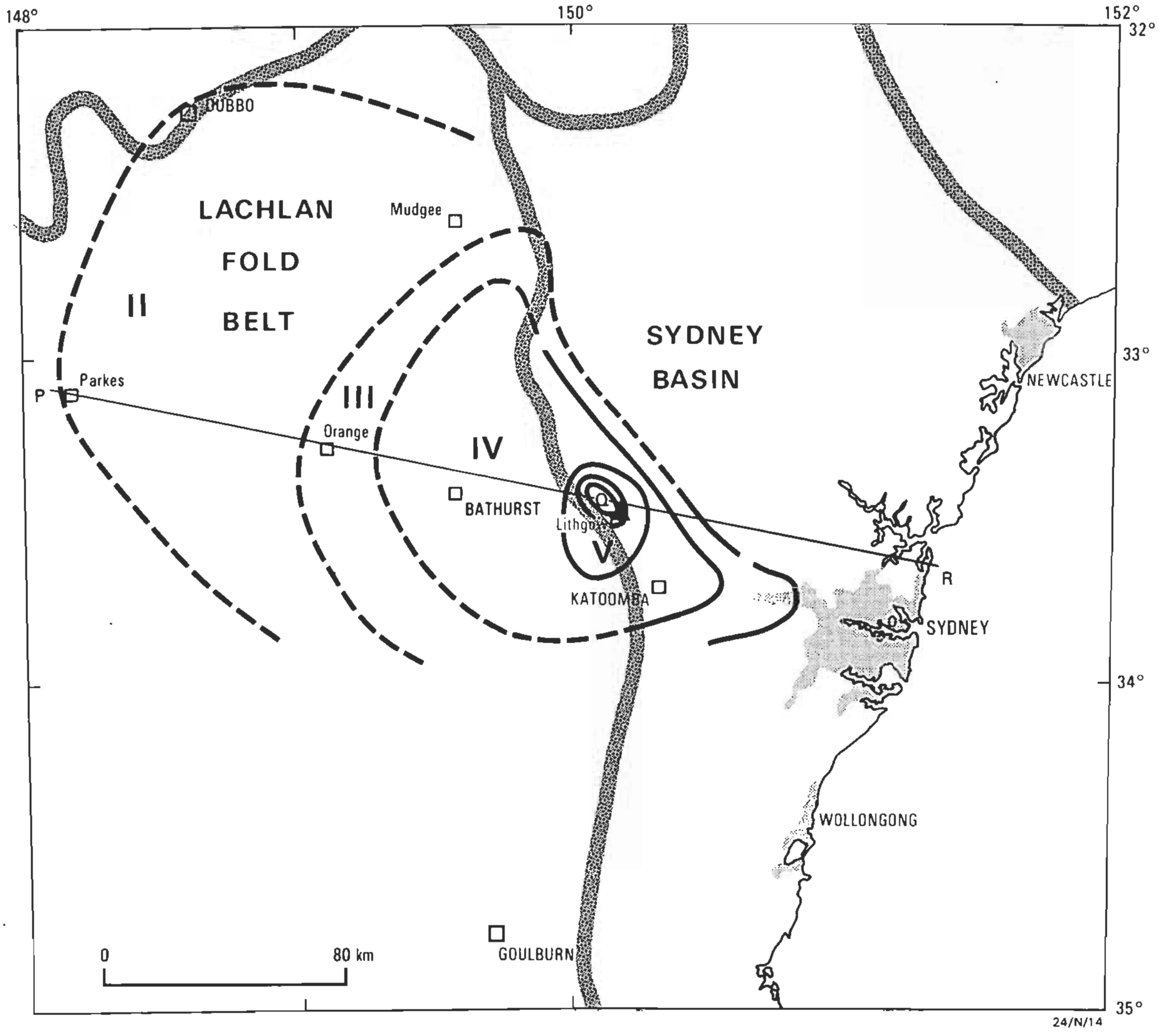

Figure 7. Relationship of the isoseismals to the major structural elements of the area.

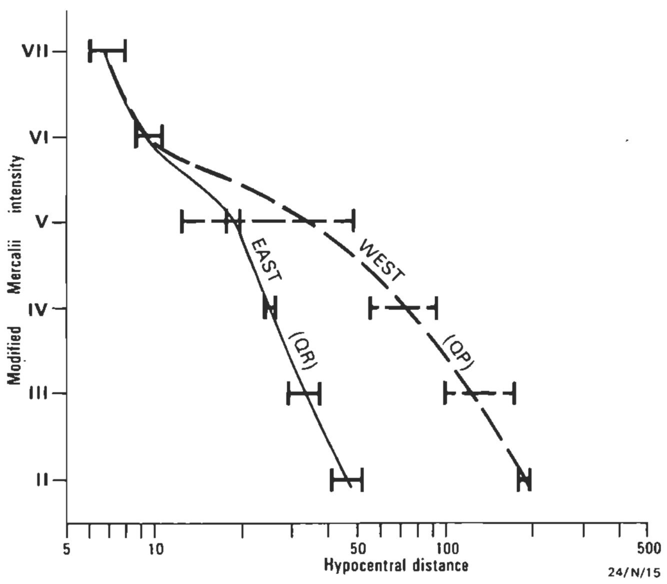

Figure 8. Attenuation curves for the intensity along segments PQ (to the west) and QR (to the east) of line PQR in Figure 7.

effects of the Lithgow earthquake. We acknowledge the help of A. Bullock, T. Jones, P. Eversons, M. Douch, and L. Hodgson, all of BMR, in collecting information related to the earthquake. We thank B. Gaull and K. McCue for critically reviewing the manuscript, P. Burrell and L. Creamer for typing it, and C. Fitzgerald for drafting the figures.

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Direction of magnetisation in core samples from drill holes

Terry Lee[1]

A solution is presented for the practical determination of the direction of magnetism in core samples from drill holes.

Introduction

This note treats the problem of finding the common direction of magnetisation in a number of cores obtained from drill holes. The problem arises because, while the direction of magnetisation may be measured in the sample, the core sample is rotated during sampling.

Some related problems are to be found in structural geology. In those cases, graphical methods of solution, employing a stereographic net, have been known for some time. Such methods of solution are in widespread use amongst geologists. A discussion of some of these problems and their solutions can be found in works by Tex (1954), Whitten (1966, pp 10-31) and Phillips (1960). In these, the reader may find a discussion of the use of the stereographic net and a statement of some of its mathematical properties. Some of these properties will be made use of here.

Solution

It is clear, when looking down the drill hole, that all the possible angles for the direction of magnetisation will trace out a cone. A cross section of one such cone, of angle ψ_i, is shown in Figure 1. Here, ψ_i is the angle that the direction of magnetisation makes with the drill hole axis. At the position where the sample is taken, the drill hole has a hade of θ_i. The cross section of the cone can be projected, stereographically, onto the equatorial plane OABC by means of the construction shown in the Figure 1.

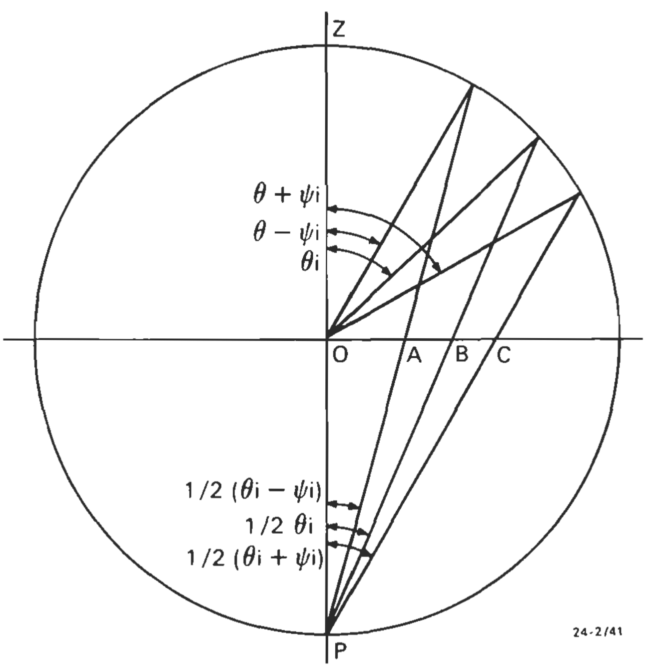

Figure 1.

In general, the direction of the i[th] drill hole, will be fixed by specifying not only the hade but also the angle γ_i. Figure 2 shows the projection of the direction of such a drill hole. Also shown is the projection of the base of the cone, which specifies the various possible directions of magnetisation. The fact that the base of the cone projects as a circle, of radius r_i, follows from a theorem concerning the stereographic projection. This theorem states that any circle on the sphere, a cross section of which is shown in Figure 1, will project as a circle (Hilton, 1963, p.3).

Suppose that the centre of such a circle is at a distance Ri from the centre of the projection (Fig. 2). The problem of finding the direction of the magnetisation vector can now be reduced to finding the point on the equatorial plane for the direction of the magnetisation vector. A moment's thought will show us that, in general, the results of at least three samples will be required.

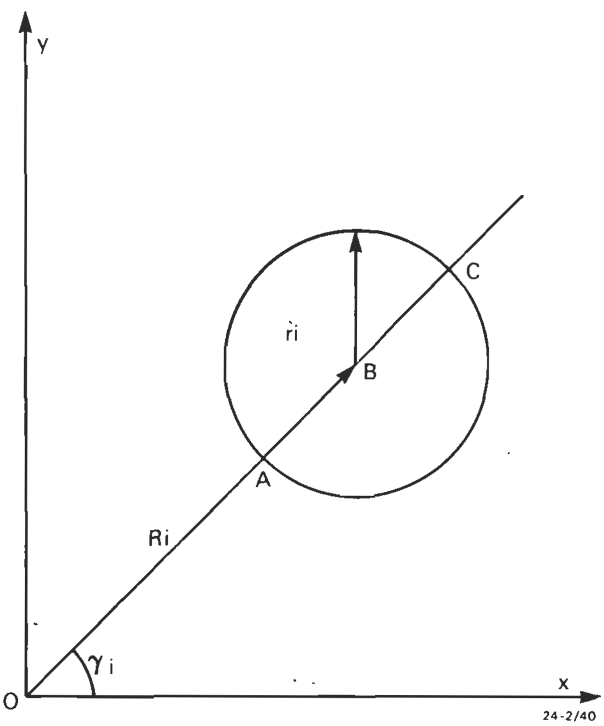

Figure 2.

From Figure 1, it can be readily seen that, for the i[th] drill hole, the various distances OB, OC and BC are given by the equations 1-3 below.

$$OB = \tan(\theta_i/2) = B_i \quad (1)$$

$$OC = \tan\{(\theta_i + \psi_i)/2\} = C_i \quad (2)$$

$$BC = \{\tan(\psi_i/2) + \tan^2(\theta_i/2)\tan(\psi_i/2)\}/\{1 - \tan(\theta_i/2)\tan(\psi_i/2)\} = A_i \quad (3)$$

Also $$AB = \{\tan(\psi_i/2)\sec^2(\theta_i/2)\}/\{1 + \tan(\theta_i/2)\tan(\psi_i/2)\} \quad (4)$$

and $$r_i = \{\tan(\psi_i/2)\sec^2(\theta_i/2)\}/\{1 - \tan^2(\theta_i/2)\tan^2(\psi_i/2)\} \quad (5)$$

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From Figure 2, we can see that, if (x_i, y_i) are the coordinates of the centre of the circle, then:

$$x_i = R_i \cos(\gamma_i) \quad (6)$$
$$y_i = R_i \sin(\gamma_i) \quad (7)$$
$$R_i = r_i - \tan\{(\psi_i - \theta_i)/2\} \quad (8)$$

Now it is easy to write down the equations for the various circles. Suppose that the equations are numbered for i = 1, 2. . .N and that the equation for the N^{th} circle is subtracted from all the other equations.

When this is done:

$$x(x_N - x_i) + y(y_N - y_i) = \tfrac{1}{2}(r_i^2 - r_N^2 - x_i^2 - y_i^2 + x_N^2 + y_N^2) = \beta_i$$

$$i = 1, 2 \ldots N-1 \quad (9)$$

When N = 3, the point on the yox plane, for the direction of magnetisation (x, y), is described by:

$$x = \frac{\beta_1 (y_3 - y_2) - \beta_2 (y_3 - y_1)}{(x_3 - x_1)(y_3 - y_2) - (x_3 - x_2)(y_3 - y_1)} \quad (10)$$

$$y = \frac{\beta_2 (x_3 - x_1) - \beta_1 (x_3 - x_2)}{(x_3 - x_1)(y_3 - y_2) - (x_3 - x_2)(y_3 - y_1)} \quad (11)$$

While equations 9,10, and 11 might be suitable for the situation where the errors in the measurements are negligible, this may not be so in the practical situation. In this case, the alternative method, based on the method of least squares (given below) should be used. In situations where the mutual inclination of drill holes is small, say the order of 10°, then the method of least squares should be used in preference to the method defined by equations 9, 10, and 11.

Where there are more than three equations, they may be solved by the method of least squares.

Writing $(x_N - x_i) = \eta_i$

$y_N - yi = \zeta_i$

$$S1 = \sum_{i=1}^{N-1} \eta_i^2 \qquad S2 = \sum_{i=1}^{N-1} \zeta_i \eta_i$$

$$S3 = \sum_{i=1}^{N-1} \beta_i \eta_i \qquad S4 = \sum_{i=1}^{N-1} \beta_i \zeta_i$$

$$S5 = \sum_{i=1}^{N-1} \zeta_i^2$$

one finds that

$$x = \frac{S3\ S5 - S4\ S2}{S1\ S5 - S2^2} \quad (12)$$

$$y = \frac{S1\ S4 - S2\ S3}{S1\ S5 - S2^2} \quad (13)$$

Any reader not familiar with the method of least squares can find all the details he needs in Froberg (1965).

Once the coordinates for the projection of the direction of magnetisation are known; the hade, θ, and the azimuth, γ, of the direction of magnetisation can be found from equations (14) and (15) below:

$$\gamma = \text{arctran}\,(y/x) \quad (14)$$
$$\theta = 2\ \text{arctran}\ \sqrt{x^2 + y^2} \quad (15)$$

Example

As an example, a synthetic data set (Table 1) was generated on a stereographic net. The direction as specified on the net was determined by γ = 30° and θ = 59°. Using the method described above, the values of 30.6° and 59.6° were found for the hade and azimuth of the direction of magnetisation, respectively.

Table 1. Synthetic data set for worked example.

θ_i	γ_i	ψ_i
20°	66°	11°
40°	74°	16½°
70°	54°	33½°
340°	48°	41½°
0°	60°	26½°

Acknowledgements

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Probabilistic earthquake risk maps of southwest Western Australia

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New earthquake risk maps of southwest Western Australia including continental margins have been prepared. The risk is depicted as contours of peak ground velocity, acceleration, and ground intensity with a 10 per cent probability of being exceeded in 50 years. The maps are based on the Cornell-McGuire methodology. Ten earthquake source zones have been thus defined and corresponding recurrence relations derived. The relation obtained, using a maximum-likelihood fit, for the primary zone to the east of Perth, is log N = 3.66-0.90 ML, where N is the number of events greater than or equal to the Richter magnitude, ML. Local intensity attenuation constants, a, b, and c, are derived for the expression $I = ae^{bML}R^{-c}$, where I is the estimated Modified Mercalli intensity at a hypocentral distance R km from an earthquake of magnitude ML. Using the relation $\log A = I/3.1 - 2.3$ to convert the intensity to peak ground acceleration, A in $m.s^{-2}$, the adopted constants were 0.025, 1.10 and 1.03 respectively. Similarly, using the empirical formula $2^I = 7v/5$ to convert intensity to peak ground velocity, v in $mm.s^{-1}$, the corresponding values were 3.30, 1.04 and 0.96, respectively. The contour expressing the greatest risk in the area of interest is that of a peak ground velocity of 160 $mm.s^{-1}$, and it encloses an area of about 2000 km^2 centred on the most active source zone east of Perth. The value for Perth city is 48 $mm.s^{-1}$. Increasing (i) the maximum magnitude from ML 7.5 to ML 8.5; (ii) the depth of earthquake foci from 5 km to 15 km; (iii) the b value from 0.90 to 0.94; and (iv) the attenuation constants to their estimated maximum value, in the primary source zone, changes the Perth velocity contour from 48 $mm.s^{-1}$ to 56 $mm.s^{-1}$, 48 $mm.s^{-1}$, 42 $mm.s^{-1}$, and 58 $mm.s^{-1}$, respectively. The omission of a suspected seismic gap 100 km east of Perth from the primary source zone changes the velocity contour from 48 $mm.s^{-1}$ to 46 $mm.s^{-1}$. Sensitivity to adopting another empirical relation between peak ground acceleration and intensity has been examined. This increases the risk at Perth from 0.44 $m.s^{-2}$ to 0.65 $m.s^{-2}$. We recommend a microzonation study of Perth and installation of more strong-motion instruments to improve our risk estimates, which should be updated in 5-10 years.

Introduction

The first significant attempt to quantify earthquake risk in the southwest of Western Australia was that of Everingham (1968), who determined the frequency of earthquakes there. Everingham & Gregson (1970) went further and determined apparent ground intensity return periods for 10 major centres in Western Australia. McCue (1973) carried out a more comprehensive study on the earthquake risk in the area of interest. His results are consistent with those of this study.

The first attempt to zone the whole of Australia was made by McEwin & others (1976), whose results overestimated the risk, mainly because they used an attenuation relation determined from Californian data. Denham (1976) published a preliminary zone map of Australian earthquake hazard, based on the results of McCue (1973, 1975, 1978) and McEwin & others (1976). The final map adopted for inclusion in the Australian Building Code by the Standards Association of Australia, and compiled by the Australian National Committee for Earthquake Engineering, is fundamentally the same as that in the BMR Earth Science Atlas (Denham & others, 1979). McCue (1973) recommended that zoning should be reviewed as more data become available. As the data base has more than quadrupled since the last earthquake risk map was prepared, this is an appropriate time to prepare new maps.

Because of interest already shown in the earthquake risk at Perth, we decided firstly to produce risk maps for the southwest of Western Australia (to the edge of the shelf) bounded by latitude 28.5°S to the north and longitude 122.5 E to the east. We have used the Cornell-McGuire method as described by Basham & others (1985).

Method

Earthquake zone configuration

Seismic risk estimation using the Cornell-McGuire method requires the definition of earthquake source zones, each having its own magnitude-frequency recurrence relationship. The zones (Fig. 1) were chosen primarily on the basis of the areal distribution of epicentres and, occasionally, geological and tectonic factors. A constraint on the choice of source geometry was that the computer program required each zone to be made up of a series of quadrilaterals.

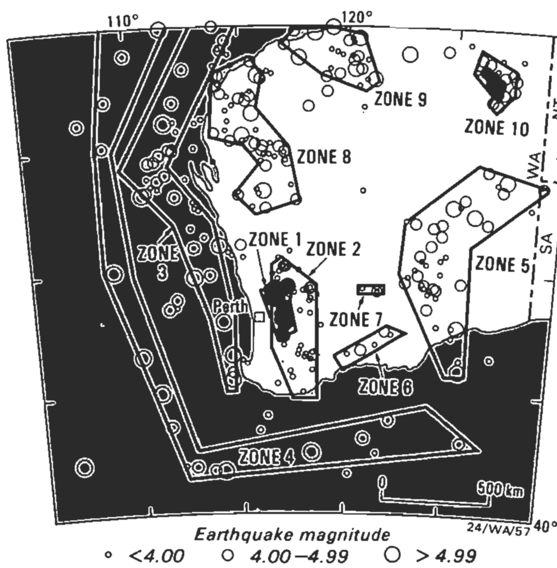

Figure 1. Earthquake source zones affecting the seismic risk in southwest Western Australia.

Because of its relatively high rate of seismicity, source zone 1 has great influence on earthquake risk in the southwest of Western Australia. Therefore, the zone 1 configuration is critical. McCue (1973) pointed out that the proximity of the zone boundary has great influence on the risk adjacent to it. Hence, the western side of source zone 1 will have the greatest effect on the risk at Perth. Everingham (1968) suggested that the western margin of source zone 1 roughly coincides with the boundary of a region of very high grade metamorphism. We agree with this and also note that the same holds true for the southern boundary (Fig. 2). If the general trend of the western boundary of the metamorphics is adopted as the western margin of source zone 1, then this zone includes an apparent seismic gap near Northam in which there is no current seismicity (Fig. 1). However, evidence from repeated levelling surveys suggests that this region has high strain rates (P.W. Wellman, BMR, personal communication)

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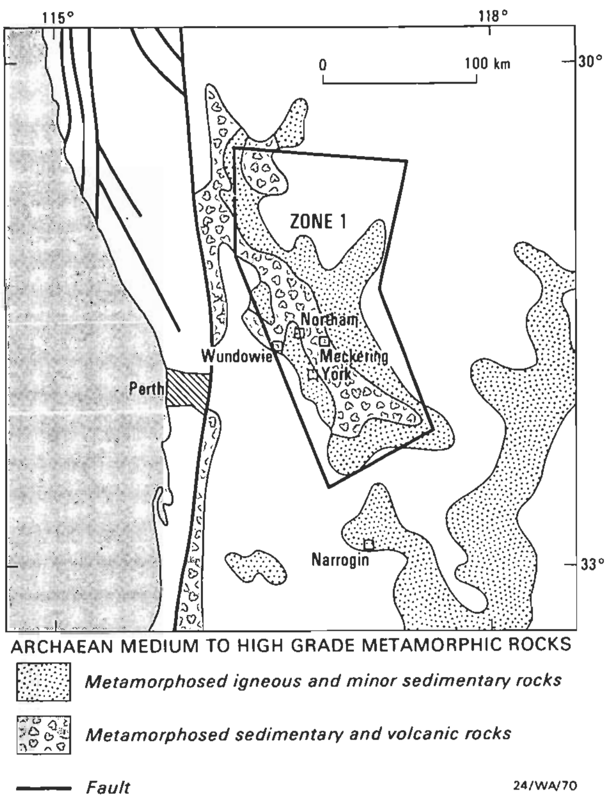

Figure 2. Relation of source zone 1 to the regional geology. The western and southern margins of the zone roughly coincide with the corresponding boundaries of the Archaean metamorphics.

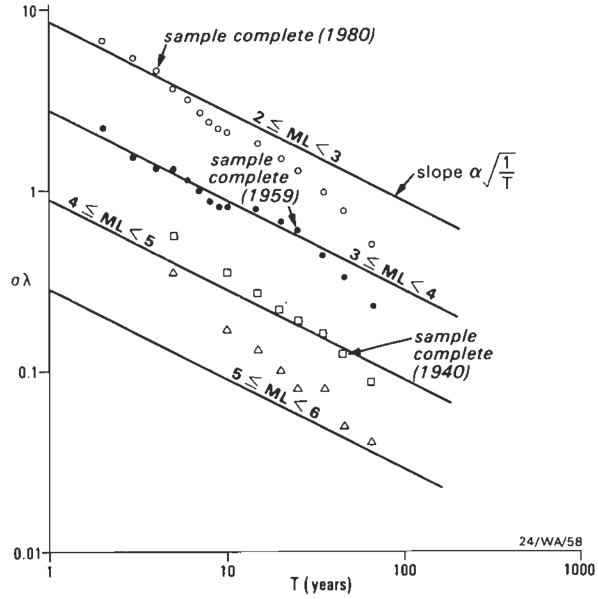

Figure 3. Completeness test for source zone 1.

and, therefore, should be included in the zone. Historical felt reports (Everingham, 1968) also suggest that the Northam area is not aseismic.

Other source zones for which tectonic or geological factors were taken into account are source zones 3, 4, 6, and 7 (Fig. 1). Source zone 3 follows the continental margin, whereas epicentres in source zone 4 are located generally along the 5000 m isobath. Source zone 6 is an expression of activity along the Fraser Fault, and the activity in source zone 7 is mainly a result of rock bursts in mines in the Kalgoorlie area. These events have contributed to many felt reports and have occasionally caused minor damage.

Magnitude recurrence relations

The second requirement for the Cornell-McGuire method of estimating earthquake risk is to determine the magnitude recurrence relation for each source zone. The maximum-likelihood procedure was used to determine this relation in source zones 1 and 2. As the number of events in each of the remaining zones was less than 20, we decided to determine graphically the recurrence parameters A and b in Richter's (1958) equation $\log_{10} N = A - bML$, where N is the number of events greater than or equal to the Richter magnitude, ML.

For the maximum-likelihood determination it was necessary to give minimum and maximum magnitudes and periods of observation for each magnitude interval. Stepp (1972) described a method by which completeness of a data set could be tested: he defined a parameter known as the standard deviation of the estimate of the mean, $\sigma_\lambda = \sqrt{\lambda}/\sqrt{T}$, where λ = mean rate of occurrence of events = N/T (total number of events N over T years). σ_λ was plotted as a function of sample length (Fig. 3) for events in source zone 1. The test also requires that events exhibit a Poisson distribution and, therefore, all aftershocks were removed from the statistics. Assuming stationarity of event frequency, we expect that σ_λ behaves as $1/\sqrt{T}$ in the subinterval of completeness. The onsets of sample completeness for different magnitude classes are shown by arrows in Figure 3 and have been used to determine first years of complete reporting (Table 1).

Table 1. Completeness intervals adopted for earthquake source zones (First year of complete reporting given. Final year was 1983)

Source zone	*ML 2-3*	*ML 3-4*	*ML 4-5*	*ML 5-6*	*ML 6-7*	*ML 7-8*
1	1980	1959	1949	1949	1949	—
1	1980	1959	1940	1904	1849	—
2	1982	1976	1960	1940	—	—
3	—	—	1976	1960	1884	—
4	—	—	1981	1960	1901	1901
5	—	—	1974	1960	1960	—
6	—	—	1974	1960	1960	—
7	13 events ML ≥ 3.5 in 80 years taken from Everingham (1968)					
8	—	—	1981	1960	—	1829
9	—	—	—	1968	—	—
10	—	—	—	1972	1930	—

Two different sets of completeness periods were chosen to establish two b values for source zone 1. See text for explanation.
Source zones 9 and 10 were neglected in the final analysis as they were more than 600 km from the area of interest.

However, there is reason to suspect that the earthquake process may not be stationary in source zone 1. Everingham & others (1972) showed that no events of magnitude ML ≥ 4.5 occurred in that zone during the period 1923-39 and probably for the entire period 1900-39, and stated that, since 1940, events of this magnitude have occurred at the rate of 0.4 to 0.5 per year. Also, Gregson (1985) indicated that there has been a five-fold increase in the seismicity of the Southwest Seismic Zone in the last 17 years. Michael-Leiba (1986—this issue) has suggested, particularly on the basis of numbers of ML ≥ 5.0 earthquakes, that an increase in seismicity started around 1949. The recurrence relation using events from completeness intervals shown in line 1 of Table 1 is shown in Figure 4, and the maximum-likelihood derivation is given by

$$\log_{10} N = (3.66 \pm 0.14) - (0.90 \pm 0.02)ML$$

As can be seen from Figure 4, this procedure weights the points according to the sample number. Consequently, the

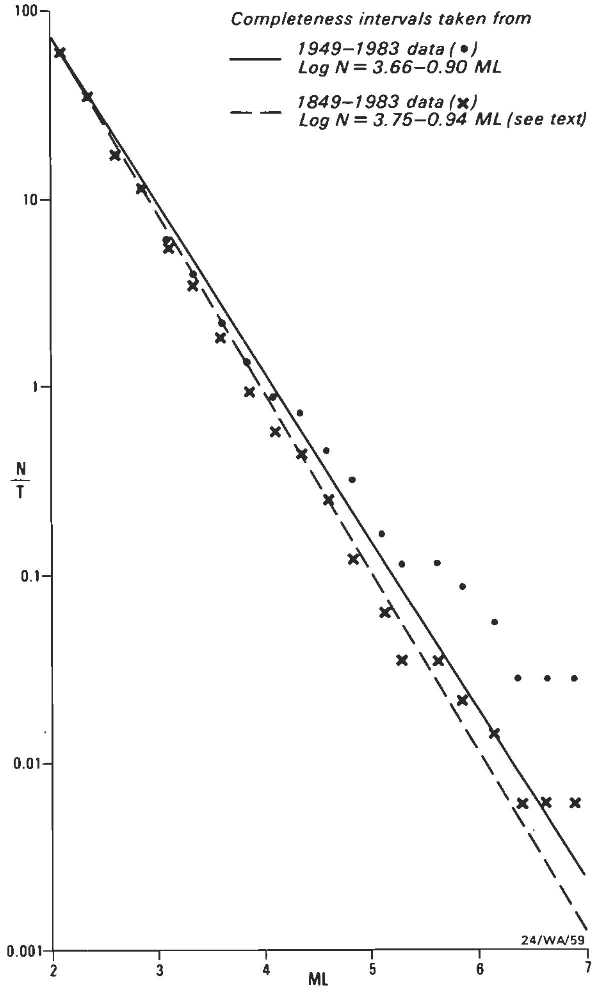

Figure 4. Recurrence relations for earthquake source zone 1, using the maximum-likelihood method.

derived line deviates from the plotted points at the higher magnitude end.

If we assume the earthquake process has remained stationary since 1849 in source zone 1 and adopt completeness periods as shown in line 2 of Table 1, the resultant recurrence relation is given by $\log_{10}N = (3.75 \pm 0.15) - (0.94 \pm 0.02)ML$. These two relations do not show a five-fold increase in seismicity because they have not been taken from the separate time periods (pre 1949 and post 1949). However, the first of these relationships does reflect an increase in level and was adopted for the analyses in this paper. The decision is also supported by McGuire (1979), who stated that the most recent seismicity levels give rise to more reliable estimates for earthquake risk in the near future. However, effects of adopting either recurrence relation above are noted in the discussion.

Guidance for first years of complete reporting in each magnitude class shown in Table 1 was provided by the Stepp test (Fig. 3) and knowledge of the history of seismograph coverage in the region. Details from historical reports by Everingham (1968) and Everingham & others (1971) were also used. The Stepp test was not used for zones 3-8 because of the small number of events on file.

For earthquakes that had been assigned magnitude in terms of body wave (MB) only, conversion to Richter magnitude (ML) was carried out using the expression ML = 1.37MB – 2.47 (McGregor & others, 1976). There were about 50 such earthquakes on file that were located in zones 3-8. From other regional earthquakes that had both MB and ML reported, it was apparent that the above relation was reasonable, but the scatter was large. The whole question of magnitudes in Australia is currently under review.

Maximum magnitude

Generally, maximum magnitudes for each source zone were chosen using the rule usually adopted by the Canadians during their recent study of earthquake risk assessment (Basham & others, 1982), i.e. the maximum magnitude in a zone was assumed to be (MAX + ½), where MAX represents the largest Richter magnitude on record for that zone. The value adopted for source zone 1 was ML 7.5.

The effects of varying this parameter on predicted ground motion at Perth are discussed later in this paper. Adopted values of completeness intervals, magnitude recurrence parameters, maximum and minimum magnitudes, and area of each of the ten earthquake source zones shown in Figure 1 are presented in Tables 1 and 2.

Table 2. Source zone parameters

Source zone	*A*	*b*	*Min*	*Max*	*Area* (km^2)
1	73.0	0.90	2.0	7.5	17 000
2	16.95	1.00	2.0	7.5	92 300
3	2.00	1.00	4.0	7.5	311 250
4	1.00	0.67	4.0	8.0	545 000
5	1.66	0.83	4.0	7.0	238 000
6	0.14	0.83	4.0	6.0	18 200
7	0.46	0.63	3.0	4.5	3 900
8	3.60	0.94	4.0	7.7	135 700
9	2.80	0.91	4.0	6.0	84 200
10	7.50	1.01	4.0	7.5	24 400
Background	0.60	1.00	2.0	5.0	10 000

Min = Minimum Richter magnitude earthquake in zone
Max = Maximum Richter magnitude earthquake in zone
A = Number of earthquakes per annum above Min
b = Richter (1958) constant called b value.

Removal of aftershocks

Michael-Leiba (1986—this issue) has also demonstrated that earthquakes in the Southwest Seismic Zone of Western Australia appear to be Poissonian in their distribution only when aftershocks are removed. Consequently, aftershocks were eliminated from the data sets for determination of magnitude recurrence parameters. The removal of aftershocks from the data set is justified because:
a) the return periods of the aftershocks are really tied to the return period of the principal shock and if they are included in the statistics they distort the recurrence relation for middle-range magnitude events; b) damage is primarily caused by the principal shock; and c) assessment of ground intensities is usually done during the aftershock sequence of a major earthquake, and, therefore, effects caused by aftershocks have been largely taken into account in the isoseismal maps that we used in deriving the attenuation constants.

For the purposes of removal of aftershocks from the data sets, it was decided to define them in both space and time. Spatially, we used the relation log L = 3.2 + 0.5M (Kasahara, 1981), where L is the length of the fault in cm of an earthquake of surface-wave magnitude M. Consequently, if an event came within about one fault length of the epicentre of the principal shock, it was deemed an aftershock. To make the rule simple to apply, we eliminated events within 0.5 and 0.1 earth degrees of the Meckering and Cadoux epicentres, respectively, provided that they satisfied the time condition as well.

The time window was defined by when the aftershock rate dropped to below 10 per cent of the rate the day after the principal shock. For Meckering (14.10.68) this occurred at the end of November, 1968, and for Cadoux (2.6.79) the corresponding date was the end of 1979.

Background seismicity

The epicentres not enclosed in one of the ten source zones (Fig. 1) are considered to be background seismicity. They have been grouped for the purpose of deriving the recurrence parameters shown in Table 2. The seismicity rate refers to a unit area of 10 000 km^2.

Strong ground-motion attenuation

To estimate values of ground motion at a site at known distance from the seismic source zones it is necessary to define the way in which strong ground motion is attenuated with distance. The Cornell-McGuire computer program then uses the attenuation and recurrence relations to numerically integrate contributions from all these zones to evaluate probabilities of exceeding different levels of ground motion at a site.

The Cornell-McGuire methodology assumes that the attenuation relations for both ground acceleration and velocity can be described by the empirical formula of Kanai (1961), $Y = ae^{bML}R^{-c}$, where Y represents peak acceleration or velocity, ML is Richter magnitude, R is hypocentral distance, and a, b, and c are constants.

There have only been three recordings of ground acceleration during large earthquakes ($ML > 5.5$) on the shield in Western Australia. These were during the Cadoux earthquake of June 1979 (ML 6.2), and the three recordings were made at Meckering. These recordings were used, but were an inadequate sample upon which to base the attenuation curves. Consequently, rather than use overseas constants that are inappropriate, as discussed later, we decided to derive them from attenuation of ground intensity. Earthquakes for which isoseismal maps have been drawn (as appear in Everingham & others, 1982) were used to define the average isoseismal radii in the shield region of Western Australia. It is apparent in Figure 5 that there is scatter in the data and that they do not follow a simple logarithmic decay. Once the constants for attenuation of ground intensity (I) were established, the following empirical relationships were used to establish the attenuation in terms of peak ground velocity (V, in $mm.s^{-1}$) and acceleration (A, in $m.s^{-2}$): $2^I = 7v/5$ (Newmark & Rosenblueth, 1971) and $\log A = I/3.1 - 2.3$ (Gaull, 1979). The effect of using another empirical relation such as these on the risk estimates is given in the discussion. The peak accelerations measured from the accelerograms at Meckering during the Cadoux earthquake are shown on Figure 5 and the fit is good. The adopted values for the attenuation constants are presented and contrasted with the overseas constants adopted by McEwin & others (1976) (Table 3). For the analysis, a depth of 5 km was adopted for earthquakes

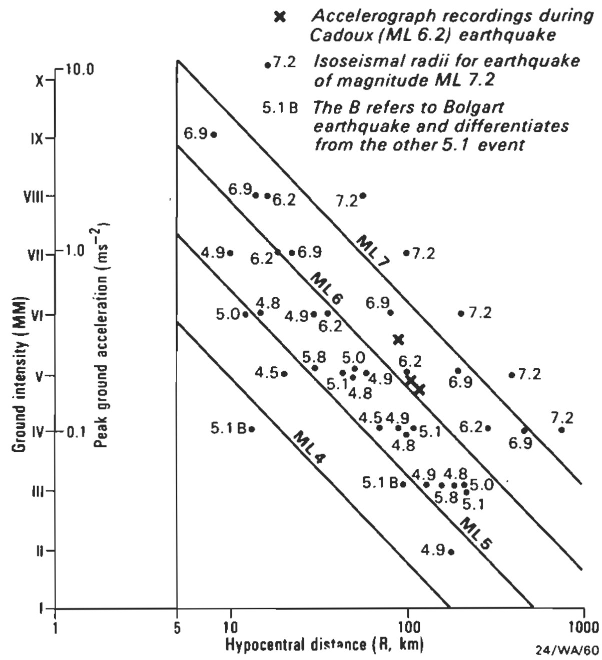

Figure 5. Isoseismal radii for earthquakes felt in the Yilgarn Block.

in all zones except source zone 7. It is evident from recorded S-P times on accelerograms in the Meckering and Cadoux areas that the seismicity is shallow. The depth of the major earthquake at Meckering in 1968 was finally adopted as 5 km. The depth of the rockbursts in the Kalgoorlie area was assumed to be 2 km, as it gave ground motions that were consistent with the historical record. The effects of changing the depth variable is discussed later.

Results

Intensity, peak ground velocity, and peak ground acceleration that correspond to a probability of 10 per cent of being exceeded over a 50 year period have been plotted and contoured (Figs. 6, 7, 8). Grids chosen for the contours were 0.25° for the region near source zone 1 where gradients were high (30–33°S, 115–118°E). Elsewhere, the grid used was 0.5°. The intensity results compare well with historical records.

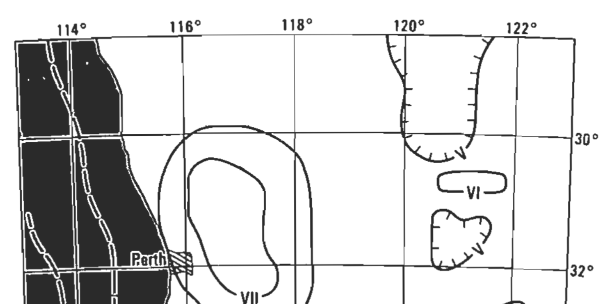

Figure 6. Contours of Modified Mercalli intensity with a 10 per cent probability of being exceeded in a 50 year period.

Table 3. Attenuation constants adopted for the Yilgarn Block, using the form: $Y = ae^{bML} R^{-c}$ (Kanai, 1961)

Ground motion parameter, Y	*a*	*b*	*c*
Intensity (MM) = lnY	9.03(2980)	1.50(1.5)	1.39(2.5)
Peak ground velocity ($mm.s^{-1}$)	3.30(160)	1.04(1.0)	0.96(1.7)
Peak ground accel. ($m.s^{-2}$)	0.025(20.0)	1.1(0.8)	1.03(2.0)

McEwin & others' (1976) constants are given in brackets: they used $R = \sqrt{(\Delta^2 + H^2 + C_o^2)}$, where Δ = epicentral distance (km), H = depth to focus (km), Co = depth adjusting constant (20 km).

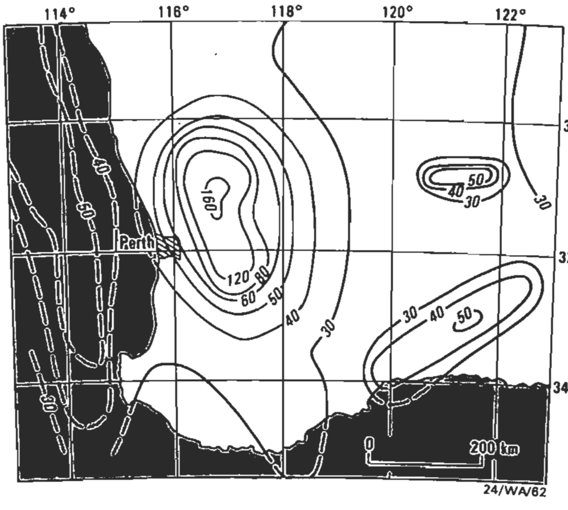

Figure 7. Contours of peak ground velocity in mm.s^{-1} with a 10 per cent probability of being exceeded in a 50 year period.

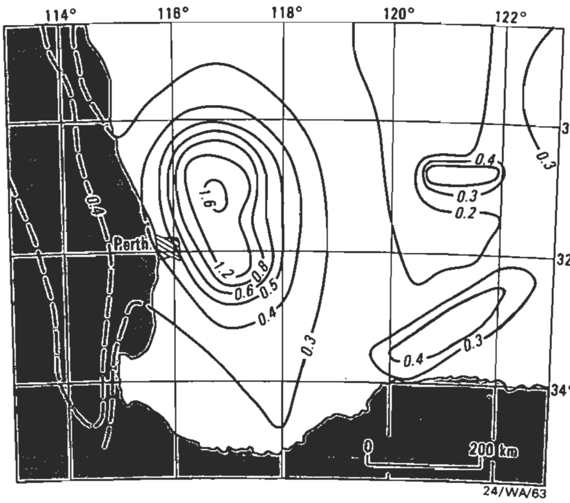

Figure 8. Contours of peak ground acceleration in m.s^{-2} with a 10 per cent probability of being exceeded in a 50 year period.

Basham & others (1982) have suggested that this probabilistic approach of expressing earthquake risk is more appropriate than the commonly adopted one of return periods. Although a 10 per cent probability of a particular event being exceeded within a 50 year period is mathematically equivalent to a return period of about 500 years, the former expression is more appropriate. This is because, in an engineering sense, structures are often designed to have a life span of about 50 years. Also, it is quite likely that seismic rates in a given source zone could change over a period of the order of hundreds of years.

The region subject to the greatest risk is the 160 mm.s^{-1} contour in Figure 7. It encompasses an area of about 2000 km^2 centred on source zone 1. Also, it is estimated that there is a 10 per cent chance that the ground motion in Perth will exceed 48 mm.s^{-1} or 0.44 m.s^{-2} during a 50 year interval. This ground motion corresponds to a Modified Mercalli intensity of about MMVI.

Discussion

In terms of the seismic risk at Perth, our results fall between McCue's (1973) two return period equations: $T = 8.55Y^{2.30}$ and $T = 14.20Y^{2.67}$, where T is the expected return period in years and Y the velocity in cm.s^{-1}. The first equation was derived using a b value of 1.0; and the second, his preferred result, 1.16. The lower b value obtained in this paper is due to the method. McCue (1973) used a least squares analysis and a 0.5 class interval (delta ML): his b value of 1.16 became 1.01 when a delta ML of 0.3 was used. Also, when he extended the upper range of the magnitudes from ML 5 to ML 7, his b value became 0.93. Our adopted class interval was 0.25 and we used the maximum-likelihood analysis.

It is now known that least squares analysis is not appropriate when dealing with cumulative data, as these type of data are not independent. Consequently, the maximum-likelihood method is the preferred procedure and was used by Basham & others (1982).

Our results were tested for their sensitivity to a change in various source zone 1 parameters, including maximum magnitude, average depth of earthquakes, b value, attenuation coefficients, and the exclusion of what has been treated as a seismic gap. These tests are discussed below.

McCue (1973) used Housner's (1968) approach to obtain estimates of the likely upper limit to earthquake magnitude in the Southwest Seismic Zone. His estimates ranged from ML 7.2 to 8.0, which agree reasonably with the ML 7.5 adopted in this paper. The sensitivity of peak ground velocity return periods at Perth and Meckering to changing this parameter from ML 7.5 to ML 8.0 or 8.5 is presented in Figure 9. Even at ML 8.5 the Perth city building code is unlikely to be changed, since such events are so infrequent.

It is evident that by changing the mean depth of earthquake foci from upper crustal to mid crustal (say 5 to 15 km) the hypocentral distance at epicentral distances of tens of kilometres or more will not be altered significantly. Therefore, the effect of changing this depth parameter should only change the risk at towns either adjacent to or inside the zone of seismicity. This test was carried out for Perth, Meckering, and Narrogin and, as expected, only Meckering's risk changed at all (Fig. 9).

The influence of the b value on risk estimates was another factor that needed to be examined. The effect of using the two recurrence relations established in Figure 4 in the risk evaluation at Perth and Meckering is also displayed in Figure 9. The corresponding risk for each town became slightly lower with the higher b value.

The effect of changes in the attenuation coefficients also needed to be investigated. The standard deviation, σ, of the residuals about the mean isoseismal radii, μ, for the Meeberrie, Meckering, and Cadoux earthquakes is 0.24 intensity units. The attenuation coefficients were then redetermined using values of $(\mu + \sigma)$ and $(\mu - \sigma)$ for the corresponding isoseismal radii and the risk calculated (Fig. 9). Expected ground motions for corresponding probabilities (or return periods) increased and decreased by about 20 per cent and 15 per cent respectively, which reflects the contribution to possible errors in the risk estimates from the uncertainty in attenuation.

The relation used to convert intensity to peak ground motion is another step in the procedure that can influence the risk estimates. To demonstrate this, the relation defined by Trifunac & others (1975), given by $\log A = I/3.3 - 2.0$, was used. The corresponding changes to the earthquake risk at Perth and Meckering were from 0.44 to 0.65 m.s^{-2} and 1.54 to 1.86 m.s^{-2} respectively. It is believed that the relation used in the analysis of this paper is the most appropriate, as it

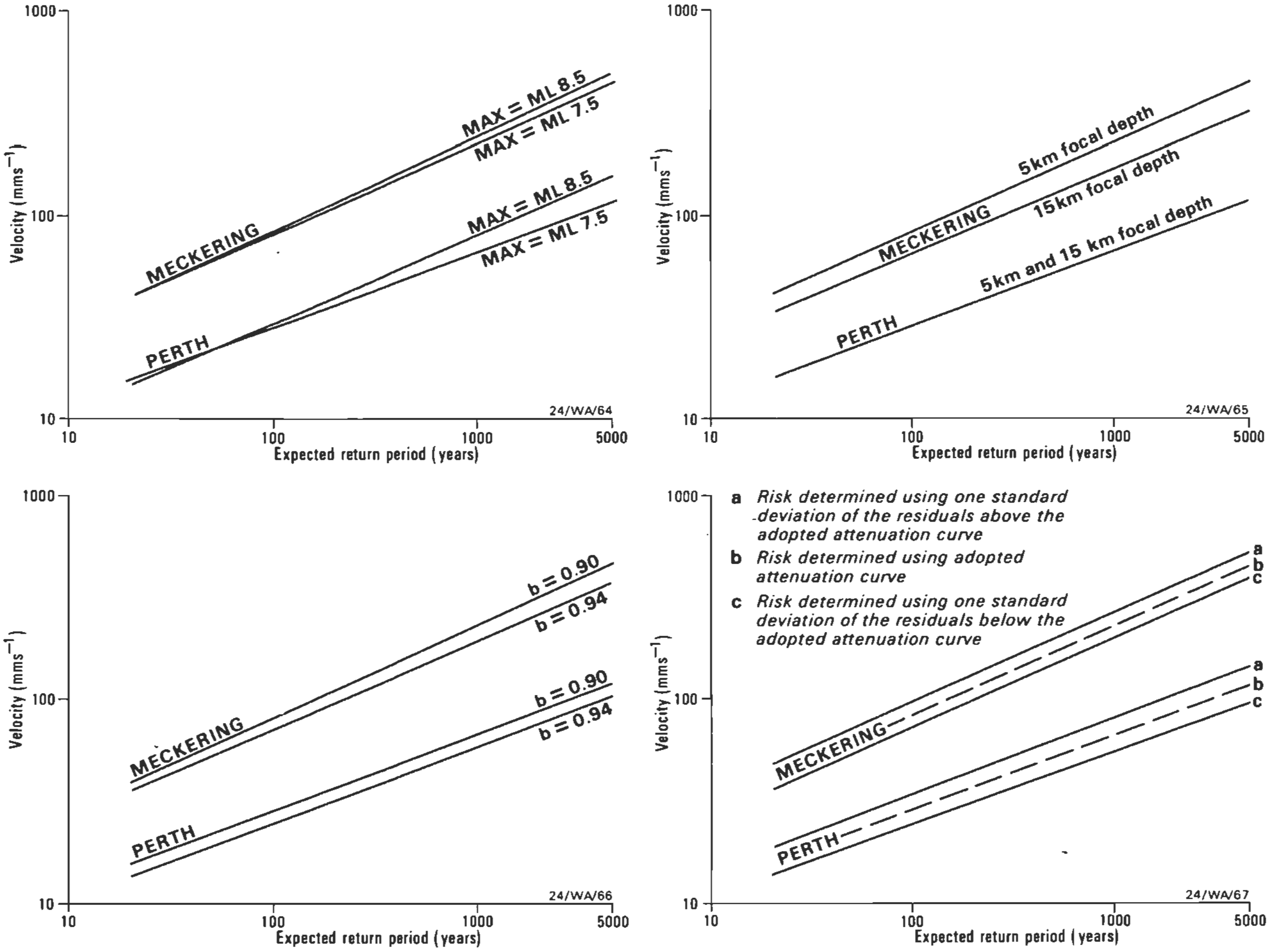

Figure 9. Top left: Effect of increasing maximum magnitude in source zone 1. Top right: Effect of increasing depth of foci in source zone 1. Bottom left: Effect of varying the b value in source zone 1. Bottom right: Effect of varying the attenuation coefficients in the Yilgarn Block.

fits the Cadoux earthquake data better than that of Trifunac & others (1975) or any of the other relations discussed by Gaull (1979). However, it is interesting to see what effect this factor has on the results.

Another sensitivity test carried out was the exclusion of the 'seismic gap' near Northam from source zone 1. The source zone configuration for zone 1 was changed to that shown in Figure 10. The gap takes the shape of a triangle, as shown, and has been deliberately omitted from source zone 1. The effects at Perth and some country towns have been presented in Figure 10. Very little change occurred at Perth, but significant reductions to the estimated risk at Northam, York, Meckering, and Wundowie were observed, as the seismicity has been effectively reduced near these towns. Because of this, it is recommended that further studies should be carried out to determine whether this region is quiescent or aseismic.

It is strongly recommended that the possibility of seismic amplification in the Perth Basin should be investigated. A microzonation study similar to that carried out by Gaull (1979) in Papua New Guinea and Grant-Taylor & others (1974) in New Zealand would be very useful.

Furthermore, it is apparent that every effort should be made to increase the data set in strong motion recordings to reduce the uncertainties in attenuation of seismic signals. Also, by inclusion of a less simplistic attenuation form than that required by the computer program in this study, a closer approximation to real attenuation in the shield could be achieved.

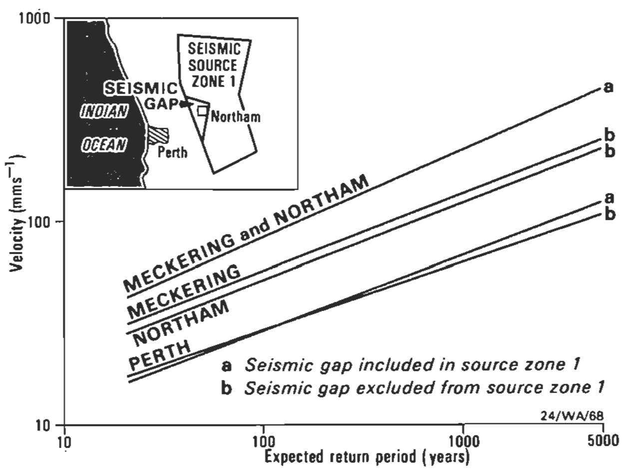

Figure 10. Effect on risk evaluation of including and excluding seismic gap near Northam.

It should be remembered that in this study offshore areas have been treated the same as onshore areas. Because there are no strong motion data available and the effect of kilometres of sea water on ground motion at the sea bed is unknown, the contours have been dotted.

Finally, we emphasise that this analysis does not include the effects on long period structures of longer period seismic waves generated by great earthquakes in the Indonesian region, as discussed by Gregson & others (1979).

Conclusions

1. Using a) Cornell-McGuire methodology for risk analysis on source zones as defined in the text, b) maximum-likelihood determination of b value on data that have had aftershocks removed, and c) attenuation constants as defined in the text, there is an estimated 10 per cent probability that within any 50 year period the peak ground velocity and acceleration of 48 $mm.s^{-1}$ and 0.44 $m.s^{-2}$ will be exceeded in Perth, Western Australia.

2. The major contributor to uncertainty in the estimation of risk is attenuation of strong ground motion. Using one standard deviation of the residuals of attenuation observations as the error estimate, the peak ground velocity and acceleration values given in conclusion (1) become 40-58 $mm.s^{-1}$ and 0.38-0.54 $m.s^{-2}$ respectively.

3. An up to date set of earthquake risk maps of southwest Western Australia has been prepared, the map contours expressing the risk both offshore and into the hinterland.

4. Mining-induced rock burst activity in the Kalgoorlie region has been reflected in the contour risk maps drawn.

5. It is recommended that (a) the 'seismic gap' near Northam should be investigated to establish whether or not it is a real seismic gap; (b) microzonation studies of the Perth Basin should be attempted to try to resolve whether seismic amplification takes place in the sedimentary basin, thereby increasing the risk; (c) an expansion of strong ground motion instrumentation throughout the area of interest to increase our knowledge of seismic attenuation should be pursued; (d) these maps should be updated in 5 to 10 years.

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Evan Richard Stanley, 1885–1924: pioneer geologist in Papua New Guinea

H.L. Davies[1]

Evan Richard Stanley was the first Government Geologist for Papua, from 1911 to 1924. Under difficult conditions, he conducted geological investigations that resulted in more than 50 papers and reports and the first comprehensive accounts (in 1923 and 1924) of the geology and resources of both the New Guinea and Papua territories. He died unexpectedly in 1924.

Evan Richard Stanley was born in Adelaide in 1885. He trained in geology at the University of Adelaide during 1902-10, working closely with the late Sir Douglas Mawson. From 1911 to 1924 he served as the first Government Geologist for Papua, conducting nine major and numerous minor geological investigations into regional geology, mineral deposits, and indications of petroleum. He was also involved in a controversial Commonwealth Scientific Expedition to New Guinea in 1920-22. He produced more than 50 papers and reports, many of which remained unpublished because of economies in force in Government at that time. His crowning achievements were the production of syntheses of the geology and resources of both the New Guinea and Papua territories in 1923 and 1924. He died unexpectedly in 1924.

From a review of his papers, surviving letters, and family recollections, a picture emerges of an uncommon man. Firstly, he was unusually energetic and had a great zest for life. Secondly, he was a practical man, who augmented the execution of his professional duties with practical skills in chemistry, surveying, and photography. And thirdly, he was a percipient geologist with an eye for the broader picture, who, had he lived his full term, would almost certainly have become one of the leading figures of Australian geology.

The following pages are an attempt to draw together information on this remarkable man, primarily as a tribute to him, drafted in the centenary year of his birth, and secondarily as a historical record of one aspect of the beginnings of earth science in Papua New Guinea.

Adelaide 1885–1910

Evan Stanley was the oldest of four sons of Robert Ernest Stanley and Elizabeth Ramage (née Thomson) (Fig. 1), and was born at the family home in Jeffcott Street, North Adelaide, on 3 May 1885. Robert and Elizabeth had both migrated to South Australia in the 1870s, he from Penzance, Cornwall, and she from Leith in Scotland. Elizabeth retained a strong Scots accent all her life, was musical, and liked to entertain. Robert was a carpenter/home builder by trade, and the four boys initially trained as carpenters before selecting their eventual careers. The boys were very close and full of fun; all learned to play the piano, and they were in demand to sing at musical evenings at home and special services at

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Figure 1. Robert and Elizabeth Stanley and their four sons; Evan Richard is on the left; probably photographed in 1908–10.

churches in the nearby hills, to which they travelled to and fro by horse and buggy. Robert Stanley died in 1926; and Elizabeth, in 1946.

Adelaide University. Evan was educated at Parkside school, and commenced part-time study at the University of Adelaide and the School of Mines & Industries in 1902. His university training did not follow a conventional pattern, but rather was spread over a period of nine years and concluded without him having completed all of the requirements for a Bachelor of Science degree. Through this period he lived at the family home, 22 Beaconsfield Terrace, Unley (then New Parkside).

During the first six years he successfully completed two one-year courses in geology, three in chemistry, and one each in physics and biology, and in three of those years he studied and passed the three components of high school senior level mathematics—geometry, trigonometry, and arithmetic and algebra. The latter enabled him to matriculate in 1908 and to be officially enrolled as a B.Sc. student in the same year. From 1904 to 1909 he also worked as an unpaid cadet in the Department of Geology, a job that involved care of laboratories and assistance in field studies (Fig. 2). In 1909 and 1910 he completed two more years of geological training (Geology Part II—no result reported—and Mineralogy & Petrology Part II—a first-class pass), but failed to complete or pass courses in mathematics and 2nd and 3rd year chemistry, which were required for the degree. One reason for failure in subjects that he had handled capably at lower levels might have been an increasing involvement in geological activities, for through 1908-10 he was working on several geological research projects (Stanley, 1909, 1910a, b), one of which was recognised with the award of a university prize, the Tate medal, in 1908.

South Australian geology. Mining had flourished in South Australia since soon after the arrival of the first settlers, to the extent that the colony was known as the Copper Kingdom.

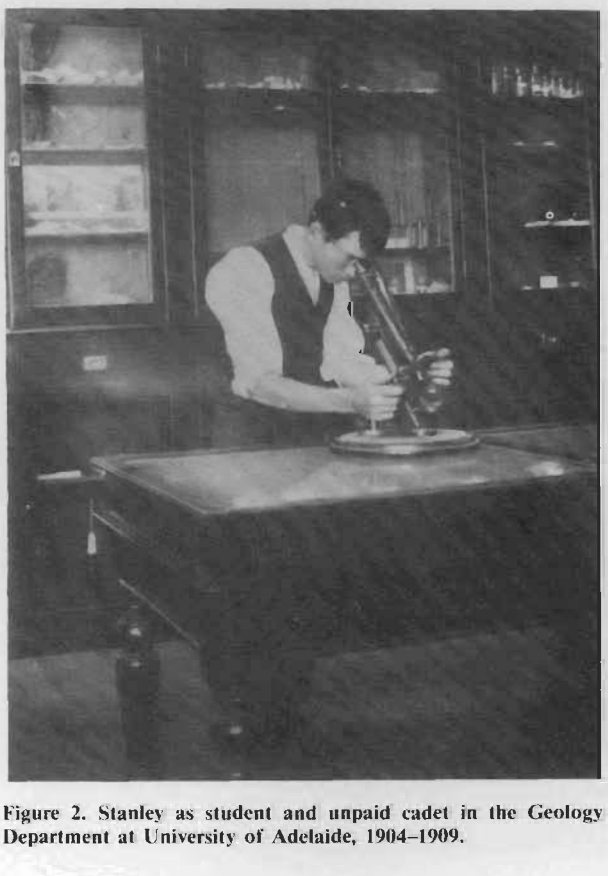


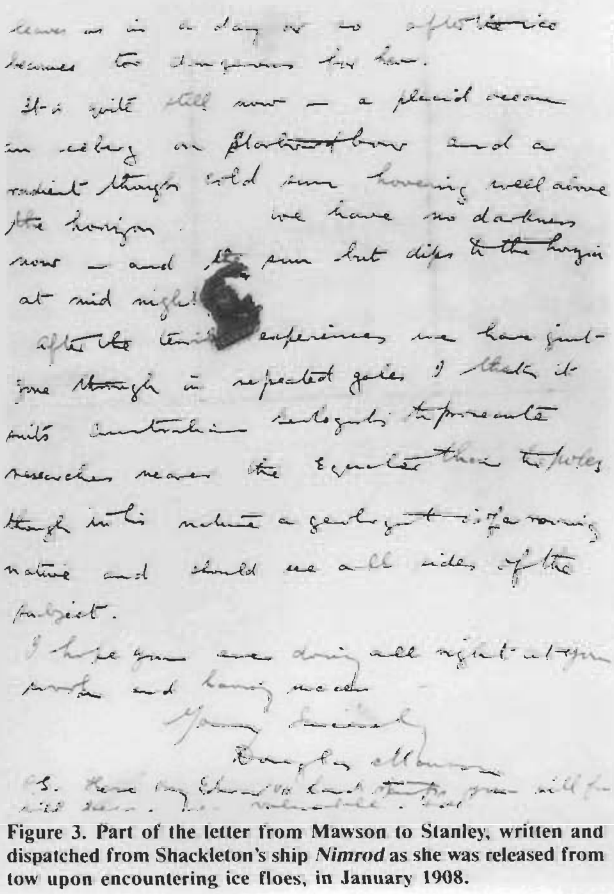
Figure 2. Stanley as student and unpaid cadet in the Geology Department at University of Adelaide, 1904–1909.

Many of the miners were Cornishmen, like Robert Stanley, and Moonta, the main copper-mining centre, was known as Australia's 'Little Cornwall'.

Perhaps as a direct result of the mining boom, a vigorous geological community developed and, in the years around the turn of the century, a number of important breakthroughs were made. These included the recognition of the Cambrian and Precambrian age of sediments in the Mount Lofty and Flinders Ranges, of evidence of a Permian glaciation at Hallett Cove (by Professor Ralph Tate), and of an earlier (Precambrian) glaciation on the Fleurieu Peninsula (by Walter Howchin), and the release of the first geological map of the colony, by Government Geologist, H.Y.L. Brown (Corbett, 1984/85).

Evan Stanley specialised in mineralogy and petrology, under the tutelage of Douglas (later Sir Douglas) Mawson, and assisted Mawson in his studies of the Broken Hill mining district (Benson, 1925). From his contacts with Mawson he acquired the skills in field and regional geology, mineralogy and chemistry, and mineral exploration that were to stand him in good stead in later years, and he might also have drawn from Mawson the inspiration to seek employment in an unexplored frontier area, as was Papua at that time. His skills in stratigraphy were perhaps imbued by Howchin, and another who certainly influenced the young Stanley was W.N. Benson, later Professor at Otago University, who taught petrology and mineralogy at Adelaide during Mawson's absence in 1908, and with whom Stanley maintained contact in later years.

According to recollections of the Stanley family, Evan was a favourite of Mawson, and there is a hint of this in the tone of a letter written by Mawson while in transit to the Antarctic with Shackleton in 1908 (Fig. 3). The letter includes one



leave us in a day or so [illegible] becomes too dangerous for her.
It is quite still now — a placid ocean [illegible] on starboard bow and a radiant though cold sun hovering well above the horizon. We have no darkness now — and the sun but dips to the horizon at mid night.
After the terrible experiences we have just gone through in repeated gales I think it suits Australian geologists to prosecute researches nearer the Equator than the poles though in his nature a geologist is of a roving nature and should see all sides of the subject.
I hope you are doing all right at your work and [illegible]
Yours sincerely
Douglas Mawson
P.S. [illegible]

Figure 3. Part of the letter from Mawson to Stanley, written and dispatched from Shackleton's ship *Nimrod* as she was released from tow upon encountering ice floes, in January 1908.

passage that, in retrospect, was particularly apt: 'After the terrible experiences we have just gone through in repeated gales I think it suits Australian geologists to prosecute researches nearer to the Equator than the poles—though in his nature a geologist is of a roving nature and should see all sides of the subject'. Another illustration of the relationship between Mawson and Stanley is in the press photograph of geology students welcoming Mawson upon his return from Antarctica—Evan Stanley is between the shafts of the cart (Fig. 4).

Contemporaries of Stanley in his student days included geologists Cecil Thomas Madigan, subsequently a key figure in South Australian geology, and George Spencer Compton, who was to make his mark in the Eastern Goldfields of Western Australia, engineer Russell John Dumas, later Director of Public Works in Western Australia, and mining engineer Frank Fancett Espie, who was to spend 30 years in mining in Burma before assuming a senior management position with Western Mining Pty Ltd. Espie's son, Frank Fletcher Espie was to play a leading role in bringing into production the first major mining venture in Papua New Guinea, the Panguna copper mine on Bougainville Island.

Royal Society. The Royal Society of South Australia was founded in 1883, largely on the initiative of Professor Tate (Corbett, 1984/85), and was a popular forum for the presentation of geological research papers. Stanley's research on basalts from Mount Gambier volcano, which had earned him the Tate Medal in 1908, was communicated to the Society by Howchin on 4 May 1909 and published in the Society's *Transactions & Proceedings* (Stanley, 1909). The paper includes petrographic descriptions of several different basalts and lherzolite from a nodule in pyroclastics, and four chemical analyses of different types of basalt for major elements and S, Cl, Cr, Ni+Co, Ba, Sr, and Li. Later papers gave a more detailed petrographic and chemical description of the lherzolite, and described enstatite-bearing basalt from Kangaroo Island (Stanley, 1910a, b).

In December 1910, and in spite of his failure to complete all the requirements for a Bachelor of Science degree, Stanley was appointed first Government Geologist for the fledgling Australian Territory of Papua. The Adelaide *Advertiser* reported the appointment, and noted that the position carried the very respectable salary, for those times, of 500 pounds. By way of comparison, the Administrator received 800 pounds; medical officers, 450; resident magistrates, 300-450; and patrol officers, 250 (Annual Report for Papua for 1910--11).

Papua in 1911

In the 1880s the European powers had divided New Guinea and adjacent islands into three territories: Netherlands New Guinea in the west, German New Guinea in the northeast—including the islands of the Bismarck Archipelago and

Figure 4. A smiling Mawson is paraded along North Terrace, Adelaide, by gowned geology students, upon his return from the Shackleton expedition in April 1909.
Stanley is between the shafts of the handcart. Photograph reproduced by courtesy of *The Advertiser*, Adelaide.

Bougainville—and British New Guinea in the southeast. British New Guinea was ceded to Australia at the time of Australian Federation in 1901, and became the Australian Territory of Papua upon proclamation of the Papua Act in 1906.

An Australian lawyer and judge who had worked in the Territory since 1904, John Hubert Plunkett Murray, was appointed Acting Administrator in 1907 and Lieutenant-Governor in 1908. Miles Staniforth Carter Smith, a politician who had stood down after serving one term as Senator in the first Federal Parliament, and who had been appointed to several senior posts in the Papua administration in 1907, was appointed Administrator in 1908—a dormant role that entitled him to act as Lieutenant-Governor in Murray's absence. As Commissioner of Lands and Director of Mines he was to be Stanley's immediate superior through much the latter's career.

Murray and Staniforth Smith (Fig. 5) shared a mutual dislike and distrust. Smith coveted the role of Lieutenant-Governor and attempted to undermine Murray through his contacts in the Federal Government in Melbourne (Souter, 1963). He seems to have been a difficult person, pompous, 'unbearably boring and interminable on politics' with no modesty whatever (the view of Malinowski as reported by Stuart, 1973) and 'domineering and arrogant' in the words of another, albeit, an opinion based on hearsay (Carne, 1912). In 1911 he was 42 years old; Stanley was 25.

Between 1907 and 1911 the white population of Papua had increased from 690 to 1032, of whom 120 were civil servants; 139, planters; and 144, miners. Most of the miners were on Woodlark Island, where there had been a recent revival of interest; this was the only field where reef gold was being worked. Others were on the newly discovered Lakekamu field, and the Gira-Aikora, Yodda, Milne Bay, and Misima fields (Fig. 6) (Knibbs, 1912; Nelson, 1976). In the financial year 1910-11 gold was the major export of the Territory, with a value of 62,000 pounds, followed by copra, 18,000 pounds; copper ore, 12,000 pounds; beche-de-mer, pearls, pearl and turtle shell, 9000 pounds; rubber, 2000 pounds; timber, 700 pounds; and sandalwood, 190 pounds (Knibbs, 1912).

The administrative headquarters, Port Moresby, or Port as it was known colloquially, was 'a rough and raw frontier town in which the majority of residents entertained themselves with uninhibited drinking, brawling and feuding, while a small elite group resolutely cultivated the amenities of civilised society amidst discouraging surroundings' (the diary of Malinowski, as quoted by Stuart, 1973). In 1911 the European population of the town was about 450; a school was newly opened on Hunter Street, a weekly newspaper was about to start, and a swimming bath was to be established on the harbour shore (Stuart, 1973).

The appointment of a geologist to the Papua administration had been one of the recommendations of a Royal Commission established by the Australian Government in 1906 and which reported to Parliament in 1907 (Jinks & others, 1973, p.96). It was a timely recommendation, as, apart from the continuing interest in gold and the recent discovery of the Lakekamu field, there had been discoveries of copper-gold mineralisation just outside Port Moresby (in the Astrolabe mineral field) in December 1906, and coal inland from the Gulf of Papua in 1908. Discovery of oil was to follow, and to cause great excitement, in 1911.

Knowledge of the geology of Papua at the time of Stanley's arrival was limited to the data drawn together by Jack & Etheridge (1892); observations recorded by a former Administrator, Sir William MacGregor, during exploratory patrols; and those recorded in May-October 1891 by geologist A.Gibb Maitland (Annual Report for British New Guinea for 1891-92; Maitland, 1905). Information was limited to

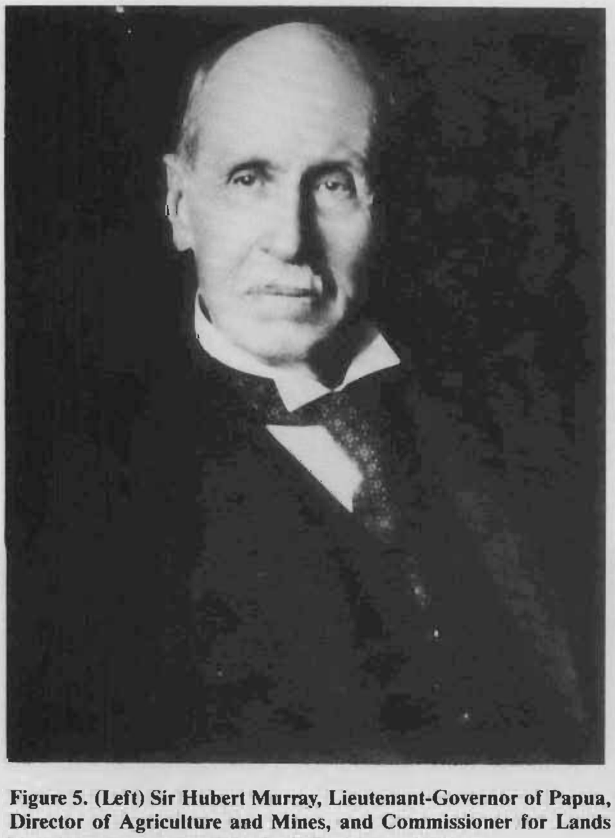


Figure 5. (Left) Sir Hubert Murray, Lieutenant-Governor of Papua, 1908–1940; and (right) Miles Staniforth Carter Smith, Administrator, Director of Agriculture and Mines, and Commissioner for Lands and Surveys, 1907–1916, 1921–1930.
Reproduced by courtesy of the Australian National Library.

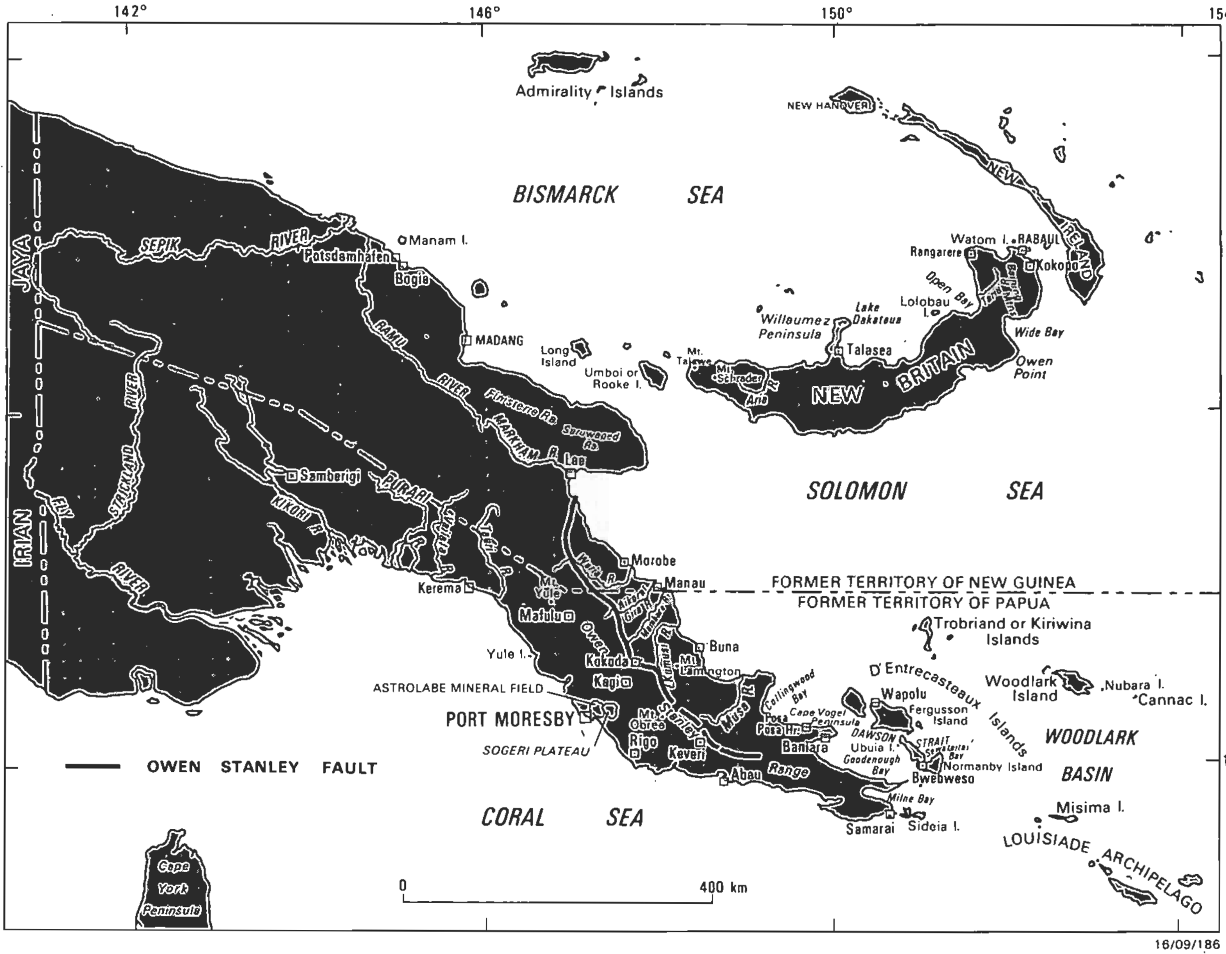


Figure 6. Locality map.
The Lakekamu gold field is between Mount Yule and the Tauri River, and the Yodda gold field near Kokoda.

parts of the coast and the southeastern islands, and part of the Owen Stanley Range.

Arrival. At the time of Evan Stanley's arrival in Port Moresby in January 1911 Lieutenant-Governor Murray was on leave and Administrator Staniforth Smith was absent from headquarters and overdue on an exploratory patrol on the Kikori River (Fig. 6). The story is well told by Souter (1963) as follows. Late in 1910 Murray took his first leave since being appointed Lieutenant-Governor. This gave Staniforth Smith an opportunity to run things as he would wish. He wasted no time in organising a major exploratory patrol, which he was to lead, with the intention of ascending from the Kikori River to the Samberigi Valley, then travelling westwards through previously unexplored country to the Strickland River. Unbeknownst to those taking part, this was a most difficult tract of country, characterised by karstified limestone ridges, swampy valleys, and dangerous rivers. The expedition was ill-fated, and seventeen lives and most possessions were lost. Search parties were sent out, and eventually Staniforth Smith and the remnants of his party were found not in the lower reaches of the Strickland as they had thought, but, in fact, on the Kikori—the river upon which they had initially embarked. This was in March 1911.

Stanley arrived in Port Moresby by Burns Philp steamer on 9 January 1911. He took up temporary quarters at the newly established school, and, being unable to find a superior officer to report to, on the same day that he had disembarked from the ship, set out on horseback to visit the Astrolabe mineral field (Fig. 6). The first night was spent at the gaol gardens at Bomana, and the following nights on the Sogeri Plateau with visits to the copper prospects during the day; he returned to Port Moresby on 14 January.

Mount Yule. In the continuing absence of the Administrator and Director of Mines, Stanley then took it upon himself to organise a more ambitious expedition, this time to the Yule Island hinterland in company with government entomologist, Jack Carson. Starting on 31 January, the pair travelled to Yule Island by coastal ship, then inland by canoe and on foot. They were away for six weeks, during which time they succeeded in climbing to about 1800 m on the slopes of Mount Yule before having to retire because of problems with carriers. Stanley wrote a long narrative of this journey directed to one of his brothers in Adelaide, including the instruction that his brother might release it for publication if there was sufficient interest. The narrative is of interest now primarily as a record of the brash confidence and vigour of the young man; the account of problems with carriers will spark reminiscence for anyone who has worked in this way, and the tributes to the Fathers of the Mission de Sacre Coeur are heartfelt. One suspects that the dangers posed by unfriendly natives, though no doubt real, might have been presented in a dramatic light for the purpose of attracting publication. Geological returns were poor, but an accurate topographic survey of their route and adjacent mountain peaks was completed and subsequently published (Stanley, 1915d). Accounts of both the Mount Yule reconnaissance and the Astrolabe mineral field were published in the *Annual Report for the Territory of Papua* for 1910-11.

Woodlark. Later in the same year (1911), perhaps having taken some time out to establish and equip his headquarters, Stanley began the first of his major geological investigations—a survey of the gold mining areas on Muyua or Woodlark Island (Fig. 6). This survey was to occupy four-and-a-half months and culminate in a comprehensive report on regional and local geology, consisting of about 20 pages of typescript, and illustrated with photographs, line drawings, and coloured geological maps, which he drafted on topographic bases that he had prepared from his own survey data (Stanley, 1912a,c). The geology of Woodlark Island remains something of an enigma, even today, partly because much of the basement is concealed by Quaternary limestone. It is now generally accepted that basement is a Palaeogene volcanic pile (probably part of a Palaeogene volcanic arc) with some contemporaneous sediment, unconformably overlain by Upper Oligocene limestone, and cut by intrusive rocks, some of which are Miocene (Davies & others, 1984, after Trail, 1967, and McGee, 1978). Stanley recognised all these rock groups with the important exception of the volcanics, and produced maps showing their distribution over the island and at the main mining centres. However, the unique value of the report is not so much in the description of the general geology as in the detailed descriptions of the different mines and the reef and alluvial mineralisation (Fig. 7), and the compilation of the history and production figures of the field—information, most of which would have been lost irretrievably had it not been recorded at the time.

Figure 7. Alluvial gold mining on Muyua (Woodlark) Island.
Photograph by E.R. Stanley.

W.A. McGee, an exploration geologist familiar with the Woodlark field, has commented (personal communication, 1985) that Stanley's mapping in some areas was superior to later work, as was proven when exposures were developed by bulldozing in 1981, but that his descriptions of the different prospects, while containing excellent observations, commonly were not quantitative and tended towards the promotional; as an example he cites Stanley's comment that the old Ivanhoe Company leases had not had a fair trial.

Oil. Indications of oil in Papua were discovered in August 1911, but not officially reported until October. They consisted of a number of seeps of oil and gas (Fig. 8) in the Vailala River area, 40 km northwest of Kerema, in the Gulf Province, and were found by two local planters, G.H. Thomas and Lewis Lett. The discovery caused great excitement and, despite the meagre indications, optimistic predictions were made and the area quickly became known as the 'oil fields'.

In November 1911, Stanley was instructed to examine the discoveries, but, being already engaged elsewhere, was unable

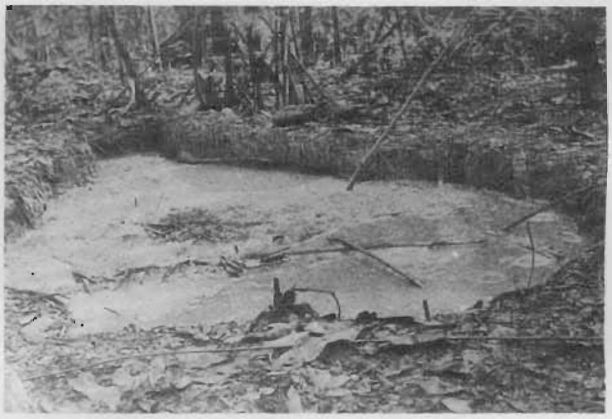


Figure 8. Oil and gas seep in the Ie Hills, near Kerema.
Photograph by E.R. Stanley 1912.

to do so until April of the following year. In the meantime, Joseph Carne, Assistant Government Geologist for New South Wales, had taken the opportunity to inspect the discoveries while returning from an investigation of coal occurrences on the Purari River in February 1912 (Carne, 1913). (The project that had engaged Stanley's attention in November was a visit to the lower Gira River, where gold prospectors had reported indications of oil (Fig. 9). He found no trace of oil and surmised that the oily film observed by the prospectors may have come from empty cans of meat or from iron oxide.)

In April-May 1912, Stanley set out for the 'oil fields' with the object of determining the limits of the potential petroleum-bearing basin. He made reconnaissance traverses between the Purari and Vailala rivers, up the Vailala, and north and northeast from Kerema (Fig. 6), and from these observations produced a reconnaissance map of the 'Papuan petroleum area'. Both he and Carne contributed reports on the 'oil field' to the Annual Report for 1911-12 (see also Carne, 1913). Stanley returned to the Vailala later in the year. In October he suffered a severe attack of malaria and was forced to retire temporarily, but in November he discovered another seep, near Aro Aro, a few kilometres west of the Vailala River (Stanley, 1913a).

Subsequently, in October 1913, Dr Arthur Wade was appointed by the Australian Government to pursue the search for oil in the Gulf Province (Fig. 10). Wade remained in the Territory until 1919, when the task was handed over to the Anglo-Persian Oil Company. Stanley started work with Wade in late 1913 and continued until mid-1914 (Annual Report for 1913-14).

Adelaide 1912–13

By the end of 1912, Stanley had served for almost two years and thus was entitled to three months' leave. He proceeded to Adelaide via Melbourne, then returned to Melbourne in mid-January to present a paper (Stanley, 1913a) on the Papuan petroleum area to the 1913 meeting of the Australasian Association for the Advancement of Science (AAAS). He returned to Adelaide after the conference to marry Helen Mary Benson Turner (Fig. 11) in the Methodist (now Uniting) Church at Parkside West on 21 January 1913. The young couple honeymooned at Mount Gambier, where the groom was unfortunate enough to once again succumb to malaria.

TERRITORY OF PAPUA.

S.S. "MERRIE ENGLAND,"
N.E. Coast.

The Government Geologist,
WOODLARK ISLAND.

16th October, 1911.

Traces of petroleum have been discovered on Lindon Creek on the lower GIRA by a miner called Larsen or Lawson. Lindon Creek is one day distant from TAMATA Station; Mr.Lawson is still there.

You will proceed to TAMATA Station by the first opportunity and examine and report upon -

(1). the nature and prospects of the alleged find of petroleum,

(2). the country between Ryan and Erichsen's claim on the lower Aikora and BOLI near the WARIA.

You will send in your report on (1) before you commence on (2). The lower AIKORA is two and a half days from TAMATA; the country from there to BOLI is very rough.

You are appointed an Officer of Armed Constabulary temporarily; the appointment only to be in force during your stay in the Mambare Division while making these investigations.

The Resident Magistrate, Mambare Divn., will be instructed to supply you with three police and to give you all assistance.

Your first opportunity of going to TAMATA will probably be by the "Mindoro" to the Mambare Beach and thence by the station whaleboat.

Please treat the information as to the discovery of petroleum as confidential until your arrival at TAMATA.

J.H.P. Murray
Lieutenant-Governor.

Figure 9. Memorandum from the Lietuenant-Governor instructs Stanley to investigate a report of traces of petroleum on Lincoln Creek on the Gira River.
There is no record that Stanley carried out the second stage of the mission, to Boli near the Waria River. Tamata station was on a tributary of the Mambare River.

Dispute over the Woodlark Report. In transit from Papua, Stanley had called at the offices of the Department of External Territories and Home Affairs in Melbourne and had been shown the newly published version of his Woodlark report, copies of which had just been shipped to Port Moresby. In the previous April and August, Stanley had addressed the question of reproduction of geological reports, and had received support from Lieutenant-Governor Murray for the establishment of a scientific bulletin series. To judge from correspondence, Staniforth Smith's response to this initiative may have been less than enthusiastic, and the matter possibly became a point of contention between the young geologist and his superior. There is evidence of a somewhat strained relationship in an exchange of quite peremptory memoranda between the two in August 1912, when Stanley first perceived that Smith was withholding parts of the Woodlark draft report from publication.

The published version of the Woodlark report, which he saw in Melbourne, must have been a great disappointment. It was

Figure 10. The first exploratory well on the Papuan 'oil fields' was spudded on 18 January 1913, by government-contracted driller F.C. Grebin, at Akauda on the Vailala River.
'A few gallons' (10–20 litres) of crude oil were recovered from a depth of 68 m. Drills encountered over-pressured muds, and drilling ceased later in 1913. Photograph by E.R. Stanley 1913.

Figure 11. Helen Mary Benson Turner and Stanley were married in Adelaide in January 1913.

a very cheap production, printed on thin paper and stapled between plain pink paper covers—no more than a pamphlet. In addition, Stanley was incensed to find that parts of his draft report had been deleted, prior to transmission from Port Moresby, and that some niggling changes had been made, such as deleting his signature from the geological maps. Specific omissions were the preface, table of contents, line drawings, and photographs of geological features, tables of annual production, and a final section of text dealing with future prospects.

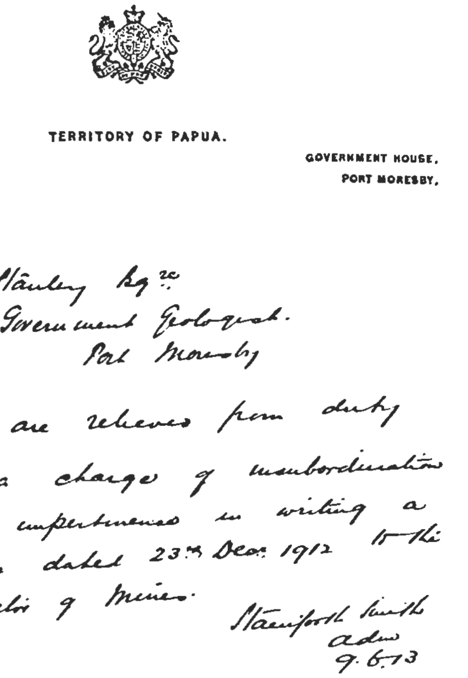
Soon after arriving in Adelaide, on 23 December 1912, Stanley gave vent to his feelings in an angry letter addressed to the Director of Mines. This letter was not well received and was to set in train an unfortunate sequence of events leading to his suspension from duty, events which must have weighed heavily upon the young man at the time. In the slightly longer term, his protest was not in vain, and was to lead to the publication (in 1914) of an addendum to the pamphlet version of the Woodlark report, and of a complete version of the Woodlark report in the Annual Report for 1911-12. A handsome and well-produced scientific series, *Bulletins of the Territory of Papua*, on the lines proposed by Stanley, was begun in 1913.

Staniforth Smith brought Stanley's indignant plaint to the attention of a meeting of the Executive Council in Port Moresby on 25 January 1913. The Executive Council consisted of Lieutenant-Governor J.H.P. Murray, Government Secretary Leonard Murray, the Treasurer, the Commissioner for Native Affairs, and Staniforth Smith in his role as Commissioner for Lands; the Council met weekly or as required through the year.

The Council agreed that Stanley had committed an act of insubordination and should be 'relieved from duty from the date of his return to the Territory on a charge of insubordination and impertinence'. Stanley was advised accordingly in a letter of 30 January. On 14 February he replied, from Adelaide, with a contrite and conciliatory letter, and received in reply a letter confirming that the matter would be held over until his return from leave.

Dismissal. The Stanleys returned to Port Moresby on 9 June 1913, having been away for almost six months rather than the standard three months' leave break. Some of the additional time was perhaps taken as duty at Departmental headquarters in Melbourne in December and at the AAAS meeting in January, and at least five weeks of the interval was unpaid sick leave. Upon arrival, Stanley received a curt note in the copperplate hand of Staniforth Smith, on Government House notepaper, to the effect that he was 'relieved from duty on a charge of insubordination' (Fig. 12). Next day there was a letter from the Government Secretary inviting him to defend his actions before the Executive Council, which he did at the Council's meeting of Friday morning 13 June, at the Council Room at Ela, Port Moresby. Council ordered that, as he had apologised to the Director of Mines and had acknowledged that the tone of his letter was ill-conceived and wrong, he should not be suspended from the service, but should be reprimanded and warned against repeating the offence. Consequently, on 14 June he was instructed to resume duty, in an Order in Executive Council signed by Staniforth Smith as Administrator.

One outcome of these events appears to have been a worsening of the relationship between Staniforth Smith and Stanley, if we may judge from the lack of reference to Stanley's activities and the omission of any geological reports in the Annual Reports of the Mines Department in the years following these events until after Staniforth Smith's departure in 1916.


TERRITORY OF PAPUA.

GOVERNMENT HOUSE,
PORT MORESBY.

E. R. Stanley Esq.
Government Geologist.
Port Moresby

You are relieved from duty on a charge of insubordination and impertinence in writing a letter dated 23rd Dec. 1912 to the Director of Mines.

Staniforth Smith
Adm.
9.6.13

Figure 12. Upon his return to Port Moresby on 9 June 1913 Stanley was advised that he was relieved from duty.

Papua 1913–15 and the First World War

The house on Spring Garden Road. In 1911 or 1912, Evan Stanley, with the help of brother Elliot, built a large and comfortable bungalow-style house on Spring Garden Road in Konedobu, and it was to this house that he brought his bride in June 1913 (Fig. 13). Two other residences lay between the Stanley house and the waterfront road, the police barracks were opposite, and the new Government House (constructed in 1913, and still in use today) was above it and to the north. Hanuabada villagers walked past the house on the way to and from their gardens higher on Spring Garden Road.

The small community at Konedobu and the London Missionary Society missionaries at Elevala in Hanuabada were relatively isolated from the main centre of government and business activity, which was on the peninsula above the main wharf, some kilometres to the southeast. Communication between the two centres was by foot track or launch.

A boom year. 1914 was a year of excitement and optimism in Port Moresby. Discovery of commercial quantities of oil was confidently expected; a company was developing the Astrolabe copper deposits and the Australian Government had provided a loan of 50 000 pounds to establish a light railway from the mines to the port; the town's first reticulated water supply was established; and the Library Institute hall constructed and opened (Stuart, 1973). However, the situation was to change suddenly with the outbreak of war, the resulting economies, and the loss of many Europeans to 'the front'.

War. When war was declared, in August 1914, it was expected that the enemy might arrive any day from bases in the German New Guinea Territory. Preparations were made to defend the radio communications centre—trenches were dug, and the available Europeans were formed into a small, ill-

Figure 13. Looking east-southeast at the Stanley's home on Spring Garden Road, Konedobu.
Evan and Helen hold the reins of two horses, partly obscured by shade.

equipped and untrained fighting force. The instruction from Australia was that the radio centre must be defended to the death. Stanley was given picket duty on the hills above the town, and Helen and her neighbour, Mrs Kendrick, the Treasurer's wife, were deputed to bury the Treasury papers upon hearing the first shot fired; after this they were to gather at Government House. Helen at this time was perhaps more concerned about her baby, Joan, who had been born only a few weeks previously, on 13 July at the family home, with Helen's mother Mary Turner in attendance.

The threat to Port Moresby was averted by the arrival of an Australian ship, the *Kanowna* (Fig. 14), with a fighting force of 500 raw recruits. A larger force, the Australian Naval and Military Expeditionary Force, sailed subsequently from Sydney on the troop transport *Berrima* and in concert with the warship *Australia* went on to capture Rabaul, the administrative headquarters of the German Territory, in September 1914. This event led, in the longer term, to the Australian administration of the New Guinea Territory.

Dependent women and children, including the Stanley family, were evacuated by ship from Port Moresby to Australia, their ship being chased by a German raider en route. Many, including Helen and baby Joan, returned to Port Moresby after only a short interval.

Extended fieldwork. The normal routine seems to have been quickly re-established in Port Moresby, and only one month after the outbreak of war Stanley began a series of field investigations that was to occupy him for the next eight months. Trips were undertaken in September and November to investigate reports of oil shows in Sewataitai Bay on Normanby Island, and an application for 'oil areas' and reports of 'flattened grains of copper and specks of a tin-white metal' on Cape Vogel peninsula.

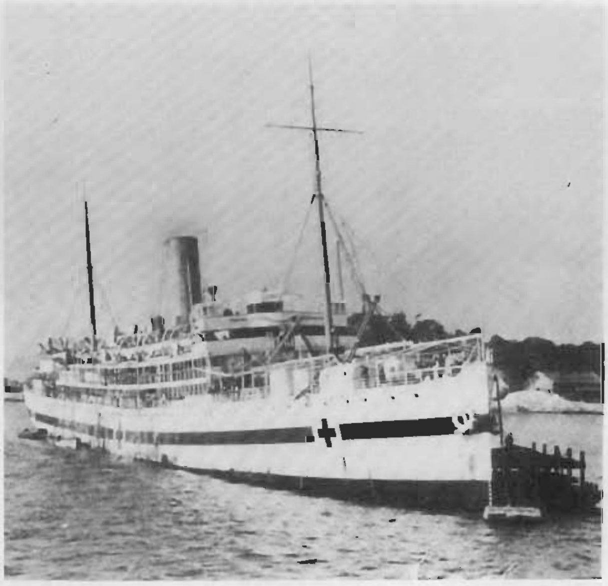


Figure 14. The Australian coastal steamer *Kanowna*, here seen in wartime colours as a hospital ship, evacuated dependent wives and children from Port Moresby in 1914.
Photograph by courtesy of the Australian National Library.

Normanby Island. Stanley examined the reported oil slicks and then, while waiting for a boat back to Samarai, reconnoitred and described the metamorphic and volcanic rocks of Normanby Island. He identified the ultramafic rocks at Ubuia as altered plutonic rocks, and those at Bwebweso (Fig. 6) as magnesian limestone locally altered to serpentine, magnesite, and meerschaum; he correctly identified the associated rocks as enstatite pyroxenite and dykes of coarse gabbro, and the alteration of the Ubuia rocks to steatite and talc. He concluded that the apparent oil slicks were an effect of a thin film of fresh water on sea water near the shore. Results were reported in a 16-page double-space typed manuscript and map. Publication in the Bulletin Series was approved by Lieutenant-Governor Murray, but the decision was reversed at the suggestion of the Secretary for External Affairs, as a wartime economy measure.

Cape Vogel Peninsula. Having returned to Samarai, Stanley proceeded to the Cape Vogel Peninsula (Fig. 6) in the company of Mr.R.A. Vivian, who operated a trade store near Baniara. Traverses were made in the head of Goodenough Bay, to investigate a brine spring, and from near Baniara north and northwest to Castle Hill and the Posaposa hinterland. A 23-page double-spaced typed report was produced in 1916, with photographs, a map, and cross-section; the cross-section would enhance any modern map of the peninsula. He recognised chrome spinel and manganese (oxide) in association with serpentine and chalcedony at Buabuami near Castle Hill, and some copper staining elsewhere along the same basement ridge; the 'tin-white metal' was found to be a silvery tarnish on probable chalcopyrite. Stanley also noted the occurrence of brine springs and drew attention to the petroleum potential of the area. His report of this investigation (also never published) includes a glossary of technical terms, and closes with an acknowledgement to Vivian for his help and 'willingness to accompany me through a considerable area of uninteresting country to reach the goal of ambition of the geologist—at any time a dry procedure, entailing considerable enervation in a climate like New Guinea'.

Misima Island. Late in 1914, three companies became active in development work on the gold prospects of Misima Island; most notable and persistent of these was The Broken Hill Proprietary Block 10 Company Limited. Stanley went to Misima in January 1915 (Fig. 15) and appears to have remained there for at least three months, for the Annual Report includes a summary that he wrote while on Misima on 24 April 1915.

He investigated the mining areas, made some reconnaissance traverses of the remainder of the island, and produced maps and a report, which were published later in 1915 as *Bulletin of the Territory of Papua* no. 3. He established the basic facts of Misima geology as they are known today, and described in some detail each of the main gold prospects; the report includes 24 pages of text, excellent photographs, a geological map and cross-section of the island, and detailed geological maps of the two main prospect areas, Mount Sisa-Umuna and Quartz Mountain. The prospect maps are at a scale of 1:3168 (4 chains to the inch) and are plotted on contoured topographic base maps.

The Mount Sisa-Umuna lode was subsequently the basis of a small and very profitable mine, Cuthberts, which operated until closed by the threat of war in 1941. Current investigations (1986) are expected to lead to large-scale mining of the same area.

Geological Society and looking to New Guinea. In December 1914, prior to his departure for Misima Island, Stanley's geological work in Papua was recognised by his election as a Fellow of the Geological Society in London. At about the same time he dispatched a first enquiry about the possibility of carrying out field work in the New Guinea Territory: . . .'I wrote asking permission to explore the Northern coastline of the late German New Guinea, and submitted an outline of a proposed expedition to investigate the reported oil occurrences and determine the geology'. He was to follow this in 1916 with a report to the interim administration of the New Guinea Territory on the oil occurrences, presumably based on written reports.

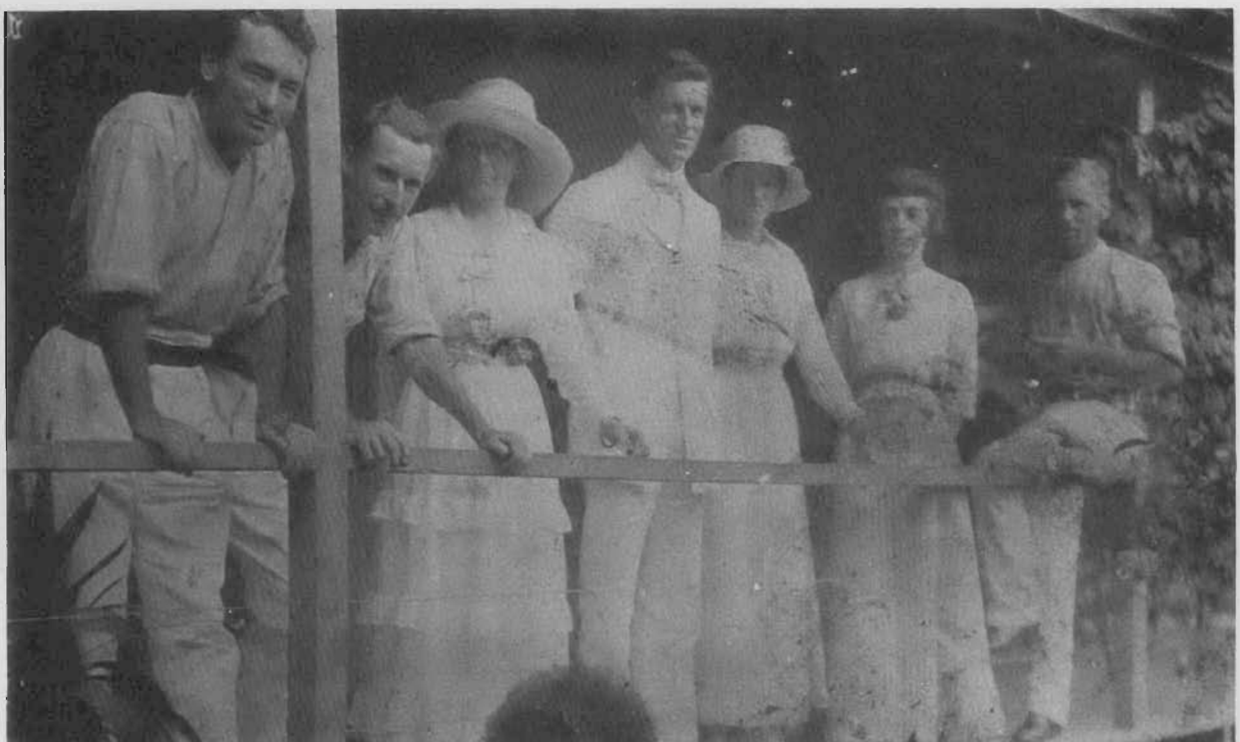


Figure 15. A social occasion on Misima Island, perhaps at one of the mining company houses; 1915.
Stanley is nearest the camera.

1915: Leave in Australia

The Stanleys were on leave in Australia probably from July to September 1915, during which time Evan Stanley delivered a 'lantern lecture on certain features of Papua' to the Royal Society of South Australia (*The Australian Statesman and Mining Standard*, September 1915, p.297); in this talk he is reported to have spoken optimistically of the future prospects for the Woodlark and Misima fields. Probably during this leave, he carried out the description, separation, and wet chemical analysis of an unusual black mica that occurs in the radioactive ilmenite-bearing lode at Radium Hill in South Australia, site of Mawson's pioneering investigation of uranium mineralisation. He reported the results to the Royal Society of South Australia in the following year (Stanley, 1916d).

1915-17: Mainland geology—the Owen Stanley Range

In the two-year term from late 1915 to October 1917, life for the Stanleys perhaps followed much the same pattern as previously. Evan Stanley made a succession of geological investigations. Helen accompanied him on some of these (their daughter, Joan Benson recalls visits to Woodlark and Misima islands), but otherwise would remain at the house in Konedobu with her young daughter. Home life was sociable—Helen was very musical, a keen bridge player, and a good hostess. There were horses to ride, friends to stay, and visits to friends and neighbours, often by launch. To augment their limited supply of fresh food she encouraged and supervised the household help to grow vegetables, and keep poultry and, from time to time, a milking cow.

Owen Stanley Range. The main thrust of Stanley's work now moved from the islands to the mainland, starting with an inspection of the Yodda gold field, near Kokoda, in March 1916, followed by a major expedition across the Owen Stanley Range to the headwaters of the Kumusi and Musa rivers in June-July, and finishing with a second visit to the Yodda and a traverse from there to the northeast coast at Buna in November 1916. From these traverses he was able to prepare a reasonably well-controlled topographic and geological map of a transect across the Papuan peninsula (Stanley, 1918b).

The first visit to the Yodda was to advise on proposals to sink a shaft to test for deeper alluvials. He advised against this and recommended the introduction of hydraulic sluicing. (Several years later a shaft was sunk without encountering significant gold values.)

The exploratory patrol in June-July was planned to investigate the probable occurrence of gold in the headwaters of the Musa and Kumusi rivers, and a reported occurrence of edible earth in the Mamama valley, south of Mount Lamington. From Rigo, Stanley headed inland, ascended the Mimai valley, crossed the main range near Mount Obree at an elevation of 2700 m, and descended to the headwaters of the Musa river just south of the Owalama Range (Fig. 16). Here he turned north, crossed the Owalama Range to the headwaters of the Kumusi River, and descended to Sirorata and thence up the Mamama River. From the Mamama he retraced his tracks to Port Moresby.

From these several investigations he produced a comprehensive report, map and cross-section, which were published in the Annual Report for 1917–18 (Stanley, 1918b). The map incorporated the improved topographic control he had established (see later).

The report included a number of significant new geological observations, including the recognition of both a lower and higher-grade series of metamorphics (the Kemp Welch and Owen Stanley series); the first record of the ultramafic rocks of what was to become known as the Papuan Ultramafic Belt ophiolite; recognition of the 'Late Tertiary' volcanic rocks of Mount Lamington and the Hydrographers Range; recognition of the fault control of the colinear valleys of the Kumusi and Musa headwaters; and the discovery of a sulphurous hot spring on the fault trace. He also recognised the fault control of the Yodda (upper Mambare) valley, and suggested that young fault movements in the Oivi Ridge area had caused reversal of the direction of flow of the upper Mambare River.

He concluded that little gold was to be found outside the Yodda and Little Kumusi (Mamama) valleys, and noted traces of nickel mineralisation and occurrences of chromite associated with the ultramafic rocks. Lateritic nickel mineralisation in the Kokoda area was to be intensively investigated 40 years later (Thompson & Fisher, 1967). The edible earth proved to be a nickel-rich clay horizon cropping out in the banks of the Mamama River, and favoured by the local people as an aphrodisiac. Looking further afield, he deduced, correctly as events have proved, that the forested plains of the Yodda and Popondetta areas would be suitable for cultivation of rubber trees.

Woodlark again. In October 1916 and March or April 1917, Stanley re-visited Woodlark Island. The purpose of the first visit was to assess a proposal that the Administration might subsidise the sinking of a shaft on the Busai prospect. Stanley recommended in favour, but his recommendation was strongly opposed by the Acting Director of Mines. The eventual outcome was that in 1919 the government agreed to a subsidy of 3.3 pounds per metre (one pound per foot) of shaft sunk, for a planned 60 m shaft. In the event, shaft sinking was halted at a depth of 16 m by an uncontrollable inflow of water.

The purpose of the 1917 visit to Woodlark Island was to inspect high-grade copper mineralisation on the southern coast. Samples in a costean averaged 11.18 per cent copper over 5.5 m, and, subsequently, parcels of this ore, averaging 10 per cent copper, reportedly were shipped to Australia.

While in the area, Stanley undertook an examination of guano deposits on Cannac (Inene) Island, 55 km east of Woodlark Island. There he found 'metamorphic slates' similar to those of Woodlark Island, dipping 30-40 degrees west-northwest, and replaced by calcium phosphate to a depth of one metre below land surface. He concluded there was about 8000 tonnes of material averaging 87 per cent calcium phosphate, and that, in view of the small volume available, commercial development was a doubtful proposition (Stanley, 1917d). He also inspected the Laughlan Islands, Nubara Island, 15 km east of Woodlark, and Entrance Island (Ginara), 20 km south of the western tip of Woodlark Island. On the last he encountered thousands of birds and detected minor quantities of guano.

Sideia. Sideia Island was proclaimed a mineral field, somewhat prematurely, in July 1915, after the discovery of copper mineralisation. Stanley inspected the island late in 1915 and reported that the exposed copper occurrences were of only limited extent (Stanley, 1916c)

Astrolabe. In December 1916 Stanley prepared a confidential report that pointed to the probable large-scale development of the Astrolabe copper deposits. Earlier in the year he had

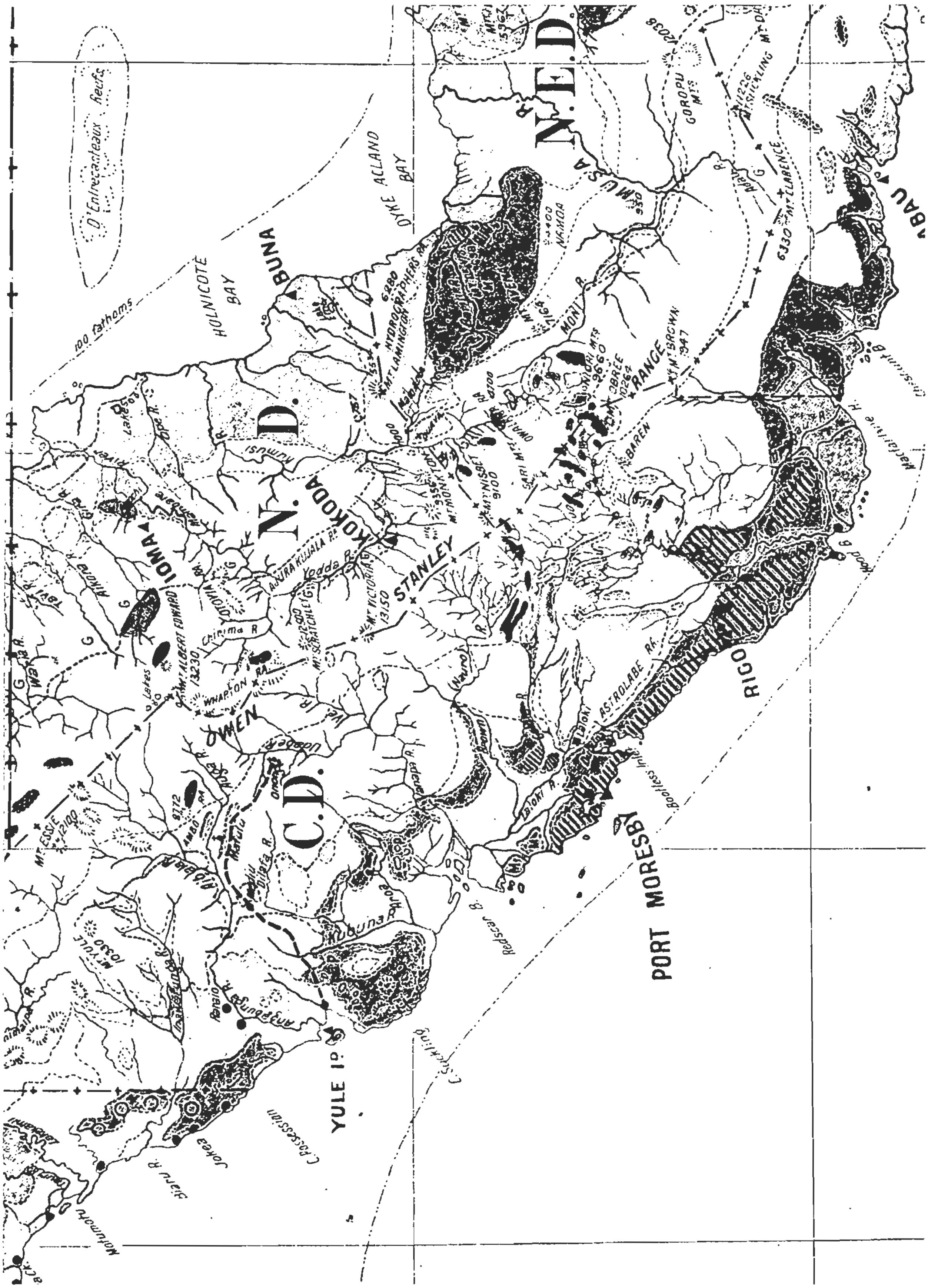


Figure 16. Part of the geological map of Papua prepared by Stanley in 1923 (Stanley, 1924a); grid of 1° squares; original scale 1:1 563 000 (just under 25 miles to an inch).

Best geological and physiographic control is in the area between Yule Island, Rigo, Ioma, Buna and Mount Obree, much of which was traversed by Stanley himself. A belt of low-grade Kemp Welch-type metamorphics is erroneously indicated on the northeastern slopes of the Owen Stanley Range, and a serpentine belt in this position, which is mentioned in the accompanying text (Stanley, 1924a), is not shown. Mount Dayman is erroneously represented as a Quaternary volcano (an inherited error). Circles northwest of Yule Island mark gas and oil seeps.

prepared a comprehensive report on the Hector Mine in which he concluded that the mine had a limited life.

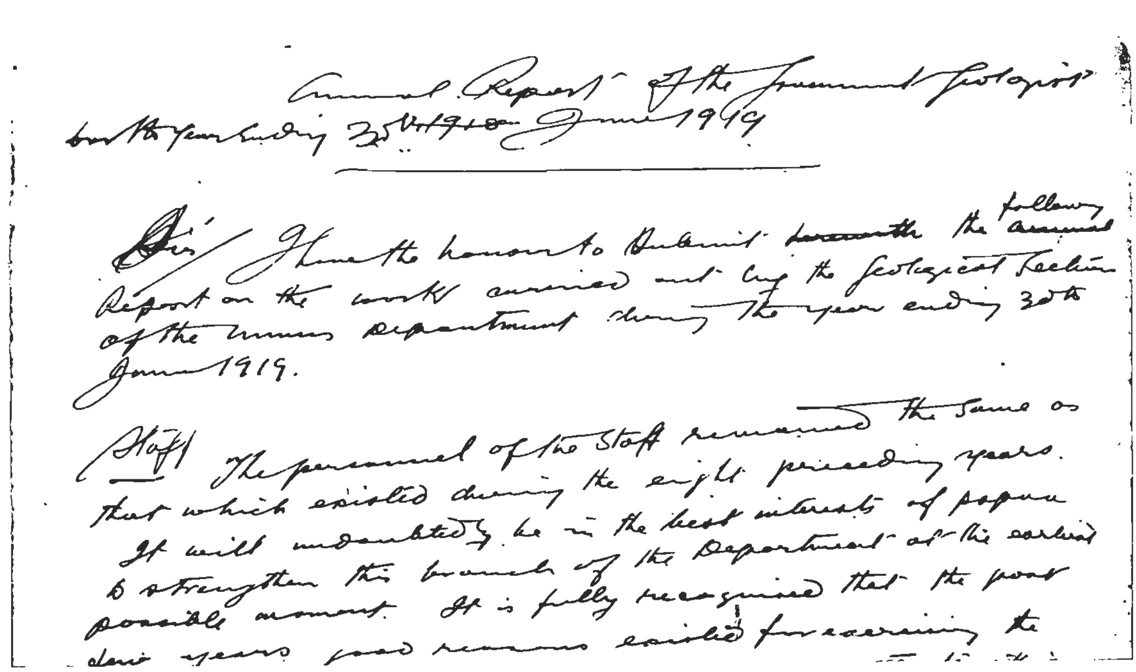
A practical chemist. The Annual Report for Papua for 1916-17 and for the following three years (Fig. 17) included, for the first time, a report by the Government Geologist—an innovation perhaps related to the departure of Staniforth Smith, who joined the armed forces in 1916. These reports round out the picture of Stanley's activities. He had now accepted responsibility for compiling mining statistics for the annual report of the Mines Department. He also had apparently become the chemical expert for the Papua Administration, carrying out not only the routine analyses of rock samples for metals, but also such divers tasks as determining the presence of lead and barium in paints, measuring the moisture content of tobacco for Customs, and, in 1918, developing a technique for fumigating the government ships against marine borer.

He was not necessarily pleased about carrying these extraneous duties, as is suggested by plaints in the annual reports. In the report for 1918-19 he noted that more than 2000 rocks and minerals collected during expeditions awaited determination, and that petrological work and additional analyses 'are in abeyance awaiting better appointments and accommodation'. He recommended the establishment of a 'National Laboratory, on the lines suggested by the Executive Council of Science and Industry', to meet the requirements not only of geology and mining, but also of animal and plant industry and forest products research.

Publication problems. Another problem to which he drew attention was the failure of those concerned to publish his reports—a prime concern of any scientist, but especially a matter of concern for Stanley, given his isolation from the geological fraternity, the possible value to science of his observations in a little-known part of the globe and, most importantly, the possible economic implications for Papua. At the time of writing his annual report for 1916-17, Stanley had recently completed two major reports (Cape Vogel Peninsula and Normanby Island), and several minor reports (e.g., those on Cannac and Sideia Islands, and a report on the Milne Bay gold field—of which report no trace remains) and apparently could see no immediate prospect of publication. In the annual report he wrote:

'Since my establishment in Papua I have endeavoured to assist in developing the natural resources, recommending at all times the publication of reports emanating from this section, and making collections of hundreds of specimens for the purposes of exhibition and classification in the economic museum. Owing to the unsettled state of affairs during the last three years, and to the shortage of paper, many reports are at present not being published. Realizing that economy must be practised in this direction, I think that all reports from this section should be published in the Annual Report of the Territory at least, and in pamphlet form as soon as can be conveniently arranged, so as to record and advertise the possibilities of development along certain lines.'

Topographic mapping. Another aspect of Stanley's work that comes to light in the Annual Reports is his concern for and contribution to topographic mapping. Almost everywhere he went the topographic maps were inadequate (an aspect of regional geological mapping that had changed little 50 years later). He routinely carried a theodolite with tripod, stadia rod, prismatic compass, two aneroid barometers (0-2400 m and 2400-4500 m), a thermometer, hypsometer, Abney level, metal chain and a 100 m length of loya vine, plumb bobs and spring balances, an accurate time-piece and a pair of binoculars (Stanley, 1925), and in each field project he would devote a certain amount of time to preparing or improving the topographic base data. For example, his patrol to the Musa and Kumusi rivers in 1916 started with several days of routine topographic surveying, intended to fix more accurately features of the coastline between Port Moresby and Rigo. Once under way, in the mountains he would halt repeatedly to determine altitude from the barometer, and would determine latitude and, as accurately as possible, longitude at major stations; he would also triangulate the major peaks, and determine their elevation above sea level by observing the angle of elevation from different points along a measured baseline (Stanley, 1918b, 1925).


Annual Report of the Government Geologist
for the year ending June 1919

Sir, I have the honour to submit the following the annual Report on the work carried out by the Geological Section of the Mines Department during the year ending 30th June 1919.

Staff. The personnel of the Staff remained the same as that which existed during the eight preceding years. It will undoubtedly be in the best interests of Papua to strengthen this branch of the Department at the earliest possible moment. It is fully recognised that the past eleven years good reasons existed for ...

Figure 17. Handwritten draft of Stanley's annual report to June 1919 was written on the back of an old topographic map. There is little evidence of revision or editing between draft and publication.

Even the published topographic maps contained significant errors, and Stanley was justifiably cautious in accepting the data of others. However, he had only praise for the work of Dr W.M. Strong, Chief Medical Officer, who had surveyed the Hydrographers Range (Stanley, 1918b). Stanley's knack with topographic mapping was recognised by the Lieutenant-Governor, who deputed to him the task of updating the official maps for each administrative division, a task that involved incorporating details of village locations, tracks, and drainage from the maps submitted by patrol officers (Stanley 1919c).

1917–18: Long leave

Having completed six years' service with the Administration of the Territory of Papua, Evan Stanley was entitled to a long leave. The family departed Port Moresby in October or November 1917 and returned seven-and-a-half months later.

1918–20: Time of transition

During the next two-year tour of duty, which started in May or June 1918, Stanley was to undertake less fieldwork and devote more time to compilation and writing—the beginnings of a phase that was to culminate in the publication of major reports on the geology of New Guinea and Papua five years later. He wrote on the promotion of hydropower and the need to start a program of measuring the flow of the nation's rivers (*New Guinea as a source for Nitrates*—October 1918); the recognition of osmiridium by prospectors, and its recovery and value (article written and reproduced in the *Papuan Courier* late in 1919; Stanley 1920b); and a review of the mining industry and the geology of the Territory intended for the Australian Yearbook and for a new Handbook on Papua, prepared in 1919 and reproduced, in part, in the Annual Report for 1919-20.

The year 1918 also was significant for the Stanley family for the birth of their second child, a son, Neville Fenton, at the hospital in Port Moresby on October 7th (Fig. 18).

The submission on hydropower found favour with the Commonwealth Institute of Scientific and Technical Studies in London, and with the Conjoint Board of Scientific Societies, which supported his proposal for monitoring stream flow and rainfall. However, almost 40 years were to elapse before the first hydropower schemes were developed. Hydro-electric schemes now provide all power for the larger centres on the Papua New Guinea mainland, and small schemes provide power for some islands centres.

The review of the geology of Papua included a stratigraphic table, which is an invaluable record of the state of knowledge at that time, and which includes some corrections to previously published data. The corrections include refining the age of the Astrolabe agglomerate (on the Sogeri Plateau) from Late Tertiary to Pliocene or possibly partly Late Miocene (now known to be Late Miocene-Early Pliocene), and revising the age of the volcanics of Mount Lamington from Late Tertiary to Pleistocene (the currently accepted age). Clearly, Stanley had recognised Mount Lamington as a Quaternary volcano, a fact disputed by some much later workers (Arculus & others, 1983).

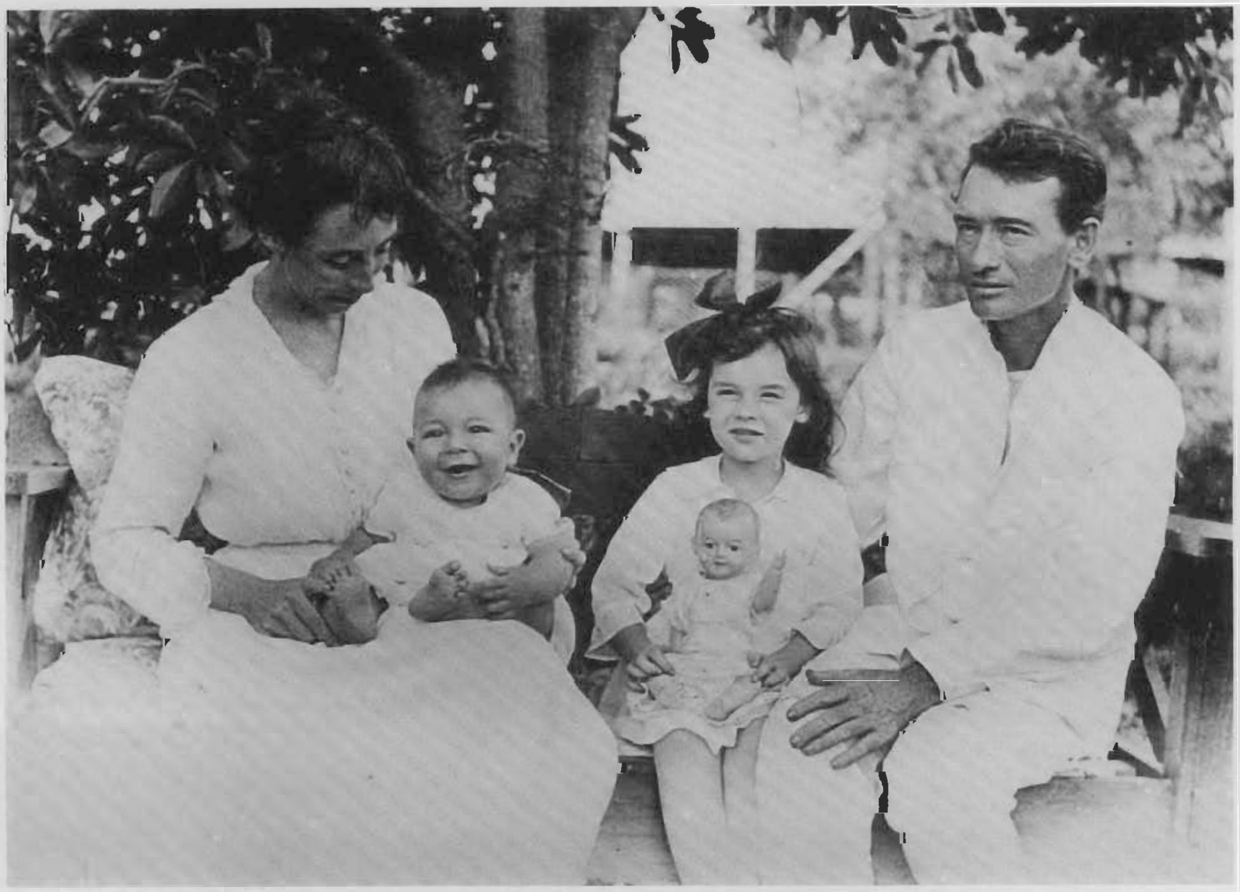


Figure 18. The Stanley family at home in Konedobu in 1919.

The article on osmiridium was written at the suggestion of a Dr Campbell Brown, who had visited Papua in October 1919 as a representative of the Waterman Pen Company, with the object of investigating the occurrence of osmiridium. The gist of the article was to describe the metal, and to encourage prospectors to search for it and present it for sale separately from their gold. The current price was 30-40 pounds per ounce, compared with four pounds five shillings for gold. The article led to an immediate increase in osmiridium production: reported production from the Gira-Aikora field jumped from about 10 ounces per year to 100 ounces worth 3000-4000 pounds in 1919-20. Gold production from the same field in that year was 200 ounces, worth a total of about 750 pounds.

The only major geological survey undertaken during this tour of duty was of Fergusson Island, in the D'Entrecasteaux group. Lesser surveys were undertaken to the Sogeri Plateau and Mafulu (in company with the government botanist, T. White), to a newly discovered copper prospect and ochre mine at Mount Louis, inland from Rigo, and to the southwestern slopes of Duau volcano, northeast of Kikori to investigate reports of alluvial gold.

Fergusson Island. The survey of Fergusson Island was undertaken in January-February 1919, primarily to investigate mineralisation on the northeast coast. Stanley walked around and across much of the island, observing the geology and developing topographic control. Results were summarised in the Annual Report for 1918-19, and an extract was given to the *Geographical Journal*, and the *Mining Review*. A full account was completed in January 1920, and was published later in the same year as Bulletin 6 of the Territory of Papua. The bulletin was accompanied by a coloured map at a scale of four miles to the inch (1:253,440); the map was inadvertently omitted from the bulletin at the time of its first release by Department of Home and Territories, Melbourne, but was distributed subsequently (correspondence 28 August 1920).

In the bulletin, Stanley outlined the geology of the island in much the same terms as it is known today. He recognised two series of metamorphic rocks, a meta-igneous suite, which he thought might be Archaean, and a meta-sedimentary suite, which might be Huronian or Algonkian (Fig. 19). The same two series of metamorphics were recognised by later workers (the Group I and Group II & III gneisses of Davies & Ives, 1965), but the age of these rocks is now considered to be much younger. In this regard, we might recall that for a geologist of those times, with a background in South Australian geology, and familiar with the geological literature of the North American continent, it was reasonable to suppose that any high-grade metamorphic rocks in Papua would be Precambrian.

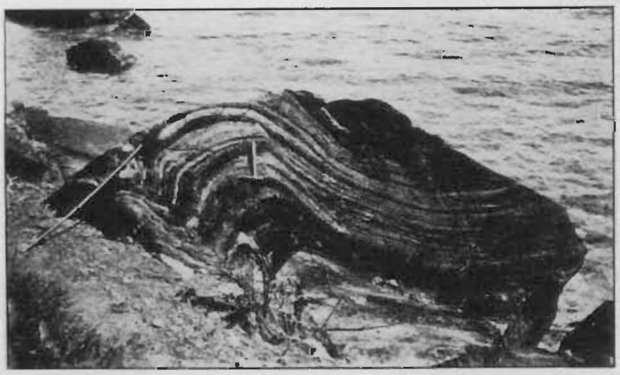


Figure 19. Folded layered gneiss on the coast of Fergusson Island, from the supposed Huronian series.
Photograph by E.R. Stanley.

Stanley drew attention to the sulphur available in the Iamalele solfatara fields, a trial shipment of which had been taken by Burns Philp some years previously (Moreton, 1898); to the large volumes of pumice readily accessible on Bwaioa Peninsula; and to indications of copper and gold mineralisation—gold mineralisation at Wapolu (Fig. 6) is currently under investigation. Looking at the broader picture, he deduced that the separation of Fergusson and Normanby islands, through Dawson Strait, was the result of rifting—a hypothesis that has become widely accepted in the last ten years with the recognition that the volcanics of Dawson Strait have the characteristics of a rift-related suite, and that the Strait has opened in response to westward propagation of Plio-Quaternary sea-floor spreading in the Woodlark Basin (Smith, 1976).

Mafulu. The expedition to the Mafulu district (Figs 6, 16) yielded more information on the metamorphic rocks of the mainland. A lower grade series of 'ilmenitic sandstone and slate' was distinguished from a higher grade series of 'crushed slate and phyllite, chlorite and epidote rocks, quartzite, schist and recrystallised limestone', the two being separated by the Kea River; Stanley speculated that metamorphic rocks closer to the axis of the Owen Stanley Range might be of even higher grade.

A significant new development arising from this trip, and from the palaeontological work of F. Chapman (1918), was the recognition of the considerable range in age of the volcanic rocks of the Mafulu region, from Miocene to Pleistocene.

Public Service Association. In 1919, Stanley was president of the Public Service Association and, in August, chaired a meeting at which it was agreed that the Association should seek the appointment of a judge of the Australian Arbitration Court to hold an enquiry into the conditions applying to the Papuan service, to make awards, to reclassify the service on the lines of the Northern Territory public service, and to recommend that a Board of Appeal be established (The *Papuan Courier*, 8 August 1919).

Stanley was also an active member of the Masonic Lodge, initially in Adelaide and subsequently in Port Moresby.

1920–22: Bulletin 7 and the Campbell Brown expedition

Bulletin 7. Stanley returned from three months' leave in about July 1920 in time to prepare another annual report, and to make improvements to his manuscript on the geology of Papua. This paper was presented at the annual meeting of the AAAS in Melbourne in mid-January, and was subsequently published as Bulletin 7 of the Territory of Papua, under the slightly misleading title of *Contributions to the Geology of New Guinea* (Stanley, 1921b).

A major advance in this paper was the recognition of the full extent of the suture on the northern slopes of the Owen Stanley Range, which is now known as the Owen Stanley Fault (Fig 6.):

'The most important tectonic fault in Papua is that of the Yodda and Kumusi valleys. It has been responsible for the formation of the Chirima River flowing southeast from Mount Albert Edward, causing the Yodda waters to flow into the Mambare. The fault passes through Oivi village, along

delay was the subject of much adverse public comment, and stirred the Prime Minister to write directly to Brown expressing his concern and to advise the Secretary for Defence and the Administrator, Rabaul, to scrutinise the expedition's expenditure and to not authorise any expenditure in excess of 10,000 pounds.

The reasons for the delay remain obscure. In a telegram to the Prime Minister on 21 March 1921, Brown attributed the delay to (1) malaria and dengue fever, which had affected seven members of the party, (2) the lack of efficient financial arrangements until that date, and (3) the fact that it took a long time to get things done in Rabaul. In the files of the Prime Minister's Department it is noted that Rabaul was in quarantine at this time, because of an epidemic of measles, and that this caused delays in fitting out the *Wattle*.

In his final report, Brown ascribed the delay to illness, with many members suffering from fever through those months, and both Callaghan and himself being released from hospital only a short time before the expedition's departure. Certainly, fever was rife and the progress of the expedition in the first months after departure was delayed several times while Brown recovered from severe attacks of malaria. Stanley also, in his official report, attributes the delay to fever, but in later correspondence with the Administrator of the New Guinea Territory expresses regret at the delayed departure, in terms that suggest that it was avoidable. In a letter to the press, Rolleston was at a loss to explain the delay once the ship was prepared and appears to lay the blame for inaction squarely on Brown, who was 'most uncommunicative on the subject'. One possible justification was that it would have been very difficult for such a small craft to work along the exposed northern coastline of the New Guinea mainland until after the cessation of the northwest monsoon in April.

Another problem for the expedition may have been resentment and lack of cooperation from officers of the New Guinea Administration. The Australian Prime Minister, W.M. Hughes, had personally supported the mounting of the expedition, and initial planning was primarily in the hands and at the expense of the Federal Government. However, once the party reached New Guinea, Hughes decreed that all costs were to be met by the New Guinea Administration. The Administrator, Brigadier-General Wisdom, newly appointed to head the civil administration, protested strongly at this, as he had limited funds and perhaps had begun to doubt the effectiveness of the entire exercise. But his protests were in vain. Stanley used the free time in Rabaul to examine the Rabaul volcano, which is described in detail in his final report.

Under way at last. In April 1921, the expedition set out on a first leg, east from Rabaul, south through the St Georges Channel, then west to Wide Bay and Owen Point. At each stop, Stanley made short traverses inland, developing some topographic control and recording geology in text and cross-sections. The party had intended to continue westward along the south coast of New Britain and thence to the mainland, but was forced to return to Rabaul when the anchor chain parted and the boat almost foundered at an overnight anchorage off Owens Spit (Owen Point on Fig. 6). During the return to Rabaul, Stanley and Captain Duncan were put ashore at Kokopo because of illness, and Duncan remained in hospital for some days.

On 10 May 1921, the party sailed again from Rabaul, this time bound westward along the north coast of New Britain. They made observations at a number of points along the north coast and eventually reached Madang on 20 June 1921. There the *Wattle* was slipped and damage from several groundings was made good.

Meanwhile, both the Prime Minister and the Administrator appear to have developed more serious misgivings about the expedition. On 19 April 1921 the Secretary of the Prime Minister's Department wrote to the Administrator (inter alia):

'Mr. Hughes has instructed that the expenditure should be strictly limited to the amount of 10,000 pounds, i.e., the expedition should return to Rabaul when this limit has been reached. Furthermore, you should take steps to ensure that Dr. Campbell Brown does not take papers or other documents from the Territory. You, yourself, should take over all papers, documents, records, etc., which relate to the Expedition.'

Their scepticism apparently was shared by Lieutenant-Governor Murray of Papua for, when invited to contribute to the cost of the expedition's planned work in Papua, he replied that he would do so only if Stanley were placed in charge, and the personnel reduced to two or three (telegram to Wisdom on about 23 May 1921).

By the time the *Wattle* reached Madang, Administrator Wisdom had become convinced that, if the expedition continued, expenditure would exceed the limit of 10,000 pounds. Accordingly, he wired Campbell Brown that he should remain in port until further advice and wired the Acting Prime Minister for instructions. Some days previously he had impounded the stores and equipment that the Expedition had sent ahead to Madang, and which had been intended for use on the next stage of the survey. Stores that had been dispatched to Morobe ('Maruhe') for planned work on the Waria and Mambare Rivers also were impounded.

Cabinet contacted the Minister for Home Affairs and Territories, the Hon. A. Poynton, who was in New Guinea at the time, and asked him to investigate the situation. On 6 July, Poynton wired the Acting Prime Minister recommending that the expedition be recalled. Cabinet considered this and concluded that 'Mr Hughes' programme should be carried out within the limits prescribed'. Presumably, this meant that the expedition was to continue until it was clear that the expenditure limit had been reached. In the event, any decision by the Australian Government was pre-empted by Brown, who, having replenished the ship's stores from his own pocket and disregarding the order from the Administrator that he was to stay put, set sail from Madang bound for the mouth of the Ramu River on 7 July.

The *Wattle* entered the Ramu River on 15 or 16 July and slowly made its way to a point about 260 km up river. Here, with the river level falling, the ship was stranded on a sand bank, and remained more-or-less stationary for the next five weeks or more. During this time rations ran very low, and many of the party were affected by fever. With fresh rains and a rising river level, the *Wattle* was refloated and regained the mouth of the Ramu on 9 September. She proceeded to Manam Island, where the party was regaled with fresh food provided by the mission, then to Monumbo (Potsdamhafen, 6 km northwest of Bogia, now abandoned; Fig. 6), and reached Madang on 21 September. From the time the party had entered the Ramu River in mid-July until their arrival at Potsdamhafen on 15 September they were out of radio contact and fears were held for their safety.

On 22 September 1921 the Acting Prime Minister, Sir Joseph Cook, telegraphed Prime Minister Hughes, who had reached Perth on his return from a Prime Ministers' Conference in London, seeking his consent to have the expedition recalled immediately. Hughes agreed to this. On the same day, Campbell Brown telegraphed the Acting Prime Minister to the effect that he proposed to wind up the expedition and return to Australia at once to report to the Prime Minister.

There followed another delay of just over a month before the members of the expedition embarked for Rabaul on the vessel *Mataram*, arriving on about 27 October 1921. For some of this time Brown was ill in hospital in Madang.

The purpose of the visit to Rabaul was to report in person to the Administrator and to hand over to him all the records of the expedition, as instructed by the Prime Minister. Not surprisingly, there was some resistance to this, but by 3 November Wisdom could report that nearly all the material had been recovered, and on 7 November 1921 the party sailed for Australia on the *Marsina*. The *Wattle* was reportedly stripped and abandoned in Madang.

Report preparation. Brown and Stanley prepared reports on the expedition. Stanley spent some time in Sydney and five months in Melbourne, starting in January 1922. He was based in the office of the Surveyor-General, where he was given typing and drafting support, and he was able to use the laboratory of Professor E.W. Skeats at Melbourne University for study of rock samples.

Two reports were tabled in Parliament on 19 July 1922. Brown's report was received unfavorably and the expedition was criticised as having been costly and ineffective. A report in the Melbourne daily, *The Age* (20 July 1922), headed 'A costly impulse' was critical of the Prime Minister's 'impulsive' decision to mount the expedition, of Brown's report as an expensive production that yielded little new information about the Territory, and of the expedition as a whole for failing to provide a result commensurate with the expenditure of 10,000 pounds of taxpayers' money.

Stanley's scientific report (Stanley, 1923a) was the only saving grace. It was described in the House by Prime Minister Hughes as 'very valuable', and in the correspondence of Brigadier-General Wisdom, Administrator of the New Guinea Territory, as 'the only thing which has justified, in my eyes, the Campbell Brown expedition'. *The Age* described it as an able report that 'presents a marked contrast to that of the leader of the party', but pointed out (and Stanley no doubt would have endorsed this) that Stanley might have achieved the same result or more, and at much less cost, had he been able to undertake the survey independently. In this regard, Stanley was to write to Wisdom, singling out Captain Duncan for praise, as distinct from the majority of other members of the party, in whom the 'qualities of occupation and unselfishness were lacking'.

The favorable comment was well founded, for Stanley had produced a valuable document, which presented not only his own carefully recorded new geological observations, but also a compilation and synthesis of pre-existing data, including, specifically, the observations of various geologists and explorers active during the German administration, and information he had gleaned from discussions with prospectors and natives. The report was enhanced by the excellent photographs taken by Jackson, and by Stanley's line drawings of volcanic features and geological sections. The title, 'Report on the Salient Geological Features . .', was no doubt selected to draw attention to the fact that the geological observations were very scattered and that this was something less than a complete account of the geology of the New Guinea Territory.

The expedition did not achieve all its objectives, partly because of the initial delay in Rabaul, partly because it was immobilised on the Ramu River for more than a month, and partly because the objectives were too ambitious. It was never likely that they could develop a comprehensive overview of the resources of the New Guinea Territory in a single expedition scheduled for only six months duration. The achievements of the expedition, such as they were, seem to have been largely a function of the energy and effort of Stanley.

Geological results. In brief, the report provided the first geological description of the active volcanoes and other volcanic features along the north coast of New Britain, including Watom and Lolobau islands, Talasea thermal area, Lake Dakataua, and the volcanoes Schrader and Tarawe; and the recognition of Pliocene marine sediments at Toriu (now known as Sinewit Formation) and on the Aria River (Aria Beds).

On the mainland, near Madang, Stanley described weakly metamorphosed fine sediments (Gusap Argillite), associated with volcanics (Finisterre Volcanics), which fine sediments he likened to the sediments of the Kemp Welch series in Papua; he also recorded, near Potsdamhafen, altered peridotite associated with 'a crushed series of crystalline limestone, quartzite, and puckered graphitic slate'. He erroneously deduced that the Finisterre Range and the ranges of New Britain had a core of metamorphic rocks.

The weeks on the Ramu River were geologically unproductive, as the party was not within easy walking distance of pre-Quaternary rocks and no doubt had a policy of not overnighting away from the ship, in view of their inability to defend themselves. Stanley made several traverses to east and west within a radius of 30 km, and otherwise used his free time to develop an accurate map of the river course, and to record vocabulary from the local native groups (Stanley, 1923a). We do not know whether Stanley was aware that much of the course of the Ramu River had been mapped previously by the German explorer Ernst Tappenbeck (Gash & Whittaker, 1975), nor whether Brown concentrated his efforts on this river because of rumours of the discovery of gold and osmiridium by the Germans (as is suggested in later correspondence in the Australian Archives).

Recommendations. At the conclusion of his report Stanley made several recommendations, which are of some interest in the light of later developments. He called for the establishment of: a Geological Bureau staffed by at least two geologists (a petrologist and a palaeontologist); a Geophysical Observatory/ Volcano Observatory to be concerned with the monitoring of both seismic and volcanic activity; a Forestry Department; sanatoria, where ex-patriates might take local leave; and a School of Tropical Medicine.

North Bainings. While in Rabaul at the start of the Campbell Brown expedition, Stanley had developed an interest in the mineral potential of the northwestern Gazelle Peninsula. The New Guinea Administration arranged for him to return to investigate this area in July 1922. He reported on the geology of the area, the iron mineralisation at Rangarere (Fig. 6), and the few signs of gold in the Gavit and Usuvit rivers, immediately to the east (Stanley, 1922a).

The Stanley family. During either the initial months of the Campbell Brown expedition or perhaps during the Bainings fieldwork, Mrs Stanley and the family spent some time in Rabaul, living in the Rabaul Hotel. By July 1921 they had moved to Australia, where daughter Joan recalls celebrating her 7th birthday in Adelaide. The following two months was the interval when the expedition was out of radio contact on the Ramu River. Joan recalls a time when her father was reported missing, and the relief when an official brown envelope was delivered to her mother in Australia with the news that he was safe. We cannot be sure that

August-September 1921 was the interval that Joan recalls, but it seems most likely.

In passing, we may note that Dr Campbell Brown refuted these reports subsequently, claiming that his expedition was at all times in daily radio contact and laying the blame for any confusion at the feet of the men of the New Guinea Administration. Probably, the explanation is that Brown maintained radio silence through those months in order to avoid being recalled to Rabaul by Administrator Wisdom.

Following the return of the expedition party to Sydney in November 1921, the family stayed with relatives in Sydney, and in January moved to Melbourne, where, after some weeks in the Sandringham Hotel, they rented a house. This was Joan's first contact with the Australian school system, a cultural readjustment, the humour of which she still recalls.

1922–24: Achievements and acclaim—and tragedy

In September 1922 the Stanley family returned to Port Moresby to embark upon a further tour of duty. Stanley had been greatly stimulated by the experience of the past several years, during which he had developed a better appreciation of the geology of New Guinea and Australia, and had received public acclaim for his contribution to the New Guinea expedition. He had developed ideas that he would pursue in the following months, and seems also to have developed a new determination to combat the scientific isolation that his posting entailed, by attending relevant scientific meetings in Australia and New Zealand. Thus, we find him planning to attend the annual meeting of the AAAS in New Zealand in January 1923 and the Pan-Pacific Science Congress in Sydney in August 1923.

One of the new ideas he brought back to Port Moresby was the compilation of a geological map of Papua with accompanying notes. He had completed a geological map of the New Guinea Territory earlier in the year, and this was a logical next step. He presented the proposal to the Director of Mines in November 1922 and it received immediate endorsement.

Another new idea was that the Mesozoic sediments of Queensland, which contain significant coal seams, may be conterminous with the (poorly known) Mesozoic sediments of Papua and that, by inference, the latter may contain coal. He speculated that the coal discovered by Staniforth Smith on his ill-fated expedition to the Kikori River in 1911 may be Mesozoic in age, rather than an equivalent of the Miocene lignitic coal of the Purari (Stanley, 1922b). (Unfortunately Smith's samples had been lost during the expedition's struggle for survival.)

In passing, we note that Staniforth Smith had at this time returned to his former posting in Papua, after war service which was followed by a term as Acting Administrator of the Northern Territory. He was now on cordial terms with the Stanleys and would commonly call at the house (Fig. 21) as the men walked up from the launch landing at the end of the working day (Joan's recollections). Several of Stanley's reports written at about this time mention (perhaps with tongue in cheek) Staniforth Smith's exploits as an explorer, and Staniforth Smith, as Director of Mines, made favorable mention of Stanley in his annual report for 1921-22.

AAAS, New Zealand. A contribution by Stanley is included in the published proceedings of the annual meeting of the AAAS, which was held in New Zealand in January 1923 (Stanley, 1923d). However, it is doubtful that he attended the

Figure 21. Staniforth Smith and Stanley stand before the steps of the Stanley home on Spring Garden Road; about 1923.

meeting, for in mid-January 1923 he was on traverse in the Owen Stanley Range (see below). The paper for the AAAS had the complicated title of 'Notes on the structural relationships of the volcanic rocks, Late Tertiary and Mesozoic deposits in New Guinea'. It was an important paper, in which much information on the two territories was synthesised in text and cross-sections, and some significant conclusions presented.

In it he noted that the distribution of volcanic centres is, to some extent, controlled by lines of weakness or rifts that trend at right angles to the regional trend, and cited the volcanoes of the Willaumez Peninsula and the volcanic centres on western New Britain as examples. He also noted the widespread distribution of Late Tertiary (Miocene and Pliocene) sediments in Papua, and in the Sepik-Ramu region and on New Britain, mentioning their possible significance in petroleum exploration.

He developed further the concept that the Mesozoic sediments of Queensland may extend to Papua, and that the Mesozoic in Papua may be much more extensively developed than was generally appreciated at that time, and illustrated this with a cross-section from Palmerville, Queensland, to the Finisterre and Saruwaged ranges of north coast New Guinea.

He also developed the idea that there may be major cross-cutting faults in the border region, longitude 141° East, as indicated by the changes in course of the Fly, Sepik, and Tamu rivers; modern mapping has confirmed that there are structural complexities coincident with the border.

The sections across New Guinea show block-faulting and elevation of basement horsts to explain the development of the main range and north coast ranges. One of these sections illustrates the general lack of awareness, at that time, of the broad region of central highlands, an area not traversed by Europeans until some years later.

Mount Obree–Kagi. From 16 January to 20 February 1923, in company with government forester C.E. Lane Poole, Stanley traversed the Owen Stanley Range between Mount Obree and Kagi. This was an ambitious venture in high forested terrain where there are only isolated pockets of population and few tracks—a trip that was, in retrospect, a celebration of the vigour of the two men and of Stanley's bush skills and ability to work with the Papuan people, which he had developed over the preceding 12 years. They made improvements to the topographic map and Stanley recorded a description of the metamorphic and intrusive rocks that they encountered. In June 1923 he submitted to his superiors a typed report with photographs (Stanley, 1923c), with the request that it be published in the Bulletin series. A quotation for printing cost was obtained (83 pounds), but the Executive Council decided not to proceed. No record remains of the geological map that accompanied this report (see later).

Geology of Papua. Through the same period, the compilation of the geological map of Papua and accompanying text was proceeding apace, being completed in July 1923. The report was published in 1924, a handsome and well-presented soft-cover volume of 56 foolscap pages of text, tables and illustrations, accompanied by a coloured geological map (Fig. 16). The illustrations are 50 of his own photographs, and include scenes of volcanoes, outcrops, mines and the early oil drilling rigs. Like his report on the salient features of the geology of New Guinea, it is a benchmark volume, the first synthesis of the geology of this part of the world since the much briefer review by David & others (1914), and the first to include a comprehensive account (11 pages) of economic geology. Further, much of the body of the report was drawn from his own observations. The report concludes with an appeal for the establishment of a Geological Survey Department.

Pan-Pacific Science Congress. In August-September 1923, Stanley attended the Second Pan-Pacific Science Congress, which was held in Melbourne and Sydney. This was a major event, which had attracted distinguished scientists (Fig. 22) from North America, the United Kingdom, Holland, Japan, and New Zealand. Stanley presented a total of eight papers, covering tropical settlement, topography, coral reefs, volcanic action, Tertiary formations, structure, and oil and ore provinces.

His paper on structure is the only one of these that exceeds three pages in length. It is a substantial document, which begins with some speculative, and, in hindsight, somewhat dubious statements about structural arcs extending through New Guinea, but goes on to make a number of valuable contributions to knowledge. These include an improved version of the cross-section from Palmerville to the north coast of New Guinea; recognition of the importance of the Mio-Pliocene orogeny in New Guinea; evidence for a land connection between Australia and New Guinea in the Late Cretaceous or Early Tertiary, and again in the Pleistocene; and recognition of the rifted nature of the Wide Bay-Open Bay depression, and of a northwest-southeast line of weakness across the Gazelle Peninsula. Also, having predicted a greater development of Mesozoic rocks in the Papuan interior than was currently recognised, he was patently pleased to be able to tell his audience of the recent discovery (by a Resident Magistrate, late in 1922) of sediments

Figure 22. The group of scientists includes T.W. Edgeworth David (right), E.C. Andrews (left), and Evan Stanley (rear), before the headquarters of the Royal Society of New South Wales, September 1923.

containing Mesozoic fossils in the Kerabi valley, east of the Samberigi (Fig. 6).

The Pan-Pacific Science Congress of 1923 was perhaps his finest hour in terms of recognition of his achievements by the scientific community. W.N. Benson was to write subsequently 'His presentation of this work, largely the result of his unaided efforts, attracted the keenest appreciation of the Pan-Pacific Science Congress .... and this body expressed its high approval by special resolution urging on the authorities to supplement the excellent work that was being done' (Benson, 1925). The resolution of the Congress reads '4. That this Congress has been greatly impressed with the scientific and economic value of the results achieved in Papua by the Government Geologist, and it expresses the hope that these investigations may receive increased support.'

There is no record of Stanley's activities in Papua through the remainder of 1923 and 1924, with the exception of a brief mention in the Annual Report for 1923-24, to the effect that he was engaged in preparation of a detailed geological and topographic map of the active mining area within the Astrolabe mineral field. Perhaps he was content to remain at headquarters, given that there was illness at home (see later). He may have visited the Fly River region (Joan's recollection) or have made another sortie into the Owen Stanley Range. Benson (1925) wrote that during this year Stanley 'made a further journey into the great central ranges of Papua, and obtained important results which are as yet unpublished'. A recollection by M.F. Glaessner (personal communication, 1985) lends some support to this. According to Glaessner, a most recent original manuscript by Stanley, which dealt with metamorphic rocks of the Owen Stanley Range, was borrowed by geologists of the Australasian Petroleum Company, and was lost when records were destroyed for security reasons, at the time of the civilian evacuation of Port Moresby during World War Two. Whether Glaessner's recollection refers to a 1924 manuscript or to the Mount Obree-Kagi manuscript and map (Stanley, 1923b) remains uncertain. Whether by coincidence or not, no copy of the map to accompany the Mount Obree-Kagi report is currently available.

Practical hints. During these years Stanley also prepared a chapter on 'Practical hints to scientific travellers in New Guinea' (Stanley, 1925), for inclusion in a book being assembled by Professor H.A. Brouwer of the University of Delft in the Netherlands. No doubt this assignment stemmed from their contact at the Pan-Pacific Congress. Stanley's contribution occupies 35 pages and is comprehensive. It has special value today as a record of how field operations were conducted in Papua New Guinea in those times, before the advent of air travel, helicopter support, and modern medicines, and before radio had come into general use.

Illness. If August-September 1923 was professionally a rewarding time for Stanley, it was also a time when storm clouds were gathering at home. Joan, now nine years old, was attending a convent school just above Ela Beach in Port Moresby. She had experienced some trouble with malaria, first contracted while the family was in Rabaul, and it was agreed that, if this should recur, she should be placed in boarding school in Australia—a most difficult decision for a close-knit family. In the event, the fever did recur, and in December 1923 the family travelled to Australia. Stanley took the opportunity to attend the annual meeting of the AAAS, which was held in Adelaide in mid-January, and to present a paper on the physiography of New Guinea, before returning post-haste to resume duty in Port Moresby. Helen and the children remained in Adelaide, where Helen was to settle Joan into boarding school, returning in company with five-year-old Neville in February, after tearful farewells.

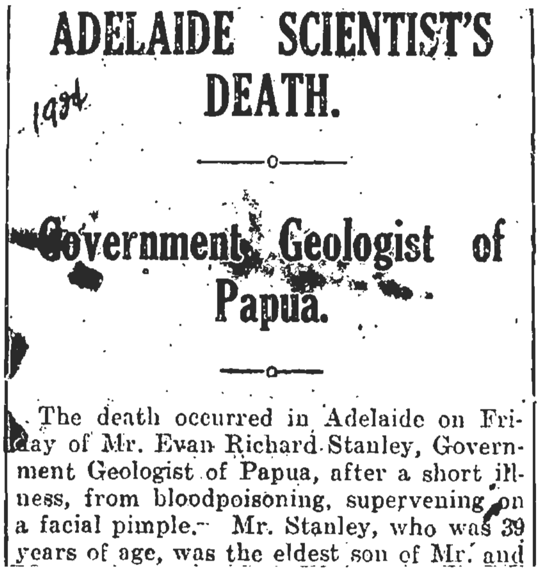
As 1924 progressed, Helen herself became ill with TB, and in December 1924 Stanley accompanied her to Adelaide, where she was admitted to hospital. He intended to remain for only a few weeks, then to return to duty in Port Moresby. However, this was not to be. He was stricken with the spread of staphylococcal infection from a carbuncle on his chin. He too was admitted to hospital and underwent several surgical operations, but his condition continued to deteriorate and, within a week, on Friday 27 December, he died.

Some of the sense of shock which must have been felt by family and friends is recorded in a letter to the press written soon afterwards by a friend, Colonel T.H. Smeaton. The letter begins as follows:

'The tragically sudden death of Mr Evan Stanley is, to his friends, a stunning shock that will not soon be got over. In the pink of good health a few days ago, he was looking up his old intimates and discussing with them the unfolding problems of life in Papua, with characteristic lucidity and enthusiasm; and this morning (Monday) there is the announcement in the press of his death from blood poisoning. And so he passes; one of the most interesting and lovable men it has been my fortune to know, and an Australian who has given his native country exceptionally fine service in a realm in which he stood alone.'

Sir Douglas Mawson delivered a eulogy on the Sunday in which he spoke of Stanley (Figs 23, 24) as 'so honest and

Figure 23. Evan Stanley, shortly before his death.



ADELAIDE SCIENTIST'S DEATH.

Government Geologist of Papua.

The death occurred in Adelaide on Friday of Mr. Evan Richard Stanley, Government Geologist of Papua, after a short illness, from bloodpoisoning, supervening on a facial pimple. Mr. Stanley, who was 39 years of age, was the eldest son of Mr. and

Figure 24. From *The Advertiser*, 30 December 1924.

lovable a character . . . . widely known and very well liked among scientists' who, while at Adelaide University had earned the reputation of a 'steady, conscientious and determined worker'. He was 'well fitted for work in Papua by reason of his grand physique and natural ability for roughing it'.

Epilogue

Helen Stanley's condition was critical, but she recovered and lived for ten years before succumbing to TB. Joan developed a highly successful career in school administration, and Neville earned an international reputation in microbiology, retiring as Professor of Microbiology at the University of Western Australia in 1984. He died in October 1984.

Despite the large contribution that Stanley had made in terms of geologic and geographic knowledge and assistance to mining and prospecting, the reasonably high level of public awareness of that contribution, and the recognition he had earned in the scientific community, and flying in the face of the recommendation of the Pan-Pacific Science Congress, the Papua Administration appointed no successor and the post of Government Geologist was allowed to lapse. This reflected the poverty of the Administration at that time; in the immediately ensuing years the government service included no scientific specialist in any primary industry field (H. Nelson, personal communication, 1985). A small geological survey was established subsequently in the New Guinea Territory, but none in Papua until after the Second World War, when the administrations of the two territories were merged.

The Murray administration recognised Stanley's contribution to the fledgling colony by naming for him the newly-reclaimed roadway on the harbour foreshore (Stuart, 1973). Stanley Esplanade is today a busy rutted thoroughfare, which provides the main access to Port Moresby's wharves—an apt memorial to a practical man!

Because of the long pause in government-sponsored geological investigations, the various reports by Stanley continued to serve as standard references for 30 and 40 years, being generally superseded only when geological investigations were accelerated in the 1960s and 70s. Even today they remain a valuable data source and, thanks to Stanley's photographic skills, a pleasure to peruse, and a fascinating record of the mid-colonial years.

And what else can be said of Evan Stanley? He was certainly an unusual man, someone who had great energy, and who placed much emphasis on the merit of practical skill and action. He was a carpenter, who was involved in building a comfortable bungalow-style house for his bride-to-be while maintaining a heavy schedule of geological work during his first term in Papua; a petrologist-chemist who could carry out a full chemical analysis of a rock sample, assay a metallic ore, or, if called upon to do so, develop a mixture to protect the government ships against marine borer; a photographer who could process his film under primitive conditions in a bush camp; and a surveyor, who did much to improve the accuracy of the early topographic maps of Papua, and who generated an accurate map of the lower reaches of the Ramu River.

He was an able and competent geologist, who always worked alone (except for the time spent with Wade in 1913-14) and could consult with professional colleagues only rarely. He had a chemical laboratory, but, as far as I can determine, no equipment to prepare thin sections or mineral separates, and no support staff. He had the breadth the job required: trained in mineralogy and petrology, he was at home in the metamorphic and igneous terrain of the Papuan mainland and on the active mineral fields. At the same time, he could turn his hand to stratigraphic mapping and regional synthesis, for example, on the Papuan 'oil field' and the Cape Vogel Peninsula. He made a major contribution to our knowledge of the volcanoes of New Britain, and developed concepts in regional structure that were innovative and have value today, including the recognition of the importance of Mio-Pliocene orogeny, of the rift origin of Dawson Strait, outlining of the Owen Stanley Fault, and prediction of a considerable development of Mesozoic strata in the Papuan Basin.

He lived through a fascinating epoch of Papuan history, from the optimism of the years immediately before World War One—when the excitement generated by successive discoveries of gold and copper mineralisation was augmented and surpassed by the prospect of major oil discoveries, to the stalemate of the post-war years, when, with commodity prices low, the mining and agricultural industries floundering, and no positive progress in oil exploration, the Administration of Sir Hubert Murray struggled to survive on limited funds.

Stanley followed a different star. For him the pre-war years and the war years were a time of steady application and effort, with little recognition for what he had achieved. By way of contrast, in the 'twenties he was thrust into the limelight, perhaps nationally known as a result of the publicity arising from the controversial Campbell Brown expedition, his work recognised and acclaimed by the general assembly of the Pan-Pacific Science Congress, and his crowning accomplishments: the reports on the geology and resources of the two Territories, published in successive years. In December 1925 he would have completed a 15-year term with the Papua Administration, and had planned to travel to southern France and North America, where Helen would regain her health and he would continue his studies.

What a cruel twist of fate that all was so suddenly and tragically brought to a halt.

Acknowledgements

This study had its beginnings in the late 1950s, when, as a junior geologist with the Administration of the Territory of

Papua and New Guinea, I was introduced to the published and unpublished works of Evan Richard Stanley and was given the opportunity to follow in his footsteps to Misima Island, the Yodda-Mamama-Kumusi area, and, later, the D'Entrecasteaux Islands.

In the 1960s, Alexander Renwick, O.B.E., then Chief Government Geologist for the Territory of Papua New Guinea, was instrumental in the inauguration of an annual Stanley Memorial Lecture, under the auspices of the Papua New Guinea Scientific Society, which lecture commemorated the achievements of both Evan R. Stanley and an un-related geologist and identity of later years, the late G.A.V. Stanley. Through the kind offices of Renwick and of my sister, Jo Donnellan, who was working as a microbiologist under Professor Neville Stanley at that time, I was able to make direct contact with the Stanley family in Perth in 1971, and to follow this with more consultation in Perth in May 1985. (Regrettably for all concerned, Professor Neville Stanley had died in the interim.)

The impetus to conclude what had become a perennial part-time project was provided by the call for papers on the history of Australian geology, which was issued in 1985 by the newly formed Specialist Group in Earth Science History of the Geological Society of Australia. W.A. McGee, who had worked in another of Stanley's field areas, Woodlark Island, had in mind to contribute a paper on Evan Stanley, and had already conducted some research in the Mitchell Library with this in mind. When he learned of my intentions, he generously withdrew and, through the course of the final stages of compilation and writing, plied me with reference material and valuable comment on various aspects of the draft manuscript. His efforts have considerably have considerably enhanced the story.

I am indebted to various reference sources for assistance in finding and copying source material, notably Ms Deanne Dorn and the library of the Bureau of of Mineral Resources (BMR), Canberra; the library of the Geological Survey of Papua New Guinea, Port Moresby; Ms Judith Robertson and the Australian Archives in Mitchell, ACT; Ms Susan Woodburn, Archivist with the University of Adelaide; the Papua New Guinea National Archivist, for cooperation in authorising access to archival material; and the Australian National Library, Canberra, for access to manuscript and pictorial records. I am also indebted to H. Upenieks, ARPS, RBP, and BMR photographic services unit for reproduction of photographs.

In addition, I am grateful to the following who contributed useful comment on drafts of the manuscript and additional information: John Jones, then Acting Chairman of the Geology Department of the University of Adelaide; Martin F. Glaessner, himself a veteran of PNG geology and now Emeritus Professor at the University of Adelaide; Colin Gatehouse, Barry Cooper, and David Corbett, all of Adelaide, and members of the inaugural Executive of the Specialist Group in Historical Geology; two other veterans of PNG geology, N.H. Fisher and J.E. Thompson; Sir F.F. Espie, formerly of Bougainville Copper P/L; H. Nelson of the Research School of Pacific Studies in the Australian National University; W.B. Dallwitz, formerly of BMR; Geoff Page of Narrabundah College; and two colleagues within the Bureau of Mineral Resources, W.D. Palfreyman and R.W. Johnson.

However, the prime source of the material upon which this study is based, and of the illustrations that accompany this text, is the Stanley family, initially through the late Professor Neville Stanley who, in 1971, went to some lengths to provide me with photocopies of letters, press-clippings and manuscripts, and copies of old photographs. More recently, Joan Benson, who provided much valuable source material, has enriched the story with her recollections of events and personalities and has improved the presentation with careful review of the draft manuscript. Dr Fiona Stanley also contributed useful records and photographs. I am indebted to them not only for source material but also for their enthusiastic support through the later stages of the project, and for the privilege and pleasure of being permitted to observe in each of them something of the energy and zest for life that made Evan Stanley an uncommon man.

In conclusion, this presentation falls far short of being a definitive account of Evan Richard Stanley and his work, for several reasons. Firstly, the search of old Papua New Guinea records, while time consuming, was by no means exhaustive, and, secondly, my attempt to synthesise his geological achievements has necessarily involved a personal perception of what was important and what not. Another geologist would surely have presented things differently.

Archival note. Copies of documents accumulated during this study have been lodged with the Stanley family, the Manuscript Room of the Australian National Library (filed under E.R. Stanley), the Geological Survey of Papua New Guinea, and, through the Geological Survey, selected papers with the Papua New Guinea National Archives, Port Moresby. My attempts to locate copies of the movie films made during the Campbell Brown expedition, and to find the box of quarter-plate glass negatives, believed to have been Stanley's, which were reclaimed by Australian authorities from the Geological Office of the Department of Lands, Surveys and Mines in Port Moresby in about 1955, have been unsuccessful. The films were entitled 'The voyage of the *Wattle*', 'Unknown lands of New Guinea', and 'Glimpses of New Guinea', and were shot by Jackson of Amalgamated Pictures Limited, Melbourne. The last two films were printed and sold to the Federal Government on 13 January 1923; as of November 1923, the first was stored at the studios of Australasian Films Limited, Rushcutters Bay (information from a letter from Campbell Brown to the Acting Prime Minister, 24 November 1923).

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Devonian fish remains from Billiluna, eastern Canning Basin, Western Australia

G.C. Young[1]

Fragmentary remains of Devonian fishes are described from the Knobby Sandstone, a thick non-marine clastic formation in the eastern Canning Basin, which is a potential petroleum reservoir in subsurface fault-bounded sequences overlain by marine carbonates. The fauna includes a new species of the antiarch *Bothriolepis*, a few dermal plates of an asterolepidoid antiarch, various coarsely ornamented placoderm fragments probably belonging to a much larger antiarch, and some isolated rhipidistian teeth and scales. The fragmentary preservation suggests a high-energy depositional environment. Associated are plant remains, including *Leptophloeum australe* (M'Coy). All fossils are preserved as moulds in a coarse sandstone. The fauna is probably Late Devonian (Famennian) in age, but better material is required for detailed correlation with other Late Devonian vertebrate assemblages in the Canning Basin and elsewhere.

Introduction

The existence of Upper Devonian or Lower Carboniferous sediments of probable non-marine origin in the eastern part of the Canning Basin was first noted by Casey & Wells (1964), who collected lycopod remains (*Leptophloeum australe*) from sandstone in the Knobby Hills, about 20 km northeast of Billiluna Homestead. Fish plates were reported by Veevers & others (1967) from the same unit (referred to by them as the Knobby Sandstone) and from rocks of similar lithology in the nearby Falconer Hills, which had previously been mapped as Grant Formation of Permian age. During 1972, further fish and plant remains were collected by the author, A.T. Wells, A.N. Yeates, and V.L. Passmore (Bureau of Mineral Resources), and geologists from Mines Administration Ltd, from the Knobby and Falconer Hills and other isolated outcrops in the vicinity (Fig. 1).

The fish-bearing Knobby Sandstone (Yeates & others, 1975) occurs on the surface as isolated outcrops over an area about 50 km long and 25 km wide (Fig. 1), but its relation to older rocks is not exposed. The nearest older strata are the Ordovician Carranya Beds, which have been mapped about 25 km to the northwest of the Knobby Hills and 50 km to the southeast. Blake & others (1977) noted seismic data indicating Knobby Sandstone equivalents in the subsurface, apparently underlain unconformably by younger Ordovician to Devonian sediments. More recent seismic and drillhole information over the Billiluna Shelf indicates that the Knobby Sandstone is underlain disconformably by carbonates of early Late Devonian age, which are probable equivalents of the Pillara or Sadler Limestones farther to the west (Botten, 1984; Smith, 1984).

Because of the nature of the outcrop (variable subhorizontal dips in sandstone outliers), field mapping gave little idea of the thickness of the Knobby Sandstone. An early drillhole indicated a thickness of at least 162 m in the Falconer Hills (Blake & others, 1977). More recent drilling increased this to at least 300 m in the Billiluna area (Botten, 1984), and seismic data across the Billiluna Shelf and Balgo Terrace suggest much greater thicknesses, in excess of 1 km (e.g. Jacobson, 1984; Purcell & Poll, 1984).

The most common lithology in surface exposures of the Knobby Sandstone is medium to coarse-grained sandstone with abundant shale clasts. There are minor red siltstone and conglomeratic interbeds at some levels. The sandstones are commonly cross-bedded, and point bars up to 15 m wide are abundant (Botten, 1984) together with extensive distributional channel-fill systems. Botten (1984) interpreted the depositional environment as a major progradational delta sequence of Mississippi type, with dominant flow towards the southwest, and various sedimentary features indicating a reasonable water depth. Derivation of the Knobby Sandstone from the eastern edge of the basin is consistent with the notion that this was an active fault-bound margin during the Late Devonian (Smith, 1984). The fish remains from the Knobby Sandstone studied by the author, although mainly small fragments, came from individuals of moderate to large size, suggesting permanent bodies of water.

Other sandstones of similar lithology occur in the region, but are probably of younger (Early Carboniferous) age. The sandstone at Red Bluffs reported by Veevers & others (1967) to contain *Leptophloeum australe* was also examined by the author, but appears to be devoid of vertebrate remains, although plant material (including *Lepthophloeum*) is quite abundant. Veevers & Wells (1961, p.56) noted the occurrence of *Leptophloeum* in a sandstone outlier about 80 km to the south, near Balgo Mission, but more recent mapping in this region failed to produce further fossil material (A.N. Yeates, BMR, personal communication).

The Knobby Sandstone has some economic potential. It has been investigated as part of a geological mapping and drilling program for possible uranium mineralisation, although results of this study indicate low potential for economic accumulations of this mineral (Botten, 1984). Thick sequences of Knobby Sandstone overlain by shallow-marine carbonates have been identified in fault-bounded blocks on the Balgo Terrace by seismic exploration. The Knobby Sandstone shows fair to good reservoir characteristics, and is a main objective for petroleum exploration in the region (Jacobson, 1984).

The vertebrate remains from the Knobby Sandstone dealt with here were all collected from its surface exposures in the Knobby Hills and Falconer Hills areas. Other isolated outcrops about 20 km to the northeast near Overlander Waterhole were not visited. The specimens are generally poorly preserved as moulds in the coarse sandstone, but with better material the fishes could have potential for biostratigraphic studies. Most of the samples available for study are indeterminate fragments of dermal bone, but it is evident from the coarseness of the ornament that they came from fairly large bones belonging to several placoderm taxa. The fragmentary condition of what would have been fairly thick and robust bones indicates a high-energy depositional environment for this part of the Knobby Sandstone. The presence of rhipidistian (crossopterygian) fishes in the fauna is indicated by three moulds of isolated laniary teeth, and five other specimens are referred to the antiarchs, a group of placoderm fishes widespread in Middle and Late Devonian continental deposits, and therefore of some biostratigraphic interest. Two of these are described as a new species of the cosmopolitan genus *Bothriolepis*, and the other three belong to an asterolepid antiarch, although its generic assignment is uncertain.

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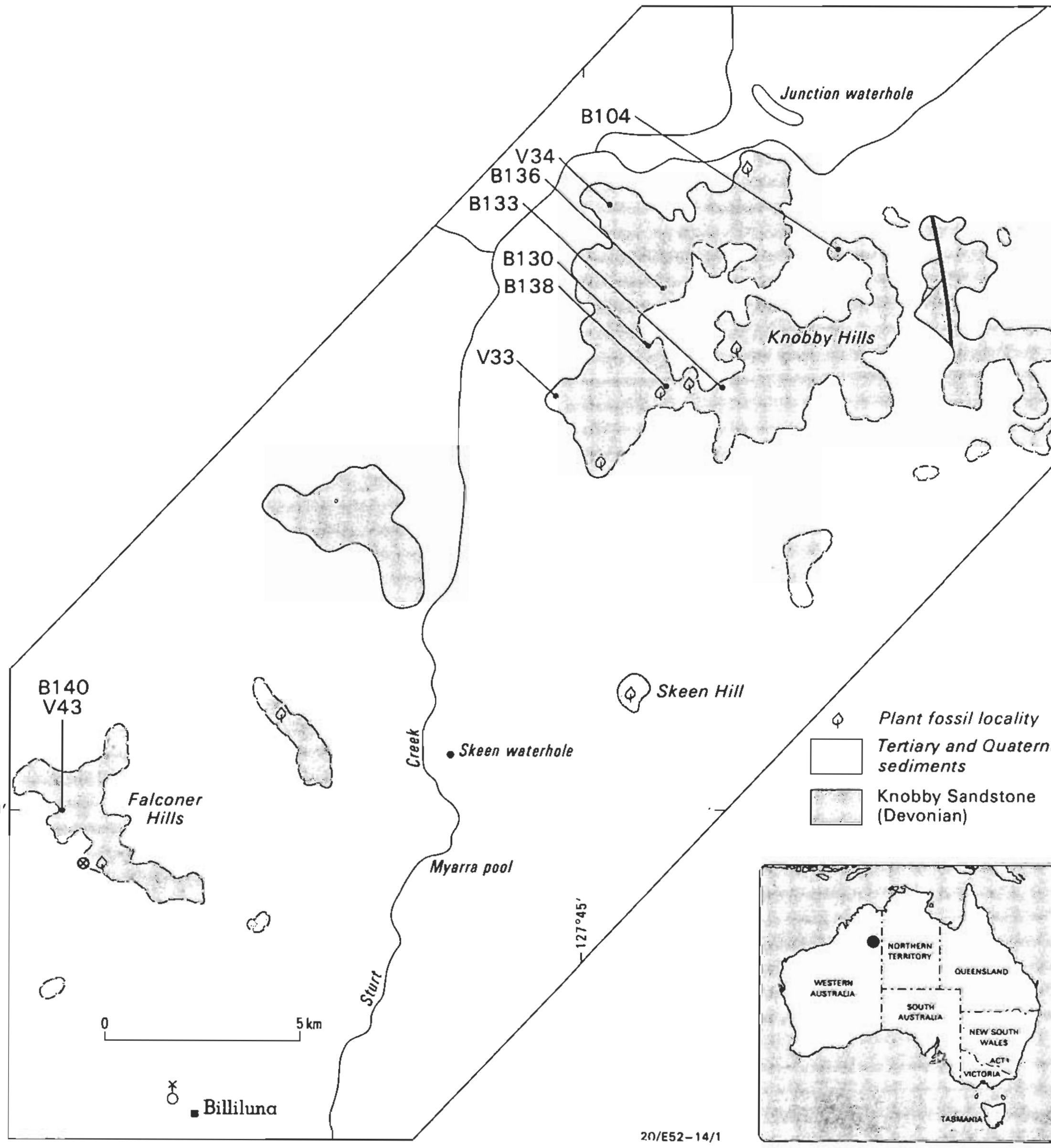


Figure 1. Geology of the Knobby Hills–Falconer Hills area (Billiluna 1:250 000 Geological Sheet), showing fossil localities for material described in this paper.

In Australia, *Bothriolepis* has been reported from many localities in Victoria, New South Wales, central, and northwestern Australia (Gilbert-Tomlinson, 1968; Gardiner & Miles, 1975; Long, 1983; Young, 1985), and is the most widely known of Australian Devonian fishes, although only a few species have been formally described (Hills, 1929; Young & Gorter, 1981; Long, 1983). Asterolepid antiarchs are apparently somewhat less common. The Upper Devonian form *Remigolepis* occurs at several localities in New South Wales (e.g. Young, 1974; Campbell & Bell, 1977), and other forms from central and southeastern Australia have been described by Young & Gorter (1981) and Young (1983, 1984a).

Age of the fauna

This is a small and poorly preserved fauna, and both the placoderms and crossopterygians are at present too incompletely known to be of much biostratigraphic use. The stratigraphic range of antiarchs in the Middle and Late Devonian was reviewed by Young (1974); more recent contributions have been made by Young & Gorter (1981) and Long (1983). The earliest species of *Bothriolepis* (known from China and Australia) may be as old as Eifelian, although most of the occurrences in southeastern and central Australia are probably Late Devonian in age (Long, 1983; Young, 1985). *Bothriolepis* from the Gogo Formation in the Canning Basin is dated by a variety of invertebrate fossils, including conodonts, as early Frasnian (e.g. Gardiner & Miles, 1975). The asterolepidoid antiarch *Remigolepis* occurs in probable Famennian strata (the Worange Point Formation) on the south coast of New South Wales, where it characterises the highest vertebrate faunal zone in the sequence (Fergusson & others, 1979; Young, 1983), and a species of *Asterolepis* (*A. sinensis*) defines the highest (late Famennian) vertebrate zone in China (Pan, 1981). The presence of an asterolepidoid antiarch in the Knobby Sandstone is therefore consistent with a Late Devonian (Famennian) age, although the fragmentary nature of the material, and the fact that this is the first record of this group from the Canning Basin, means this evidence must be regarded as provisional.

Other evidence on the age of the Knobby Sandstone fishes comes from the associated plants, palynology, and fossiliferous carbonates above and below the formation inferred from seismic and drillhole data. The lycopod plant *Leptophloeum australe* (M'Coy) is generally considered to have a Late Devonian/Early Carboniferous range, but may be as old as Late Emsian in eastern Australia (e.g. Gould, 1975, p. 455). The *Leptophloeum*-bearing beds at Red Bluffs, about 150 km to the northwest, overlie late Famennian limestones (Veevers & others, 1967) and are probably Early Carboniferous. *Leptophloeum* also occasionally occurs in the marine Gumhole Formation of the Fairfield Group (Druce & Radke, 1979, p. 38, fig. 8C), which is dated as late Famennian, but similar remains have not been found in younger or older limestones in the region (E.C. Druce, personal communication). This suggests that in this region *Leptophloeum* may have been more abundant during the Famennian-Tournaisian, but of course was not necessarily restricted stratigraphically to this interval. Botten (1984) also records *Leptophloeum* in sandstones of presumed late Famennian age in the Van Emmerick Range on the Lennard Shelf. However, an Early Carboniferous age for the Knobby Sandstone fish fauna can be discounted on the presence of placoderms, since there are no confirmed reports of this group extending into the Carboniferous (e.g. Young, 1974: Westoll, 1979; Pan, 1981). This is consistent with seismic evidence that Knobby Sandstone equivalents in the subsurface are overlain by carbonates of the Tournaisian Laurel Formation (Jacobson, 1984; Botten, 1984). Botten also cites palynological evidence from the Knobby Sandstone for a late Famennian age, but details of horizon and locality are not given. It is assumed here that the palynological data and the fish and plant remains collected in surface outcrops refer to the upper 300 m of section, relative to the much thicker sequences of Knobby Sandstone identified by seismic methods (e.g. Jacobson, 1984).

More detailed comparisons with other fish faunas known from elsewhere in the Canning Basin are of limited value because of the fragmentary nature of this material, but some general points can be made. Fishes are fairly well represented at various levels within the Late Devonian-Early Carboniferous sequence in the Canning Basin, but apart from the diverse fauna of the Gogo Formation (Miles, 1971, 1977; Gardiner & Miles, 1975; Dennis & Miles, 1979-1982; Young, 1984b) they are very poorly known. As noted above, a species of *Bothriolepis* also occurs in the early Frasnian Gogo fauna, but the *Bothriolepis* material described below clearly represents a different species. Fish remains are also known from the Late Famennian Gumhole Formation at Red Bluffs (locality WCB 014; see Druce & Radke, 1979, p.15). These consist mainly of large coarsely ornamented bones of a brachythoracid arthrodire reminiscent of the genus *Aspidichthys*, which is known from the Frasnian and Famennian of North America, Europe, and the Middle East (Denison, 1978). Also present are a few fragments of lungfish toothplates, but apparently no antiarchs. This faunal difference could be attributed to the different environments of deposition of the two formations. A few fish remains from another locality in the Gumhole Formation (WCB 005, near Oscar Hill) again have dipnoan tooth fragments and also a small piece with possible antiarch ornament. From the lower part of the overlying Yellow Drum Sandstone at the same locality are fragmentary antiarchs and acanthodian and dipnoan remains. A microfauna from the Yellow Drum Sandstone includes elasmobranch remains (J. A. Long, personal communication). According to Druce & Radke's (1979) stratigraphy, the Yellow Drum Sandstone crosses the Devonian-Carboniferous boundary. The fish fauna from the overlying Laurel Formation is of typical Early Carboniferous aspect, dominated by elasmobranchs (Thomas, 1957, fig. 1; 1959, fig. 4; Druce & Radke, 1979, p.29). Thus, on the limited evidence available, the Knobby Sandstone fauna may be compared with the Gumhole Formation-lower Yellow Drum Sandstone interval, which contains the only other antiarchs of Famennian age so far known from the Canning Basin.

The only positively identified form in the Knobby Sandstone fauna is a new species of the antiarch *Bothriolepis*. Elsewhere in the world, *Bothriolepis* is widely distributed in Famennian strata in Europe (e.g. Denison, 1978), but in the uppermost vertebrate succession in East Greenland its highest occurrence is *B. nielseni* in the lower part of the *Remigolepis* Series (e.g. Jarvik, 1961). The higher assemblages in this sequence (the upper *Remigolepis*, and the *Groenlandaspis* Series) may broadly correlate with the uppermost vertebrate-bearing strata on the New South Wales south coast where *Remigolepis* and *Groenlandaspis* are associated. According to Pan (1981), *Bothriolepis* also extends to the top of the Late Devonian vertebrate succession in China. However, according to Sandberg & others (1983), in the western United States *Bothriolepis* does not extend above the *Polygnathus styriacus* Zone in the late Famennian, which is older than either the Gumhole Formation or Yellow Drum Sandstone in the Canning Basin (P.J. Jones, personal communication). Relevant here is a new fauna from Turkey recently described by Janvier & others (1984), which contains a mixture of latest Devonian and earliest Carboniferous fishes and ostracods, and is dated as post-Famennian (Strunian, Tn 1a) in age, but also lacks antiarchs. The only placoderm in this fauna is *Groenlandaspis*, and the presence of typical Carboniferous osteichthyans and chondrichthyans have led Janvier & others (1984) to suggest that their new fauna may represent a level between the uppermost faunas of East Greenland, and the Early Carboniferous faunas of Glencartholm in Scotland and Bear Gulch in Montana. One of the Devonian elements in this fauna is a new species of lungfish tentatively referred by Janvier & others (1984) to *Chirodipterus*. This genus is represented by two older species from the Frasnian Gogo Formation in the Canning Basin (Miles, 1977). However, the illustrated toothplates from Turkey differ in various respects from the corresponding elements in the Gogo species. A preliminary examination of the fragmentary dipnoan toothplates from the Gumhole Formation, mentioned above, showed strong development of columnar dentine, and an extensive pulp cavity between the dentine of the toothplates and the underlying bone (K.S.W. Campbell, personal communication). These are relatively advanced features, not seen in *Chirodipterus* from Gogo, but present, for example, in the Carboniferous form *Sagenodus* (e.g. Smith, 1979). Such differences may prove of biostratigraphic use when this group is investigated in more detail.

This discussion may be summarised as follows. Various lines of evidence noted above point to a Famennian age for the Knobby Sandstone fish fauna. The presence of a *Bothriolepis* species might indicate an older age than the upper vertebrate assemblages in East Greenland or the upper *Polygnathus styriacus* conodont Zone in the western United States. Alternatively, the asterolepid antiarch in the fish fauna permits a tentative correlation either with the *Remigolepis* series in East Greenland, or the zone of *Asterolepis sinensis* in China. Fragmentary fish from the Gumhole Formation and lower Yellow Drum Sandstone apparently include antiarchs, and, apart from the Frasnian Gogo Formation, this is the only other occurrence of the group known so far from the Canning Basin. Facies differences may account for other differences in the fish faunas. A *Groenlandaspis* fauna, which elsewhere apparently represents the youngest known Devonian vertebrate assemblage, has not yet been identified from Western Australia.

Systematic descriptions

All fossils described below are housed in the Commonwealth Palaeontological collection, Bureau of Mineral Resources, Canberra, A.C.T. The classification adopted is that used in Young & Gorter (1981) and antiarch bone terminology follows Stensiö (1948) and Miles (1968).

Subclass **Placodermi**
Order **Antiarcha**
Suborder **Bothriolepidoidei**, Miles, 1968
Family **Bothriolepididae** Cope
Genus ***Bothriolepis*** Eichwald
Bothriolepis billilunensis sp. nov.
(Fig. 2; Pl. 1, figs 1-3)

1974 *Bothriolepis* Young, pp. 252, 254
1975 *Bothriolepis* Yeates & others, p. 50
1977 *Bothriolepis* Blake & others, p. 19
1983 *Bothriolepis* Towner & Gibson, p. 26

Material. A detached, imcomplete left mixilateral plate (CPC13853) preserved as an internal and external mould, and a detached incomplete right posterior ventrolateral plate (CPC13854) preserved as an external mould.

Holotype. CPC13853, a left mixilateral plate.

Occurrence. Locality B130 in the Knobby Sandstone, Knobby Hills, eastern Canning Basin, Western Australia (see Fig. 1).

Diagnosis. A *Bothriolepis* with a mixilateral plate only slightly less broad than long, the dorsal lamina about 1.3 times as long as broad and the lateral lamina twice as long as deep. Dorsal and lateral laminae enclosing an angle of about 100° at the dorsolateral ridge. The posterior ventrolateral plate with a length/breadth index of about 2, the lateral lamina about 2.8 times as long as deep and the ventral lamina about 3.7 times as long as broad. Subanal division of ventral lamina about 10 per cent of the total length of the plate. Angle between lateral and ventral laminae about 130°.

Remarks. The mixilateral and posterior ventrolateral plates in *Bothriolepis* are contiguous overlapping bones, but the ventral margin of the external cast in the holotype is not preserved, so there is no good morphological evidence that the two specimens are conspecific, although this is assumed for the purpose of description. Ornament is coarser on the posterior ventrolateral, which comes from a larger individual, but in other respects is similar to that of the holotype.

Description. The internal surface of the mixilateral plate is complete except for portions of the dorsal and posteroventral

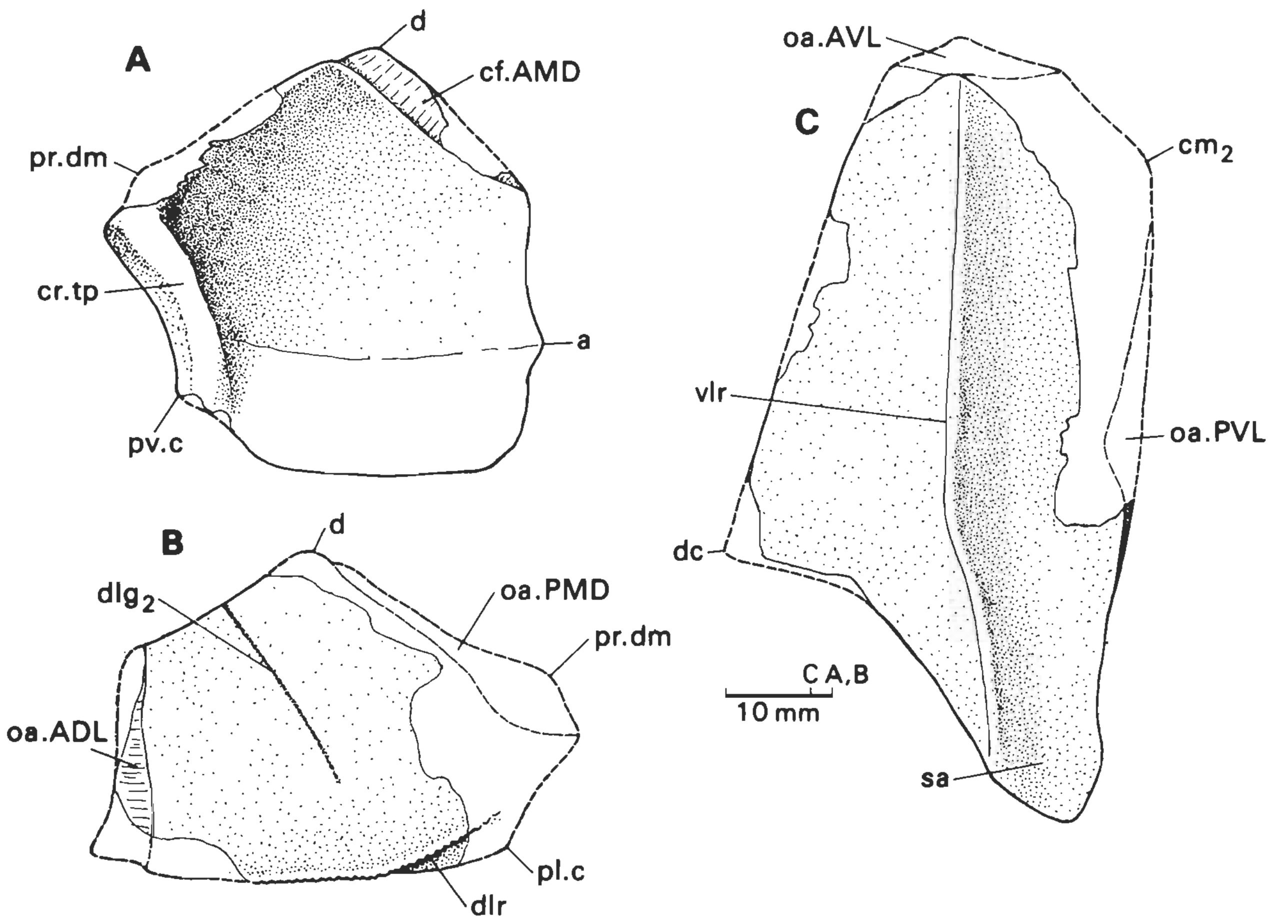


Figure 2. ***Bothriolepis billilunensis*** **sp. nov.**
A, left mixilateral plate in visceral view (holotype, CPC13853). **B**, reconstruction of the dorsal lamina of the left mixilateral plate in dorsolateral view (after CPC 13853). **C**, reconstruction of the right posterior ventrolateral plate in ventrolateral view (after CPC13854).
a, anterior corner of mixilateral; *cm_2*, anteromesial corner of ventral lamina of posterior ventrolateral; *cf.AMD*, area that overlapped anterior median dorsal plate; *cf.tp*, crista transversalis interna posterior; *d*, dorsal corner of mixilateral; *dc*, dorsal corner of lateral lamina of posterior ventrolateral; *dlg_2*, posterior oblique abdominal pitline groove; *dlr*, dorsolateral ridge; *oa.ADL*, area overlapped by anterior dorsolateral plate; *oa.AVL*, area overlapped by anterior ventrolateral plate; *oa.PMD*, area overlapped by posterior median dorsal plate; *oa.PVL*, area overlapped by left posterior ventrolateral plate; *pl.c*, posterolateral corner of trunk armour; *pr.dm*, dorsomesial process of mixilateral; *pv.c*, posteroventral corner of mixilateral; *sa*, subanal division of ventral lamina of posterior ventrolateral; *vlr*, ventrolateral ridge.

margins and posteroventral corner (*pv.c*, Fig. 2A). Of the external surface, the anterior two-thirds of the dorsal lamina and the dorsal part of the lateral lamina are preserved and show parts of the anterodorsal margin, the posterior oblique abdominal pit-line groove, and the dorsolateral ridge. As reconstructed, the plate is unusually short and broad with a total length of 39 mm and total breadth of 38 mm. The posterodorsal margin is 1.5 times as long as the anterodorsal, and the angle enclosed at the dorsal corner is about 114°. The anterior margin is 1.3 times as long as the posterior. The ornament is typical of *Bothriolepis*, with anastomosing ridges and occasional tubercles. A ventrolaterally directed keel is developed along the dorsolateral ridge. An unusual feature is the very short posterior margin.

The posterior ventrolateral plate is preserved as an impression of its external surface (Pl. 1, fig. 3). It is deficient along the anterior and anteromesial margins, and lacks the dorsal corner of the lateral lamina.

As preserved, it is 87 mm long, but the restored overlap area for the right anterior ventrolateral (*oa.AVL*, Fig. 2C) indicates an original length of about 95 mm. On the mesial edge of the ventral lamina the posterior end of the overlap area for the left posterior ventrolateral is preserved (*oa.PVL*). On the lateral lamina the dorsal corner was apparently abraded or broken off before embedding. Total breadth of the restored plate between the dorsal corner and the mesial margin of the ventral lamina is estimated at 45-50 mm.

The breadth of the incomplete ventral lamina can be estimated on the assumption that the lamina was broader at the anteromesial corner (cm_2, Fig. 2C) than across the subanal division, as it is in other species of the genus. This gives a minimum breadth of about 200 mm. As restored in Figure 2C the ventral lamina has a breadth of 25 mm, giving a length/breadth index of 3.7. This is an unusually high value, but is considered reasonable in view of the constant narrow width of the posterior portion of the lamina, where the mesial margin is almost parallel to the ventrolateral ridge. In most other species of *Bothriolepis* the subanal division differs in being more or less triangular in shape, with the lamina itself correspondingly more or less broad behind the middle mesial corner.

The preserved length of the lateral lamina is 77 mm, and is estimated to have been about 83 mm originally. The subanal division of the ventral lamina is very short, comprising just over 10 per cent of the total length of the plate. The height of the lateral lamina as restored at about 30 mm, giving a length/height index of 2.8. The margins and overlap areas of the plate as far as preserved appear normally developed. There is no indication of a posterodorsal corner, and the plate was overlapped mesially by the left posterior ventrolateral, as is normal for *Bothriolepis*.

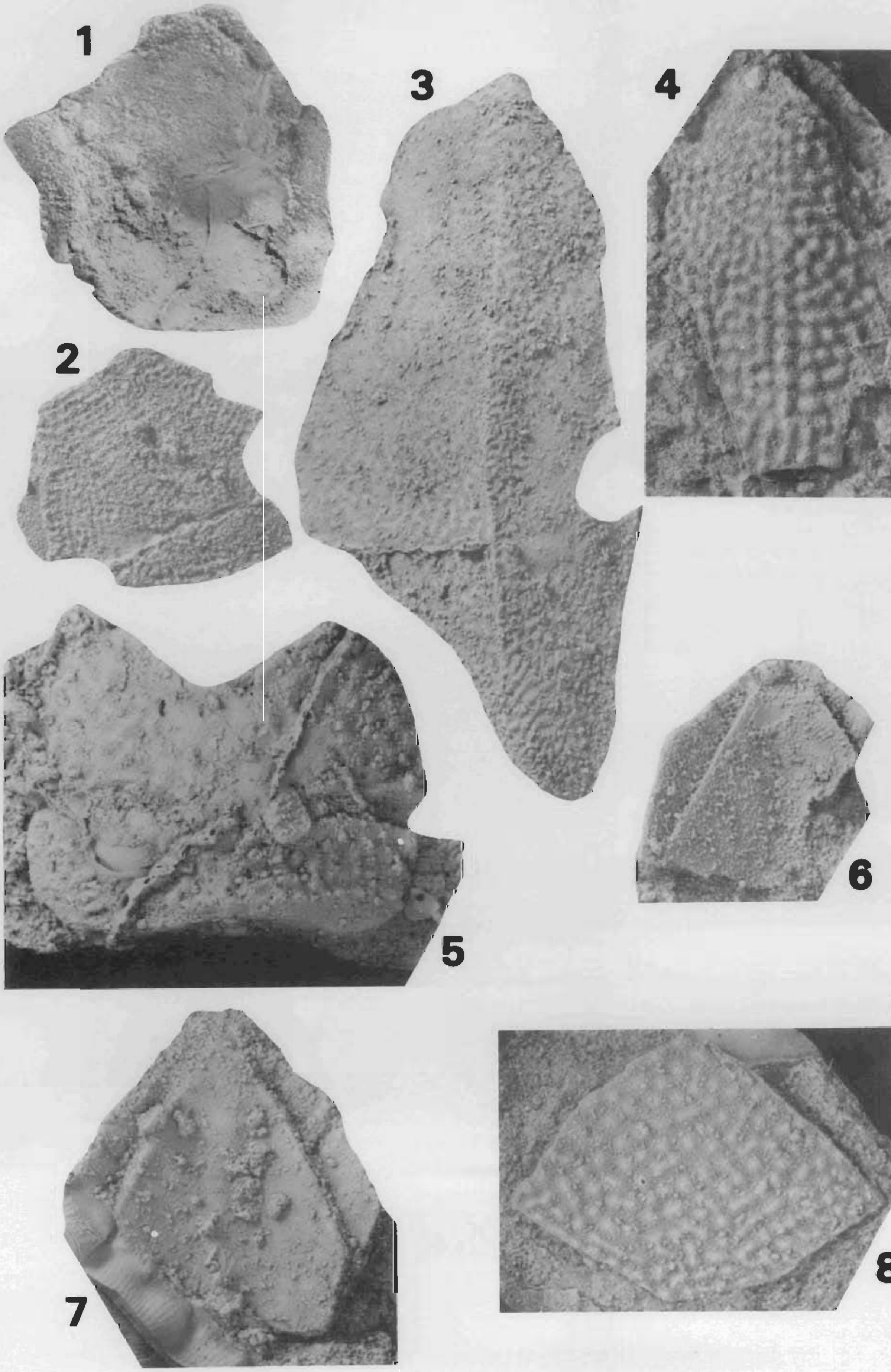
The ventrolateral ridge is distinct, but there is only slight development of a keel. Ornament is similar to, but slightly coarser than that of the mixilateral plate.

Discussion. The features of the mixilateral plate show that this material is referable to *Bothriolepis*. The mixilateral is represented by separate posterior dorsolateral and posterior lateral plates in *Remigolepis, Byssacanthus, Gerdalepis, Stegolepis, Pambulaspis*, and *Yunnanolepis*, and in the asterolepidoids *Asterolepis, Pterichthyodes*, and *Sherbonaspis* the so-called mixilateral is differently developed, with an external anteroventral overlap area for the anterior ventrolateral. Janvier & Pan (1982) have suggested that this plate is not homologous to the mixilateral of bothriolepids. *Bothriolepis* is the only member of this group so far recorded in Australia, and there is every reason to believe, therefore, that the specimens described here belong to a species of this genus.

In its proportions the mixilateral of *B. billilunensis* sp. nov. is quite distinctive, with a broad dorsal and unusually deep lateral lamina, combined with the acute angle enclosed at the dorsolateral ridge. The plate may be compared with that of *B. canadensis* and *B. cellulosa*, in which, however, the length/breadth indices are always greater than 1.5 and 2.25 for the dorsal and lateral laminae respectively (Gross, 1941b; Stensiö, 1948). *B. laverocklochensis* is also similar in the proportion of the dorsal lamina and the acute angle between laminae, but differs in having a long, low lateral lamina, and apparently lacking a distinct dorsolateral ridge (Miles, 1968, p. 53; pl. 5, fig. 5). *B. cristata* may be distinguished by the more obtuse angle between laminae (Miles, 1968, p. 57).

Of species recently described from Australia, the mixilateral of *B. verrucosa* is much more elongate in both dorsal and lateral laminae (Young & Gorter, 1981). Species recently described from Victoria (Long, 1983) include *B. bindareei*, which has a mixilateral broader than long, and *B. warreni*, which is said to have a breadth/length index for the dorsal lamina of 36. Material from the Amadeus Basin in central Australia described by Gilbert-Tomlinson (1968) did not include a mixilateral, but new material from here shows that at least two species are represented (Young, 1985). Mixilateral plates in this collection can be distinguished on various characters from the specimen described here. The left mixilateral figured by Young (1985, fig. 8A) has a more obtuse angle between laminae, a lower dorsal and deeper lateral lamina, and a less-marked dorsolateral ridge. Other plates, with the dorsolateral ridge similarly developed to *B. billilunensis* sp. nov., are readily distinguished as a separate species by their more elongate overall proportions. Unnamed species are probably represented by an isolated mixilateral from Mount Canoblas, New South Wales figured by Hills (1932, pl. 6, fig. 8), but this is much more elongate, with a dorsal lamina about twice as long as broad, and a lateral lamina twice as long as deep. Finally, undescribed mixilateral plates of a *Bothriolepis* species from the Gogo Formation in the Canning Basin of Western Australia have finer ornamentation, no dorsolateral keel, and a more obtuse angle of about 125° between the laminae (personal observation on BMR material).

The referred posterior ventrolateral plate is also readily distinguished from other *Bothriolepis* species by the unusually short subanal division of its ventral lamina. The subanal division in other species is generally at least one third as long as the total length of the plate, and only in *B. wilsoni* does its relative length decrease to 20 per cent (Miles, 1968, pp. 85, 88), but this is still proportionately longer than in *B. billilunensis* sp. nov. The other characteristic feature of the plate is the high length/breadth index of the ventral lamina. The Canadian antiarch *Bothriolepis* ? *traquairi* Bryant is comparable in this regard (Stensiö, 1948, p. 398), but is readily distinguished by the more uniform width of the subanal division, and the posterior concavity in the ventrolateral ridge. The Chinese species *B. kwangtungensis* from the Mangzixia Series of northern Kwangtung as described by P'an (1964) probably also had a long and narrow ventral wall of the trunk armour although the posterior ventrolateral is unknown. The anterior ventrolateral in this species varies from 3.4 to 4 times as long as broad, a value not attained by any other species. In other species the ventral laminae of both anterior and posterior ventrolaterals have similar proportions, but with the length/breadth index for the latter plate increased somewhat by the subanal division. It is probable therefore that the posterior ventrolateral of *B. kwangtungensis* had



similar proportions to the corresponding plate of *B. billilunensis* sp. nov.

Considering Australian species, the description given by Hills (1931), p. 221) of the posterior ventrolateral of *B. gippslandiensis* suggests an unusual 'square cut and not rounded' configuration of the posterior margin. However, according to Long (1983), the posterior ventrolateral in this and other Victorian species is typically developed for the genus, with normal proportions. Another incomplete posterior ventrolateral from the Dulcie Range, Northern Territory, was briefly described by Hills (1959). It bears little similarity to the specimen described above, with lateral and ventral laminae meeting at about 100°, and a conspicuous keel of fused tubercles along the ventrolateral ridge. Posterior ventrolateral plates have also been figured from the Amadeus Basin by Young (1985), but again are readily distinguished in shape and proportions from *B. billilunensis* sp. nov.

Comparisons with some other species of *Bothriolepis* in the proportions of both plates considered together are summarised in Table 1. The length/breadth index for the ventral lamina of the posterior ventrolateral varies between 2 and 3, whilst the length/breadth index for the dorsal lamina of the mixilateral is generally lower, ranging between 1.4 and 2. Two exceptions are *B. jarviki* (Stensiö, 1948) and *B. alvesiensis* (Miles, 1968), in which both indices have about the same value. This would suggest that *B. billilunensis* sp. nov. as described above is unusual in combining a very elongate ventral lamina with a short broad dorsal lamina. In the lateral wall of the trunk armour, length/breadth indices are about the same for the lateral laminae of both plates in several species, including *B. leptocheira* and *B. wilsoni* (Miles, 1968), *B. cellulosa* and *B. canadensis* (Stensiö, 1948) and *B. tungseni* (Chang, 1965). The mixilateral lamina is proportionately much longer than that of the posterior ventrolateral in *B. alvesiensis, B. hayi, B. gigantea* and *B. obesa* (Stensiö, 1948), and is proportionately shorter only in *B. cristata* (Miles, 1968) and *B. billilunensis* sp. nov. (Table 1). In two respects, therefore, the trunk armour of this new species is unusual: it resembles *B. cristata* in the anomalous proportions of the lateral wall, and shows a difference in indices for the dorsal and ventral walls comparable to that in lateral lamina proportions in *B. gigantea*, which is also much greater than in other known species (Table 1). However, the inferred trunk armour proportions in *B. billilunensis* sp. nov., although unusual, are not considered to lie outside the expected range of variation for species of the genus, and, for this reason, both plates are provisionally treated here as one species.

Table 1. Approximate length/breadth values for laminae of the mixilateral and posterior ventrolateral plates in some *Bothriolepis* species.

Bothriolepis species	*Mixilateral plate*		*Posterior ventrolateral plate*	
	dorsal lamina	*lateral lamina*	*lateral lamina*	*ventral lamina*
gigantea	—	4	1.5	2
alvesiensis	2	4	3	2
cristata	1.4-2	2	3	2.5
leptocheira	2	3	3	2.8
obesa	1.5	2.5	1.3	2
wilsoni	2	2.5	2.5	2.5
hayi	2	3	1.5-1.7	2.5
canadensis	1.5-2	2.25-2.33	2-2.5	2-2.3
cellulosa	1.5-2	2.5-3	2.5	2.5-2.75
jarviki	2	2	—	2
tungseni	1.7-1.8	2.5-2.7	2.4	2.8
billilunensis	1.3	2	2.8	3.7

Data from Stensiö (1948), Chang (1965), and Miles (1968).

Suborder **Asterolepidoidei** Miles, 1968
asterolepidoid indet.
(Figs 3, 4; Pl. 1, figs 5-7)

1967 'fish plates' (*pars*) Veevers & others, p. 331
1968 'arthrodiran plates' (*pars*) Gilbert-Tomlinson, p. 210
1974 *Asterolepis* Young, p. 252
1975 *Asterolepis* Yeates & others, p. 50
1977*Asterolepis* ? Blake & others, p. 19
1978 *Asterolepis* sp. Denison, p. 113
1983 *Asterolepis* or *Remigolepis* Young, p. 71
1983 *Asterolepis* Towner & Gibson, p. 26

Material. A detached incomplete nuchal plate (CPC13855) preserved as an external mould, and two detached incomplete anterior median dorsal plates (CPC 13856, 13857), both preserved as internal impressions of parts of their anterior divisions.

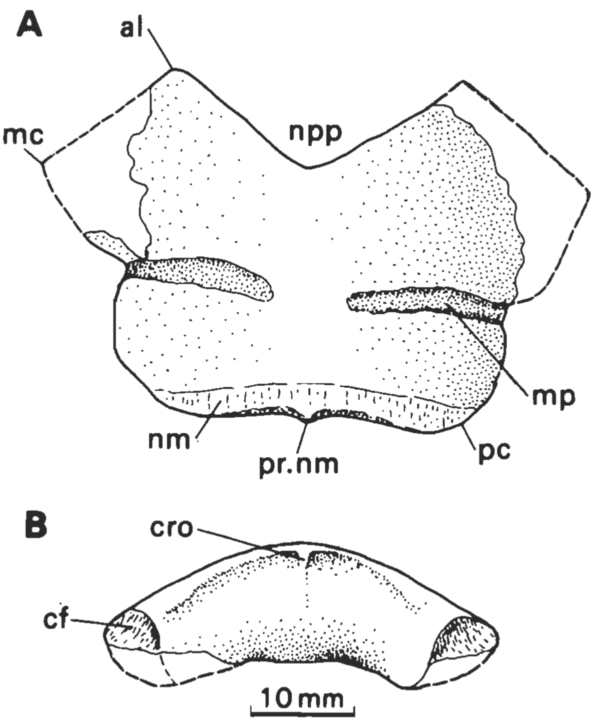


Figure 3. Asterolepidoid indet.
Reconstruction of the nuchal plate in dorsal (A) and posterior views (B). After CPC13855.
al, anterolateral corner; *cf*, contact face for paranuchal plate; *cro*, median occipital crista; *mc*, lateral corner; *nm*, obtected nuchal area; *npp*, postpineal notch; *pc*, posterolateral corner; *pr.nm*, posterior median process, *mp*, middle pitline sensory groove.

Plate 1. *Bothriolepis billilunensis* sp. nov.
Figs. 1, 2. Holotype (CPC13853), an incomplete left mixilateral plate in visceral and lateral views respectively (x1.5). **Fig. 3.** Incomplete right posterior ventrolateral plate (CPC13854) in external view (x1.5).
asteropidoid indet.
Fig. 5. Incomplete nuchal plate (CPC13855) in dorsal view (x2). **Figs. 6,7.** Incomplete anterior median dorsal plates (CPC13856, 13857) in visceral view (both x1.5).
antiarch indet.
Fig. 4. Undetermined plate (CPC13939) in external view (x1.5). **Fig. 8.** Undetermined plate (CPC13940) in external view (x1.5).
(all photographs of latex rubber casts whitened with ammonium chloride).

Occurrence. Localities V33 (CPC13856) and V34 (CPC13857) in the Knobby Hills, and locality V43 (CPC13855) in the Falconer Hills, in the Knobby Sandstone, eastern Canning Basin, Western Australia (see Fig. 1).

Remarks. The three specimens included here are clearly asterolepidoids and are described together on the assumption that they are conspecific.

Description. The nuchal plate is preserved as an impression of its dorsal and posterior surfaces (Pl. 1, fig. 5). It shows the posterior margin and posterolateral corners (*pc*, Fig. 3), left anterolateral corner (*al*), most of the postpineal notch (*npp*),and well-developed transverse sensory grooves (*mp*). The lateral margin is only preserved posterior to the sensory grooves and on the left side for a short distance anterior to the groove, and the position of the lateral corners (*mc*, Fig. 3A) is, therefore, uncertain. The postpineal notch clearly lacked orbital facets, which shows that the postpineal plate excluded the nuchal plate from the orbital margin, as in non-bothriolepid antiarchs.

The plate has a total length of 30.5 mm, and a median length (excluding the postpineal notch) of 23.5 mm. Width at the posterior margin is 32.5 and, as restored in Figure 3A, the anterolateral corners are 25 mm apart. The breadth across the lateral corners was probably at least 40 mm.

The ornament consists of low irregular anastomosing ridges and occasional tubercles, with an unornamented strip, the obtected nuchal area (*nm*), extending along the posterior margin. This margin is slightly concave with a small posterior median process (*pr.nm*). Posterolateral processes are not developed.

Several features of the nuchal plate as developed in other antiarchs are absent. The external openings for the endolymphatic ducts are not preserved, and other sensory grooves or pit-lines are apparently not developed. Significant is the absence of a central sensory line, which is typically well developed on the nuchal plate in *Bothriolepis* and related genera.

In posterior view (Fig. 3B) the specimen exhibits a fairly deep occipital surface with a strongly developed transverse nuchal crista. The median occipital crista (*cro*) is present, but not pronounced, and there are no clearly defined fossae for the insertion of the levator muscles of the head, as are known in *Asterolepis ornata*(Stensiö, 1931, fig. 15). At each side a contact face is developed for the adjacent paranuchal plate (*cf*).

The anterior median dorsal plate is represented by two incomplete specimens showing part of the ventral surface of the anterior division (Pl. 1, figs. 6, 7). CPC13856 (Fig. 4A) shows most of the contact face that overlapped the right anterior dorsolateral (*cf. ADL*), and the anterior end of the contact face for the left plate. The anterior margin and supra-nuchal area (*sna*) are completely preserved. Total preserved midline length is 27.5 mm and the width between the anterolateral angles (*a*) is 6 mm. The plate is slightly arched to enclose an angle of about 150° at the midline. As restored in Figure 4A, the breadth between lateral corners (*lc*) is estimated at about 35 mm, giving a midline length for the anterior division of the plate of about 30 mm. The contact faces are deeply impressed into the visceral surface and reach a maximum width of about 6 mm approximately halfway between the anterior and lateral corners. Somewhat in front of this maximum width the contact face is crossed by a shallow groove (*f*).

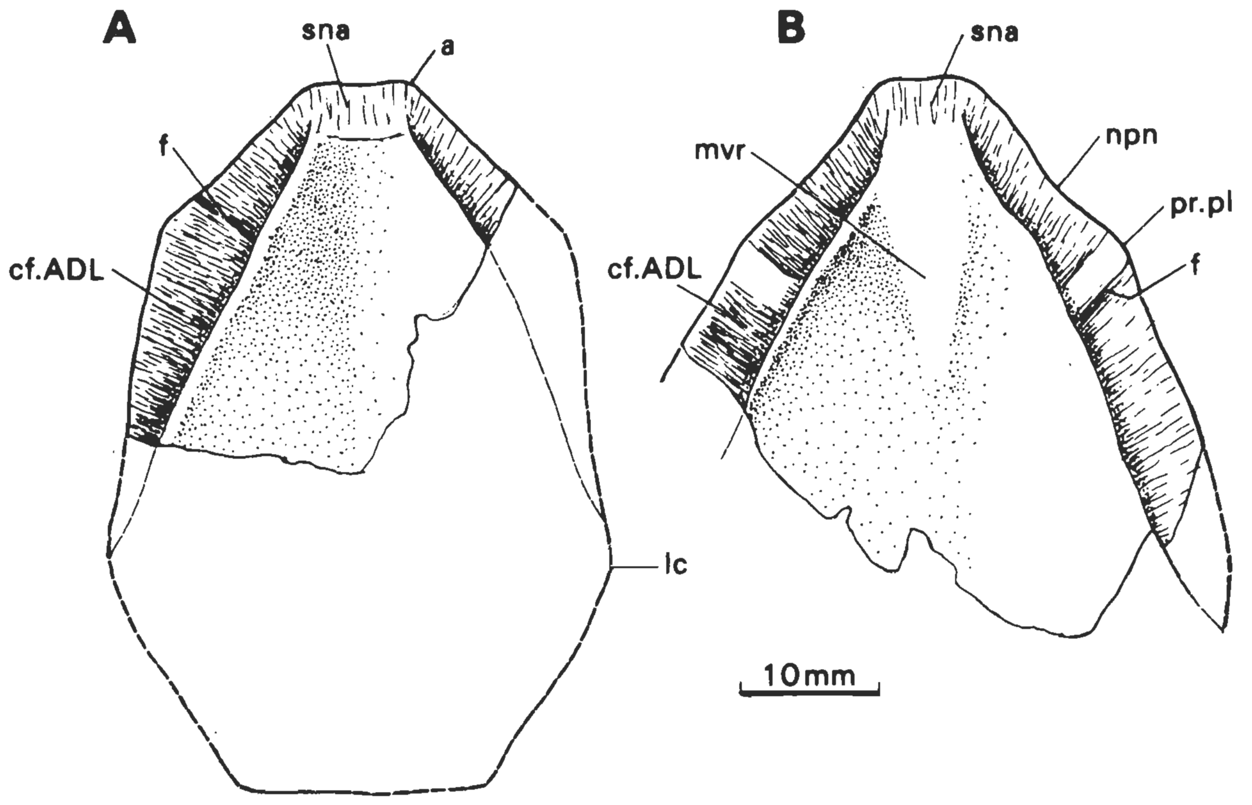


Figure 4. Asterolepidoid indet.
Two anterior median dorsal plates in visceral view: **A**, CPC13856; **B**, CPC13857.
a, anterolateral angle; *cf.ADL*, area that overlapped anterior dorsolateral plate; *f*, groove crossing contact faces for anterior dorsolaterals; *lc*, lateral corner; *mvr*, median elevation on the visceral surface; *npn*, postnuchal notch; *pr.pl*, postlevator process; *sna*, supra-nuchal area.

CPC13857 (Fig. 4B) is a similar portion of another anterior median dorsal plate, with a preserved midline length of 36 mm. The anterior margin is more rounded than in the previous specimen and anterolateral angles are indistinct. It is also flatter anteriorly, with a slight broad elevation on the ventral surface in the midline (*mvr*). Again a groove (*f*) crosses the contact face for the anterior dorsolateral plate, in front of which the margins of the plate are slightly concave (*npn*). As in the previous specimen, the contact faces are deeply impressed into the visceral surface of the plate.

Discussion. The absence of orbital facets on the nuchal plate and the narrow anterior margin of the anterior median dorsal plate, are features found in only two antiarch groups—the yunnanolepids and the asterolepidoids. Since members of the first group are not known to occur outside south China, and display a variety of primitive features not seen in other antiarchs, including an oblong nuchal plate (see Zhang, 1978), I assume that the specimens dealt with here belong to an asterolepidoid antiarch. Within the Asterolepidoidei, the anterior margin of the anterior median dorsal plate is fairly broad and truncated in *Pambulaspis* (Young, 1983), *Pterichthyodes* (Hemmings, 1978), *Sherbonaspis* (Young & Gorter, 1981), *Gerdalepis* (Gross, 1941a), *Byssacanthus* (Gross, 1940, fig. 10B; Karatajute-Talimaa, 1960, fig. 2), and probably *Lepadolepis* (Gross, 1933, pl. 3), whilst in *Grossaspis* it is broad and somewhat rounded (Gross, 1937, fig. 10). Only in *Asterolepis* and *Remigolepis* is the anterior margin as narrow as in the material described above, but the three available specimens provide too few characters for confident assignment to either form. In addition to published accounts, I have made a preliminary examination of well-preserved *Remigolepis* collected by the Geology Department, Australian National University, from near Forbes, New South Wales (Campbell & Bell, 1977), and this has been used in the following discussion to supplement Stensio's account with data on Australian species.

The main characters by which *Remigolepis* differs from *Asterolepis* are the absence of a distal joint in the pectoral appendage, the separate posterior dorsolateral and posterior lateral plates, and the overlap relationship between the anterior median dorsal and posterior dorsolateral. Species in both genera vary considerably in size, and the specimens from Billiluna suggest a moderately large form comparable with *Asterolepis scabra* (Nilsson, 1941) or *Remigolepis acuta* (Stensiö, 1931).

In both genera the nuchal plate and the anterior division of the anterior median dorsal are closely similar. In *Asterolepis* the breadth/length index of the nuchal ranges from 132 in *A. savesoderberghi* (Stensiö & Säve-Söderbergh, 1938, fig. 1) to 210 in *A. scabra* (Nilsson, 1941, pl. VI). In *Remigolepis* it may also be low, as in R. *cristata* (130) and *R. acuta* (125) (Stensiö, 1931), whilst the *Remigolepis* sp. figured by Stensiö (1948), fig. 16) has an index of over 200. In CPC13855 the index was at least 130, placing it within the range of several species in both genera (Table 2).

Regarding the size and shape of the postpineal notch (*npp*, Fig. 3A), the Greenland species *R. cristata* and *R. kochi* have the midline length of the plate over five times the midline length of the notch, which is much more shallow and broad in relation to total length and breadth than is normal in *Asterolepis* (Table 2). Similar proportions occur in *Remigolepis* from New South Wales, although nuchal plates ascribed to *R. incisa* and *R. acuta* by Stensiö (1931, pl. 3, figs 2, 3) have somewhat deeper notches, and this feature may vary within a single species (e.g. Stensiö, 1931, figs 13B, G). In general, however, the notch tends to be broader and shallower in *Remigolepis*, and in this regard CPC 13855 shows closer affinity to *Asterolepis* in having a notch about 3.5 times as broad as deep.

In *Asterolepis* the notch normally extends back to a position near or behind the level of the lateral corners; in *A. maxima* (Traquair, 1894) and *A. sinensis* (P'an, 1964) it extends well behind this level. An exception is *A. estonica* (Gross, 1940, fig. 8) in which the lateral corners have a more posterior position. By comparison, the various nuchal plates described for *Remigolepis*, including the species recently described from China (Pan & others, 1980), and the undescribed material from New South Wales, always show the level of the lateral corners to lie well behind the postpineal notch. Furthermore, the posterolateral margin has a simpler configuration than the nuchal plate of *Asterolepis*, which always shows a constriction in its breadth behind the lateral processes. The nuchal plate from the Knobby Sandstone resembles that of *Asterolepis* in both these features.

Regarding the anterior median dorsal plate, CPC13856, as reconstructed above, has a median breadth about 1.2 times the length of the anterior division, which compares closely with many species of *Asterolepis* and *Remigolepis*. Only *A. orcadensis* (Watson, 1932), *R. kochi*, and *R. cristata* (Stensiö, 1931) are appreciably broader in proportion to length (Table 2). The relative length of the anterior margin varies intraspecifically in both *Asterolepis* (Gross, 1940, p.33; Karatajute-Talimaa, 1963, p. 159), and *Remigolepis* (Stensiö, 1931). One Greenland species, *R. acuta*, has been defined on the extreme narrowness of this margin, and a similar development is evident in *Remigolepis* material from Forbes,

Table 2. Nuchal and anterior median dorsal plate measurements in different species of *Asterolepis* and *Remigolepis* compared with specimens described here.

Species of Asterolepis or Remigolepis	*Nuchal plate*		*Anterior median dorsal plate*	
	Breadth/ length index	*Total length/ length post-pineal notch*	*median breadth/ length anterior division*	*median breadth/ length anterior margin*
A. savesoderberghi	132	2.9	1.14	2.6-4.3
A. radiata	150	3.4-4.4	1.2	9.4-16
A. ornata	159	3.3-4.6	1.2	4.3-8.2
A. orcadensis	188	2.7	1.55	3.4
A. scabra	210	3.1	1.25	6.8
R. acuta	125	4	1.14	24
R. cristata	130	5.5	1.36	3.5
R. kochi	175	5.7	1.45	4.3
CPC13855	>130	3.5	—	—
CPC13856	—	—	1.2	4.9

Data from Stensiö (1931), Watson (1931), Gross (1931, 1940), Nilsson (1941), and Karatajute-Talimaa (1963).

New South Wales (M.W. Bell, personal communication). Stensiö (1948, footnote, p. 188) noted the tendency towards development of a postnuchal notch and external postlevator process in the anterior median dorsal of *Asterolepis scabra*, and similar structures have been figured for *A. ornata* and *A. estonica* (Gross, 1931, 1940; Karatajute-Talimaa, 1963, fig. 33). In *A. estonica* there is a distinct groove crossing the contact face for the anterior dorsolateral (Gross, 1940, p. 34; Karatajute-Talimaa, 1963, fig. 14), as described above. In CPC13857 this groove is associated with a distinct postlevator process (*pr. pl*) and slight postnuchal notch (*npn*, Fig. 4B). CPC13856 has a less pronounced groove situated in front of the maximum width of the contact face. In *Remigolepis*, however, these features are generally absent or only very slightly developed.

To summarise, in the configuration and structure of the anterolateral margins of the anterior median dorsal, the form of the postpineal notch, and the shape of the posterior part of the lateral margin of the nuchal, this material shows closer similarity to *Asterolepis* than to *Remigolepis*. However, these are only minor distinctions, and until further material becomes available the three specimens described here are left in open nomenclature.

Asterolepis has been reported from the Australian Devonian on two previous occasions. McCoy (1876) named placoderm plates from Buchan, Victoria as *Asterolepis ornata* var. *australis*, but these belong to an arthrodire (see Young, 1979, p. 347). Hills (1958, p. 89) referred to *Asterolepis* an antiarch posterior median dorsal plate previously figured by him (Hills, 1936, fig. 3; see also Hill & others, 1967, pl. DXV, fig. 1). The lateral margins in this specimen appear to be slightly convex, and Stensiö (1931, p. 77) suggested that in this feature *Asterolepis* could be distinguished from *Bothriolepis*, in which the margin is normally slightly concave. However, this distinction is not reliable (e.g. Miles, 1968) and Hills' original conclusion that 'generic determination of this specimen is not possible' (1936, p. 163) still applies, although there are no good reasons to indicate that the plate does not belong to a species of *Bothriolepis* (Young & Gorter, 1981, p. 90; Turner, 1982).

antiarch indet.
(Fig. 5; Pl. 1, figs. 4, 8; Pl. 2, figs. 1,2,9,10)

1967 'fish plates' (*pars*) Veevers & others, p. 331
1968 'arthrodiran plates' (*pars*) Gilbert-Tomlinson, p. 210

Material. An incomplete median dorsal plate (CPC13937), preserved as an internal mould; a large incomplete plate, (CPC13943), and various ornamented fragments (CPC13938-42), all preserved as external moulds.

Occurrence. Localities B104 (CPC13938), B130 (CPC13939, 41, 42), B133 (CPC13943), B138 (CPC13937, 940) in the Knobby Sandstone, Knobby Hills, eastern Canning Basin, Western Australia (see Fig. 1).

Remarks. The most common vertebrate fossils in the Knobby Sandstone are moulds of fragmentary plates with a coarse ornamentation of low rounded tubercles. These may be arranged in even rows (Pl. 1, fig. 4), or are widely spaced and irregular (Pl. 2, fig. 10), but in general show some degree of fusion into an anastomosing arrangment of nodose ridges (Pl. 2, figs. 1, 9). Determination of such remains is difficult in the absence of plate margins or any preserved bone. Hills (1932, pl. 56, fig. 7) previously figured a similar coarsely ornamented fragment from Jemalong Gap near Forbes, New South wales, which he subsequently compared (1936, p. 168) with the ornament of the holonematid arthrodire *Gyroplacosteus panderi* Obruchev (see Obruchev, 1932, pl. 6, fig. 3; 1964, pl. 2 fig. 3). However, I consider it much more likely that such remains belong to a large antiarch, and this is borne out by what is now known of the Jemalong Gap fauna (Ritchie, 1975), where the only arthrodire so far recorded (*Groenlandaspis* sp.) has a much finer pustulose ornament. On the other hand, some of the *Remigolepis* specimens from here attained a large size with coarsely ornamented dermal bones.

The Knobby Sandstone remains evidently came from an even larger fish, as indicated by one incomplete dermal plate, the largest in the collection (Pl. 2, fig. 2), with a maximum preserved dimension of 167 mm. Otherwise, the specimens are generally less than 40 mm across, and show no features other than ornament. Position in the skeleton can be positively determined for only one specimen, and there are no distinguishing features to show whether this large antiarch is a bothriolepidoid or asterolepidoid.

Description. The only specimen in this material identified with any reliability is an antiarch median dorsal plate exposed in visceral view (Fig. 5), showing the diagnostic median ridge (*mvr*) and pit (*pt*) on its inner surface. The external surface and ornament are not preserved, but the specimen is assumed to belong to the same form as the ornamented fragments.

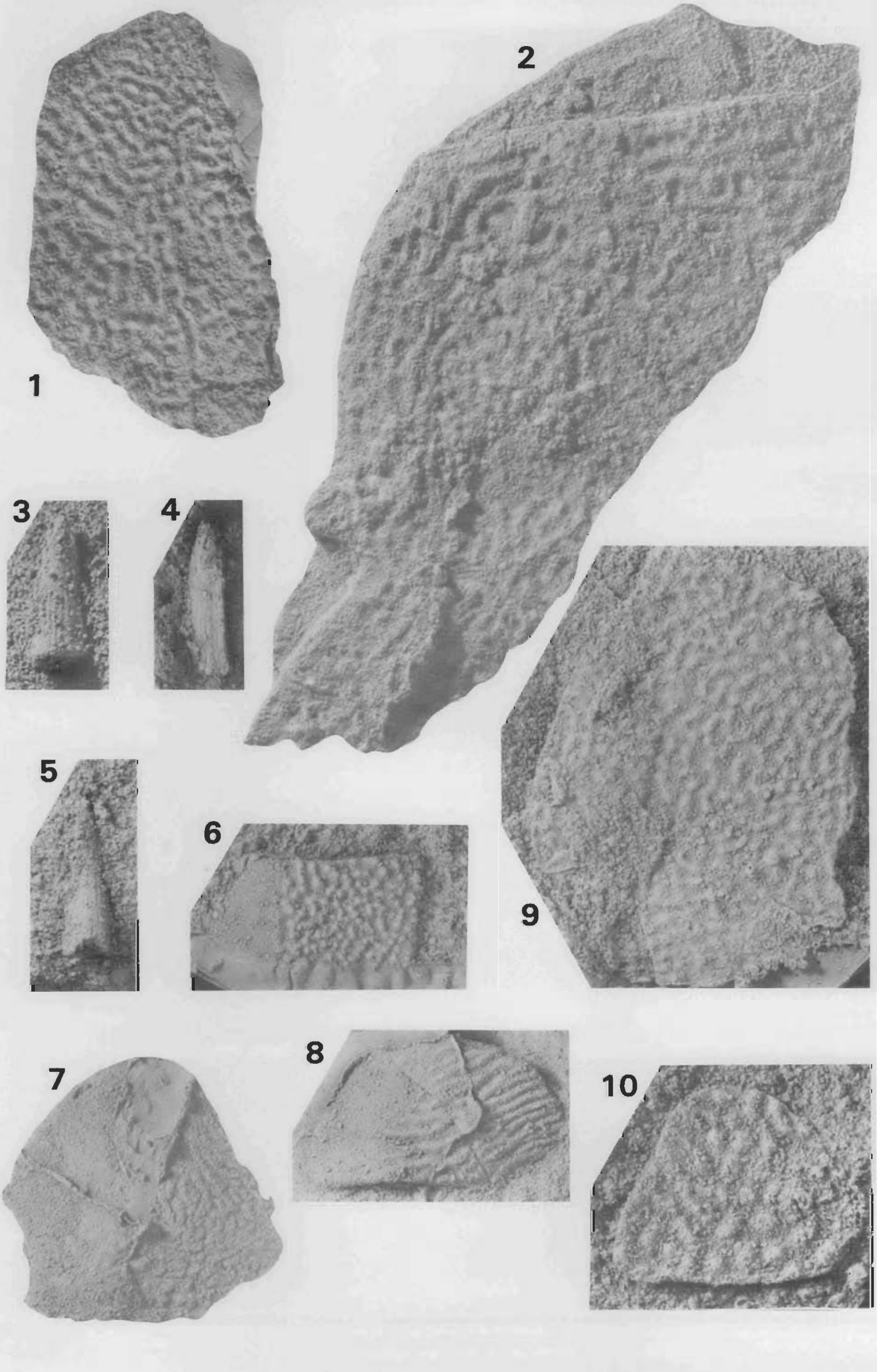
None of the margins is complete, but one appears to have broken along the edge of the contact face for overlapping the adjacent bone (cf. *MxL*, Fig. 5). The orientation of this margin suggests that this fragment is part of a posterior median dorsal plate, probably with an original length of 70-80 mm. The median ridge is strongly developed for a posterior median dorsal, and there is no clear development of a ventral tuberosity. The posterior thickening of the transverse crista is missing, and was probably broken off. No other significant structures are shown by the specimen.

It is clear that this plate does not belong to the asterolepidoid *Remigolepis*, in which a posterior ventral pit and process are not developed. On the other hand, in *Asterolepis* the process may be separately developed behind the pit (e.g. Stensiö, 1948, p. 114), but this region is not fully preserved in CPC13937.

In *Bothriolepis* the pit is developed essentially as displayed here, but a more complete example is required to determine to which taxon the specimen belongs.

The largest specimen in the collection (Pl. 2, fig. 2) is preserved as an external mould of a somewhat triangular fragment with two natural margins, both truncated by a long broken edge. The surface is ornamented with coarse anastomosing ridges, which tend to align along the margins of the ornamented area. The shorter of these margins carries a well-developed overlap area, and along the longer margin are two shorter overlap areas separated by a distinct process and notch. The plate may be slightly arched about an axis

Plate 2. antiarch indet.
Fig. 1. Undetermined plate (CPC13938) in external view (x1). **Fig. 2.** Undetermined plate (CPC13943) in external view (x1). **Fig. 9.** Undetermined plate (CPC13942) in external view (x1.3). **Fig. 10** Undetermined plate (CPC13941) in external view (x1.3).
rhipidistian indet.
Fig. 3. Isolated tooth (CPC13949) (x2). **Figs. 4, 5.** Isolated teeth (CPC13947, 13946) (x 1.3) **Figs. 6–8.** Incomplete scales (CPC13945, 13946, 13944) in external view (x1). (all photographs of latex casts whitened with ammonium chloride).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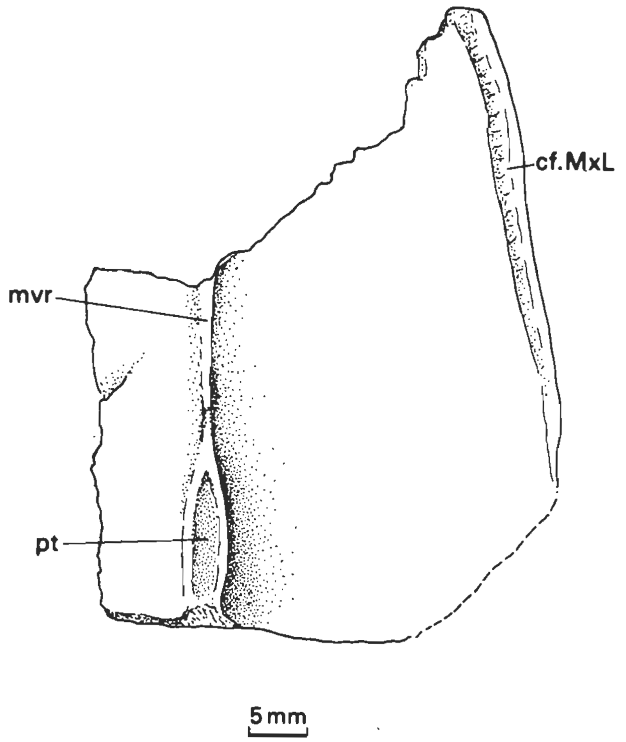

Figure 5. Antiarch indet.
Incomplete plate in visceral view, interpreted as a posterior median dorsal (CPC13937).
cf.MxL, remnant of the contact face for overlapping the left mixilateral plate, *mvr*, median ventral ridge; *pt*, posterior ventral pit.

passing through the notch, but this could be a post-mortem feature.

This specimen shows that the antiarch in question attained a very large size, comparable to that of *Bothriolepis maxima* or *B. gigantea*, and *Asterolepis maxima* or *A. scabra*. However, the specimen is still too incomplete for its position in the skeleton to be determined, except for the fact that it is almost certainly a bone from the trunk armour. It may be an anterodorsal portion of the dorsal lamina of a left mixilateral plate, or an anterior part of the ventral lamina of a right posterior ventrolateral, both of which are overlapped on adjacent margins by contiguous bones.

The other illustrated fragments (Pl. 1, figs 4, 8; Pl. 2, figs 1, 9, 10) seem to have at least one natural bone margin, but apart from ornament show no features facilitating their identification.

Subclass **Osteichthyes**
Superorder **Rhipidistia**
rhipidistian indet.
(Pl. 2, figs. 3-8)

1975 'crossopterygian remains' Yeates & others, p. 50

Material. Three grooved teeth (CPC13947-49) and three ornamented scales (CPC13944-46) preserved as external moulds.

Occurrence. Localities B130 (CPC13947, 48), B136 (CPC13944, 46), B140 (CPC13949), and V34 (CPC13945) in the Knobby Sandstone, Knobby and Falconer Hills, eastern Canning Basin, Western Australia (see Fig. 1).

Description. The presence of rhipidistians in the Knobby Hills fauna is demonstrated by the three isolated teeth (Pl. 2, figs. 3-5).

CPC13949 is 15 mm long, with a diameter of 65 mm at the base of the preserved portion. It is oval in cross section and slightly curved, smooth at the tip, and grooved towards the base. The total number of grooves was probably about 25.

CPC13947 is 21 mm long, laterally compressed in cross section, and has a width of 6 mm. It is slightly curved, with a posterior cutting edge, and is ornamented with fine longitudinal grooves over most of its preserved length.

CPC13948 is also 21 mm long, but is subcircular in cross section, with a diameter of about 6 mm. It is slightly curved and more slender and pointed than the previous two specimens, with a posterior cutting edge. It is similarly ornamented with thin longitudinal grooves.

These specimens are only preserved as moulds, so there is no information on the degree of infolding of dentine walls and other histological details that may be distinctive amongst the major rhipidistian subgroups (e.g. Schultze, 1970). Otherwise, there is no way of identifying such isolated teeth on external morphology, which can be highly variable even in a single individual. Jarvik (1937, p. 67) noted that in material of the osteolepiform species *Eusthenopteron foordi* from Scaumenac Bay, Canada, all combinations of round, compressed, straight, blunt, pointed, striated, and smooth teeth may occur, often with several different morphological types and a large size range in one individual. Clearly the poor preservation here, and the few available specimens, preclude any positive identifications being made.

The three specimens identified as probable rhipidistian scales differ in shape and ornament, and several taxa may have been present. In each there is a smooth anterior region, which, presumably, was overlapped by the preceding scale. The boundary between the unornamented and ornamented parts is not marked by any groove or step in the bone surface. Such features are usual in rhipidistian scales that lack cosmine. CPC13945 (Pl. 2, fig. 6) is very incomplete, and only short sections of the anterior and posterior margins are preserved undamaged. The broken dorsal and ventral margins are extensive, suggesting that significant parts of the scale are missing. This specimen may be interpreted as the central part of a cycloid scale about 30 mm across, with about the anterior third of the scale being the smooth overlapped part. The exposed portion of the scale is ornamented with crowded tubercles aligned in short irregular rows. CPC13944 (Pl. 2, fig. 8) appears to be fairly complete. Again, the anterior unornamented area is a little over one third the total length (50 mm) of the specimen. The exposed surface is ornamented with subparallel ridges. A third scale (CPC13946) has a subcircular shape, and about half the external surface is unornamented (Pl. 2, fig. 7). Its maximum width is about 50 mm, and the anteroventral and posterodorsal margins are incomplete. This scale is ornamented with vermicular grooves.

Little can be concluded from these specimens, except that they probably belonged to one or more large rhipidistian fish, which were advanced in possessing cycloid rather than rhomboid scales. Cycloid scales in Late Devonian deposits may belong either to porolepiform or osteolepiform rhipidistians, which can be readily distinguished by the presence or absence of a boss on the inner scale surface. This detail is not preserved for the examples dealt with here, and like the isolated teeth, they must remain indeterminate for the present.

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