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VERTICAL METAMORPHIC AND AGE ZONATION OF THE EARLY PRECAMBRIAN WESTERN AUSTRALIAN CRUST, AND THE ORIGIN OF PHOTOCONTINENTS

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ABSTRACT

Variations in metamorphic grade, structural pattern, isotopic ages, and granite geochemistry between the low-grade eastern Yilgarn granite-greenstone system (Kalgoolie System), the Pilbara granite-greenstone system, and the southwestern Yilgarn (Wheat Belt) gneiss-granulite terrain, are believed to correspond to increasing depth in the Archaean crust. A progressive exposure of deeper levels from east to west across the Yilgarn craton is related to an eastward tilting of this block, shown by seismic refraction studies. The southwestern Yilgarn suite contains high-grade metabasic rocks, and is regarded as the counterpart of coeval infracrustal roots of the granite-greenstone association.

The lower ultramafic-mafic sequences of the Kalgoorlie and Pilbara systems are interpreted as pre-shield oceanic crust remnants; isotopic age determinations register metamorphism at ca 2.65 b.y. and cannot place a lower age limit on these rocks. Upper ultramafic-mafic sequences also occur in the eastern Yilgarn greenstone belts. As in Western Australia, no lower age limits can so far be placed on early ultramafic-mafic units in South Africa, Rhodesia, and Greenland. The post-granite greenstones in Canada and India may be equivalent to the upper ultramafic-mafic units of the Kalgoorlie System which postdate granites, and therefore are not contradictory to an interpretation of the lower greenstones as oceanic crust remnants.

Three granitic phases are represented in the Yilgarn: (a) 2.9 - 3.1 b.y. in the western part of the Yilgarn, (b) 2.55 - 2.7 b.y. common throughout the Yilgarn craton, and (c) 2.2 - 2.3 b.y. confined to the western part of the Yilgarn craton. A secular increase in Rb and initial $Sr^{87/86}$ ratios is

indicated. It is suggested that phase (b) granites grade in depth into phase (a) granites, and were derived from the latter by anatexis and upward migration of K, Rb, U, and Th-enriched phases. This resulted in the formation of an upper high-radioactivity granite layer concomitantly with regional metamorphism of the greenstone belts.

A model emerges whereby the Archaean crust evolved from a primitive oceanic ultramafic-mafic layer, with sodic granites and potassic granites forming in this order. Estimate of metamorphic gradients from the Yilgarn craton yield a value of about 45°C/km, and explain aspects of Archaean petrogenesis. Small-scale convection cells are supported by observed geotectonic patterns.

1. INTRODUCTION

Widely diverging interpretations have been given of the relations in time and space between low-grade granite-greenstone systems and gneiss-granulite suites of Archaean age. Hepworth (1972) regarded high-grade complexes in Uganda, Tanzania, Botswana, and Swaziland as older than the greenstone belts, an approach supported by Hunter (1970) in connexion with the Ancient Gneiss Complex of Swaziland. Windley & Bridgewater (1971) viewed basic volcanic outliers in southwestern Greenland as younger than engulfing gneiss-agmitite assemblages, and Windley (1973) advanced a model based on basement-cover relations between granulite-gneiss terrains and greenstone belts. Similar problems apply in Ontario and Manitoba regarding the relations between the Superior Province greenstones and gneiss-granulite blocks such as the Pikwitonei (Bell, 1971), Kapuskasing-Mooneehorst (Gaucher, 1966) and the Minnesota River gneiss (Goldich et al., 1970). In India and Canada the occurrences of cross-bedded quartzites below the volcanic sequences of greenstone belts is regarded as indicative of earlier sialic source tarrains, a possibility supported in India by the pre-Dharwar System age of the Nilgiris charnockites (Sarkar, 1972). In contrast, Engel (1968), Glikson (1972b), and Anhaeusser (1973) have interpreted the early ultramafic-mafic assemblages of greenstone belts as primeval oceanic crust.

This enigma is considered in this paper with particular reference to Western Australia. Bouguer anomaly and seismic refraction data by the Bureau of Mineral Resources (BMR) (Fraser, 1973; Mathur, 1973) geochemical data (Lambert & Heier, 1968a), isotopic age determinations (Arriens, 1971; Turek & Compston, 1971; de Laeter & Blockley, 1972), heat flow measurements (Hyndman et al., 1968), as well as geological information (Wilson, 1958; Prider, 1965; McCall, 1969; Durney, 1972; Glikson, 1970, 1972a) enable an integrated investigation of the relations between the low-grade granite greenstone Kalgoorlie System, the high-grade Wheat Belt terrain, and the granite-greenstone Pilbara System. Correlations with analogous patterns in South Africa, India, Greenland, and other terrains are attempted, with the aim of gaining an insight into processes underlying Precambrian shield evolution.

2. ARCHAEAN DOMAINS IN WESTERN AUSTRALIA

Granite-greenstone cratons: The oldest isotopic ages recorded to date in Western Australia from the Pilbara craton (Fig. 1) where oval-shaped syntectonic sodic granites which extensively intrude greenstones yield a Rb-Sr isochron age of 3125 ∓ 366 m.y. (de Laeter & Blockley, 1972), and where ages in the range 2.9 - 3.1 b.y. predominate (Arriens, 1971). An age of ca. 2.6 - 2.8 b.y. is recorded for granites intruded into the Kalgoorlie System, Yilgarn craton (Turek & Compston, 1971), although yet undetected older rocks may well be present in this terrain (Glikson & Sheraton, 1972). The Pilbara and the Yilgarn cratons include respectively linear and irregular synclinal greenstone belts engulfed by very poorly exposed expanses of granite. At the structural level exposed in the Kalgoorlie System the volcanic and sedimentary rocks have been subjected to low pressure, middle to upper greenschist facies metamorphism. The total thickness of sequences of the Kalgoorlie System has been estimated as 20 000 m (Williams, 1968; Glikson 1971a) and 30 000 m (McCall, 1969). Two stratigraphically distinct ultramafic-mafic associations can be separated in the Kalgoorlie System. The lower belts are thicker and represent the earliest recognizable units in this region, whereas the upper ultramafic-mafic belts are thinner, post-date granites (Durney, 1972), and overlie a regional unconformity (Glikson, 1973). Late granitic events in the Pilbara and the Kalgoorlie Systems occurred about the same time; measured ages are 2670 ∓ 95 m.y.

(Moolyella Granite, de Laeter & Blockley, 1972) and 2615 + 15 m.y. (Turek & Compston, 1971) respectively. Younger cratonic igneous events include the intrusion of an east-northeast trending basic dyke swarm dated in the Yilgarn as about 2.4 b.y. (McCall & Peers, 1971; Campbell et al., 1970).

Gellatly (1971) argued for the existence of a buried Archaean craton beneath the little-deformed Carpentarian (ca. 1800 m.y.) platform sediments of the Kimberley Basin. Likewise, gravity data indicate that concealed cratons may occur beneath the Canning Basin and the Eucla Basin (Fraser, 1973).

The Wheat Belt gneiss-granulite craton: The southwestern part of the Yilgarn craton, known as 'Wheat Belt' (Fig. 1), is made up of amphibolite to granulite facies rocks (paragneiss, orthogneiss and migmatite) and granites (Wilson, 1958), and shows a longer time span of thermal activity than the low-grade granite-greenstone Kalgoorlie System. Rb-Sr age determinations in this region have been carried out by Arriens (1971). The most ancient rocks known are 2.8 - 3.1 b.y. old gneisses exposed in the Armadale-Northam and Koolanooka Hills areas. Granites dated about 2.5 - 2.8 b.y. by far predominate in the Wheat Belt, and granites dated at 2.2 - 2.5 b.y. occur along the western part of the Yilgarn craton. Prider (1965) described a progressive increase in metamorphic grade from east to west across the Kalgoolie/Southern Cross/Northam section, i.e. from the Kalgoorlie System into the Wheat Belt gneiss-granulite terrain. Wilson (1971) considered pyroxene granulite lenses in gneiss at South Quairading (Wheat Belt) as equivalents of the ultramafic-mafic greenstone suite of the Kalgoorlie System on structural and geochemical grounds. The relations between the low-grade and high-grade zones of the Yilgarn craton will be considered later.

3. GEOPHYSICAL DATA

Regional helicopter gravity surveys by the Bureau of Mineral Resources (Fraser, 1973) delineated several gravity provinces which correspon closely to established divisions of the Western Australian Precambrian shield (Fig. 2), as well as indicating the occurrence in depth of hitherto unknown structures.

The low-grade granite-greenstone cratons are represented by gravity provinces of disturbed contour patterns and regionally low Bouguer anomaly levels. Local 'highs' in the gravity field correspond to the greenstone belts, and gravity 'lows' to granites and gneisses. In the Yilgarn craton, linear north-northwest-trending gravity 'highs' in the east give way to more disjointed 'highs' or greater amplitude in the west. These changes reflect a decrease in the size and continuity of greenstone belts from east to west, as well as an increase of the density of the basic belts westward as a result of both a rising metamorphic grade and a higher ratio of igneous to sedimentary rocks. Gradual westward rises in the overall Bouguer anomaly levels take place along the western flank of the Yilgarn craton, particularly towards the Wheat Belt (up to +30 mgl. peak value), and in the northwestern corner of the Yilgarn craton. These anomalies can be accounted for by a combination of shallow and deep crustal features, as they correspond both to an increase in metamorphic grade to granulite facies and to a consistent westward increase in the thickness of the lower crustal (7.24 km/s velocity) layer (Mathur, 1973) (see below). The gravity pattern in the Pilbara craton is broadly similar to that of the Yilgarn craton, but shows little or no linearity; this is explained by the oval shape of granites in the Pilbara and the narrowness of the greenstone belts.

Seismic refraction data obtained by BMR (Mathur, 1973) indicate a three-layer crust in the Yilgarn block (Fig. 3). The boundaries between the upper crustal layer (Vp = 6.12 km/s), the intermediate layer (Vp= 6.67 km/s), and the lower crustal layer (Vp = 7.49 km/s) become progressively shallower from east to west across the Yilgarn craton. In contrast the Moho underneath the shield shows a well pronounced westward slope component.

4. RELATIONS BETWEEN LOW-GRADE AND HIGH-GRADE SECTORS OF THE YILGARN CRATON.

The following observations place constraints on interpretations of the relations between the Wheat Belt gneiss-granulite terrain and the granite-greenstone Kalgoorlie System:

1. There is a gradual metamorphic transition between the greenschist facies greenstone belts of the Kalgoorlie System and the granulites of the Wheat Belt (Prider, 1965), with amphibolite facies rocks developed at Southern Cross (Fig. 1). In the Wheat Belt, basic granulite enclaves are regarded as the remnants of synclinal greenstone root zones (Wilson, 1969, 1971); there is no evidence of angular or metamorphic unconformity between the basic granulites and surrounding gneiss
2. The Wheat Belt and an adjoining zone to the north along the western margin of the Yilgarn craton are the only high-grade metamorphic terrains recognized within the Yilgarn craton. The eastward tilting of upper crustal layers indicated by the seismic refraction data suggests that deeper crustal levels should be exposed in the Wheat Belt (Fig. 3); this is supported by the increase in metamorphic

grade and the decrease in the size of greenstone belts from east to west, as the latter are considered to be synclinal outliers which pinch out in depth (Fraser, 1973)

3. Rb-Sr age data (Arriens, 1971; Turek & Compston, 1971) show that igneous activity in the Wheat Belt extended over a longer time span than in the central and eastern parts of the Yilgarn craton. Thus, of the three plutonic episodes dated in the Wheat Belt (2.9 - 3.1. b.y.; 2.55 - 2.7 b.y.; 2.2 - 2.3 b.y.), only the second episode has been recorded so far in the granite-greenstone terrain of the Kalgoorlie System.

Three alternative models for the relations between the Kalgoorlie granite-greenstone and Wheat Belt gneiss-granulite provinces are:

(a) lateral variations in metamorphic grade within the same crustal level;

(b) basement-cover relations between the high-grade suite (Wheat Belt) and the supracrustal rocks (greenstone); and

(c) coeval syntectonic relations between the granite-greenstone suite and infracrustal equivalents represented by the Wheat Belt rocks.

Possibility (a); Primary lateral metamorphic facies changes within the same crustal level are inconsistent with the seismic and gravity data, which suggest an eastward tilting of upper crustal layers of the Yilgarn craton. This implies that the Wheat Belt rocks represent deeper crustal zones than the Kalgoorlie System, and that their equivslents may thus occur beneath the central and eastern parts of the Yilgarn craton.

Possibility (b): The possibility that the high-grade association of the Wheat Belt represents the basement on which the greenstones were deposited is in apparent agreement with the older ages recorded for the gneiss-granulite complex. According to this interpretation, the lack of angular and metamorphic unconformities between the basic granulites and surrounding gneisses in the Wheat Belt could reasonably be ascribed to an obliteration of original field relations by younger metamorphism. Because the regional metamorphism in the greenstone belts of the Kalgoorlie System is dated at 2675 ∓ 35 m.y. (Turek & Compston, 1971), and in view of the progressive rise in metamorphic grade westward across the Yilgarn, it is possible that the Wheat Belt rocks were effected by the same metamorphic eposide, a possibility supported by the abundance of gneisses of similar age in the Wheat Belt. If this is correct, the ca. 3 b.y. old gneisses in the Wheat Belt represent relics uneffected by this thermal event. However, whether these relics were derived from a basement on which the greenstones were deposited, or from granites intruded into the latter can only be answered if (1) the primary (igneous) ages of the earliest ultramafic-mafic igneous rocks are known and/or (2) the field relations between the earliest ultramafic-mafic units and the earliest granites and/or high-grade metamorphics are known. These questions are the key for an understanding of Archaean shield evolution.

Geochronological studies of the low-grade metamorphosed Kalgoorlie System in the Eastern Goldfields area have placed an upper limit of ca. 2.7 b.y. on the lower ultramafic-mafic assemblages, but so far have not yielded confident older age limits for these rocks (Turek & Compston, 1971). Because the upper greenstone belts of the Kalgoorlie System in the Eastern Goldfields region are separated by a major unconformity from the lower greenstones belts in this area (Durney, 1972; Glikson, 1973), the latter may represent a considerably older volcanic phase. Thus, the original (igneous) ages of the lower ultramafic-mafic assemblage of the Kalgoorlie System are not necessarily younger than the ca. 3 b.y. old gneisses of the Wheat Belt. It is pertinent to note here that the greenstones of the Warrawoona System in the Pilbara craton are intruded by ca. 3.1 b.y. old granites (Arriens, 1971; de Laeter & Blockley, 1972), and that later in this paper it will be shown that the Pilbara craton may be contemporaneous with the Yilgarn craton, implying similar minimal ages of 3.0 - 3.1 b.y. for the greenstones in both terrains.

Various factors militate against the existence of a sialic basement below the lower ultramafic-mafic assemblages. For example, it would be reasonable to expect to see at least occasional exposures of any basement - such has nowhere been observed. Large scale remobilization of the basement through anatexis may explain this difficulty in the case of highly metamorphosed roots of greenstone belts, as proposed by Windley & Bridgwater (1971) and Windley (1973), but it is very unlikely that this process could have operated to the complete obliteration of basal contacts of the lower ultramafic-mafic sequences at high crustal levels. Further, had the ultramafic-mafic volcanics extruded above sialic crust, some examples of acid inclusions, sialic contamination, or granite-derived sedimentary intercalations could be expected. In contrast, the greenstones of the Kalgoorlie System are chemically similar to oceanic tholeiites, high-Mg basalts and peridotitic flows and sills of uncontaminated nature (Glikson, 1971; Hallberg, 1972; Hallberg & Williams, 1972; Williams & Hallberg, 1973). The existence of sialic crust before a simatic crust also is not in accord with experimental evidence, which indicates that a direct derivation of granites by partial melting of mantle peridotite is improbable (Nicholls & Ringwood, 1972). Granites can form, however, from partial fusion of basic rocks, e.g. through subduction or downbuckling of an earlier basic crust (Green & Ringwood, 1967; Lambert & Wyllie, 1970, 1972).

The occurrence of granites before deposition of the Canadian and Indian Dharwar greenstones sequences is not considered as contradictory to the primitive ocean crust model, as for reasons given later these volcanics are correlated with the post-granite upper greenstone belts of the Kalgoorlie System.

Thus, a basement-cover interpretation for the Wheat Belt - Kalgoorlie System relations is faced by difficulties arising from the inability of placing lower limits on the age of the lower ultramafic-mafic sequences, and the lack of field, geochemical, and experimental evidence for pre-existing sialic rocks in this region.

Possibility (c); The difficulties encountered with the basement-cover model merit a detailed examination of the possibility that the Wheat Belt rocks represent the exposed equivalents of infracrustal roots of the Kalgoorlie System. In this coeval-syntectonic relations model both systems evolved as a result of a succession of contemporaneous igneous and metamorphic events, the effects of which are manifested differentially at the various crustal levels. According to this concept, the ultramafic-mafic assemblages are the oldest recognizable members at the supracrustal levels and by inference in the high-grade Archaean suites, and are therefore used as a starting point. It will be argued that the earliest greenstones are the vestiges of an early Earth-wide crust from which sialic protocontinents have evolved through extensive downbuckling, partial melting, plutonism, volcanism, and later anatectic events. In the following sections it will be shown that such a model is consistent with a wide variety of geochemical and geochronological data from the Yilgarn craton.

5. CRUSTAL ZONATION OF THE YILGARN CRATON.

Lambert & Heier (1968a, b) and Lambert (1971) argued on the basis of heat flow and geochemical data that the Yilgarn craton is capped, on average, by an approxi mately 4.5 km thick layer enriched in K, Rb, U, and Th, which grades quite rapidly with depth into rocks strongly depleted in these element (Fig. 4). Radiometric ages, Rb and Sr analytical data, and initial $Sr^{87/86}$ ratios (Arriens, 1971) define the following classification of granites in the Yilgarn craton (Fig. 5).

1st phase (2.8 - 3.1 b.y.): Rb = 90 - 140 ppm (principal range);
$Sr^{87/86} = 0.702 \pm 0.004$ and 0.704 ± 0.003 (pooled isochron).

2nd phase (2.5 - 2.8 b.y.): Rb = 160 - 270 ppm (principal range);
$Sr^{87/86} = 0.705 \pm 0.03$ (pooled isochron).

3rd phase (2.2 - 2.5 b.y.): Rb = 190 - 250 ppm (principal range);
$Sr^{87/86} = 0.725 \pm 0.005$; 0.717 ± 0.026; 0.747 ± 0.943; 0.802 ± 0.164.

It is apparent that there was a general encrease in initial $Sr^{87/86}$ ratio and in Rb content between the first and the second plutonic phases. The increase in Rb suggests a corresponding increase is potassium and thereby a decrease in the Na/K ratio with time, but there are not enough data to substantiate this directly.

These relations are consistent with a derivation of 2nd phase K-granites from melts and aqueous phases arising from the anatexis of sodic gneisses of the 1st plutonic phase (Glikson & Sheraton, 1972), which suggest that remnants of the latter exist at depth beneath the Kalgoorlie System. Such zonation is well documented from the eastern part of the Kaapvaal Shield, eastern Transvaal, where tonalites (3.2 - 3.4 b.y.) grade into migmatites (Nelspruit Migmatite, ca. 3 b.y.) (Viljoen & Vilfoen, 1969b). A similar stratification of granites probably occurs in the Kalgoorlie System, where K-rich varieties with a pooled age of 2615 ± 15 m.y. (Turek & Compston, 1971) are common, and only rare outcrops of tonalite have been recorded*. This is in accord with the high crustal level indicated by the consistent low-pressure middle to upper greenschist facies (except for thermal aureoles) of the greenstones in the Wiluna-Kalgoorlie-Norseman area. The transition in depth to low radioactivity Na-rich granites is supported by the low heat flow values measured in these greenstone belts (Hyndman et al., 1968), which indicate that the base of the K-granite layer is located well above the synclinal keels of the greenstone belts.

Differences in crustal depth also explain the observed structural and compositional distinctions between the Yilgarn and Pilbara cratons. In the latter, the narrowness of the greenstones belts, the high proportion of ultramafic-mafic to sedimentary rocks (i.e. the limited areal distribution of upper sedimentary Mosquito Creek Series), the wide contact metamorphic aureoles**, and the relatively high degree of shearing are all consistent with a crustal level intermediate between that of the Kalgoorlie System and the Wheat Belt. This interpretation is strongly supported by the predominance in the Pilbara of ca. 3.1. b.y. old granites with high plagioclase/K-feldspar ratios, as contrasted to ca. 2.6 b.y. old granites with lower plagioclase-K-feldspar ratios (de Laeter &Blockley, 1972). The variations in shape and size of the granitic plutons and greenstone belts are likewise explicable in terms of structural depth. Thus, the irregular pattern of greenstone belts in the Pilbara as compared to the parallel north-northwest-trending Kalgoorlie System may well reflect a transition from supracrustal levels, where folding of volcanic-sedimentary sequences is determined by a uniform stress field, into deeper

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* The abundance of K-granite, however, could be amplified owing to their higher resistance to weathering than Na-rich granites (Glikson & Sheraton, 1972).

** Following Engel (1968), telescoped metamorphic aureoles within greenstone belts can be used to estimate the depth of intrusion.

interbatholithic levels where folding is controlled by the geometry of theintrusive closely-spaced granites. It follows that the Pilbara greenstones occur at a structural level analogous to that of the amphibolite-facies greenstones at Southern Cross, central Yilgarn craton, a correlation supported by the decrease in the regularity of greenstone belt patterns in this area (Figs. 1, 6). These lines of evidence suggest that the Kalgoorlie System, Pilbara craton, and Wheat Belt terrain represent shallow, intermediate, and deep levels of one and the same early Precambrian shield.

6. ARCHAEAN EVOLUTION OF WESTERN AUSTRALIA

In this section, we present our concept on the evolution of Archaean cratons, principally based on data from Western Australia. It is contended that until about 3.1 b.y., a primitive oceanic crust extended throughout the Western Australian Precambrian Shield area (Fig. 7). About 2.9 - 3.1 b.y. ago this crust was extensively intruded by Na-rich granites, metamorphosed and transformed into a granite-greenstone type terrain. The early granites crop out in the Pilbara and Wheat Belt areas and are believed to underlie the Kalgoorlie System, a widespread occurrence which can be understood in terms of broadly simultaneous ocean-wide granite-forming episodes, rather than by orogeny confined to narrow geosynclinal or arc-trough type zones. We consider that these episodes occurred as a result of partial melting of primitive crust which was extensively downbuckled, possibly by closely spaced convection cells (Fyfe, 1973a) coaxial with global Archaean tectonic trends (Dearnley, 1966; Engel & Kelm, 1972). This is supported in the Kalgoorlie System by the parallel orientation of north-northwest-trending folds and long batholith axes. This model explains the high granite*/greenstone ratio in the Yilgarn craton (about 5:1) in terms of close-spaced conveyor belt-like circulation and fusion of oceanic crust.

As a result of the early plutonic phase the crust evolved into Na-granitic nuclei and linear inter-batholithic synclinoria of remnant oceanic crust (Glikson, 1972b; Anhaeusser, 1973) (Fig. 7).

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* referring to both the Na-granites and the K-granites, with the assumption that the latter are mostly derived from the former by anatexis (see below).

Progressive exposure through denudation of the batholiths and continuing volcanic activity resulted in the formation of volcano-sedimentary piles which rest unconformably above both deformed remnants of oceanic crust and sodic granites. In the Kalgoorlie System this break is represented at the base of the upper greenstone belts (Durney, 1972; Glikson, 1973), and in Rhodesia and the Transvaal by the sub-Bulawayan unconformity and the Middle Marker paraconformity, respectively. Thus, two greenstone suites are defined: a pre-granite lower ultramafic-mafic assemblage, and a post-granite upper greenstone assemblage. The lower greenstones are represented in the Kalgoorlie System by the Coolgardie, Ora Banda, Bulong, and possibly Norseman belts, in the Kaapvaal Shield by the lower part of the Onverwacht Group, and in Rhodesia by the Sebakwian Group. The later greenstones are exemplified by the upper ultramafic-mafic belts of the Kalgoorlie System (Kalgoorlie-Kambalda, Yilmia Red Lake, and Mount Monger belts) (Glikson, 1973). Also, the Canadian basalt-andesite-rhyolite cycles (Wilson et al., 1965; Baragar & Goodwin, 1969), and the Indian Dharwar greenstones contain in places basal cross-bedded quartzites which point to stable shelf conditions and sialic source rocks (F.J. Elber, pers. comm., 1973; Srinivasan & Sreenivas, 1972). These greenstones therefore appear to correlate with the upper post-granite assemblage. In India, pillowed ultramafic relics of an early ultramafic-mafic suite occur as enclaves in peninsular gneiss of the Dharwar anticlinorium (R. Srinivasan, pers. comm., 1973). Although ultramafic lavas were described from Ontario (Naldrett, 1972; Pyke et al., 1973), these rocks are incorporated in calcalkaline volcanic sequences correlated here with the upper greenstone belts, and no equivalents of the lower greenstone belts have as yet been reported from Canada.

In the Kalgoorlie System regional metamorphism preceded the intrusion of the second (ca. 2.6 b.y.) phase granites by only about 60 m.y. (see Turek & Compston, 1971), and it seems reasonable therefore to regard these processes as genetically related. Probably a rise in the geothermal gradient, first manifested by regional metamorphism, has subsequently effected extensive anatexis at the base of the sodic granites and at the roots of the synclinal greenstone belts. The migration to shallow levels of partial melts and aqueous phases enriched in 'incompatible' elements (e.g. K, Th, U, Rb), resulted in migmatization, metasomatism, and the formation of an upper K-granite layer, as well as in discrete plutons such as the Mungari Granite (Glikson, 1971b; Lambert & Heier, 1968a, b; O'Beirne, 1968). Subsequent cooling and deep fracturing possibly related to crustal dilation by lateral subcrustal flow was accompanied by the intrusion of basic dyke swarms dated at 2.4 b.y. Subsequently, eastward tilting at the Yilgarn craton along the Darling Fault (Fig. 1, 3), which is considered to date back to the Precambrian (Glikson et al., in press), resulted in denudation and exposure of progressively deeper crustal levels in the west. Uplift of the Pilbara craton relative to the eastern and central parts of the Yilgarn craton resulted in exposure of intermediate crustal levels in that area.

7. EVIDENCE FROM INDIA, TRANSVAAL AND GREENLAND

Peninsular India: The proposed Archaean model for Western Australia is supported by evidence from peninsular India, which in turn implies fundamental analogies between these Precambrian shields. In India a rise in metamorphic grade with deeper structural level southward is recognized within the north-northwest to northeast-striking and northward-plunging greenstone belts of the Dharwar System. Thus, the Chitaldrug schist belt (Naqvi & Hussain, 1972) and greenstone belts north of Mysore (cf. Bababudan and Holenarsipur belts) were affected respectively by greenschist and almandine-amphibolite facies metamorphism (Pichamuthu, 1967), the latter grading southward into charnockites of the Nilgiris-Salem belt. Following Sarkar (1972), igneous activity and metamorphism within the Dharwar System include an early phase at about 2.8 b.y., and culminated at ca. 2.6 b.y. ago, whereas the charnockites register dates of about 3 b.y. Geochemical and petrographical data indicate that the charnockites and enderbites have high Na_2O/K_2O ratios (Pichamuthu, 1967), the Peninsular Gneisses (ca. 2.6 b.y.) have high plagioclase (40-50%) and low K-feldspar (5-8%) contents, and the late Chitradurga Granite (ca. 2450 m.y., Sarkar, 1972) and Closepet Granite (2380-2000 m.y.; Sarkar, 1972) have low plagioclase (10-16%) and high K-feldspar (40-60%) contents (Divaleara Rao et al., 1972). In agreement with the present concept, these authors favour a derivation of the K-granites through palingenesis and metasomatism of the peninsular gneiss. The above relations indicate increase in metamorphic grade, Na/K ratio, and isotopic age with structural depth, in an almost identical pattern to that in Western Australia.

Eastern Transvaal: The relations between the intermediate-grade Ancient Gneiss Complex in Swaziland (Hunter, 1970) and the greenstone belts of the Swaziland System (Anhaeusser et al., 1969; Viljoen & Viljoen, 1969a, b, c) can be interpreted in terms of: (a) a pre-greenstones origin for the gneisses (Hunter, 1970), or (b) metamorphism of equivalents of the granite-greenstone Swaziland System of the Barberton Mountainland. A broad correspondence in ages between these terrains is indicated (ca. 3340 m.y. for the Ancient Gneiss Complex, Allsopp et al., 1969; ages of 3310 ± 40, 3250 ± 40, 3220 ± 40 m.y. for tonalites and granodiorites intruded into the Swaziland System (Oosthuyzen, 1970). Common to both is the abundance of mafic and ultramafic xenoliths or conformable lenses, and the recognition of at least two granitic phases. An interpretation of the Ancient Gneiss Complex as the coeval syntectonic roots of the low-grade Swaziland granite-greenstone association is therefore possible. On this basis the scarcity in metasediments in the Ancient Gneiss Complex (Hunter, 1970) is readily explained by the scarcity of sediments at low stratigraphic and structural levels of the greenstone belts. The juxtaposition of gneisses and low-grade greenstone belt rocks at Pigs Peak (Hunter, 1970) may represent strong faulting. In analogy with the Wheat Belt terrain the low-pressure andalusite-sillimanite facies series is characteristic of the Ancient Gneiss Complex.

Southwestern Greenland: The occurrence in the Godthab area of concordant greenschist to amphibolite facies inliers of the Malene greenstones (including pillowed, amygdaloidal, and agglomeratic types) and paragneiss was interpreted by Windley & Bridgwater (1971) as evidence for basement-cover type relationships between these rocks and the Amitsoq gneiss (3700-3750 m.y., Moorbath et al., 1973).

The original nature of the boundary between the Malene greenstones and the Amitsoq gneiss is invariably obscured by shearing and thrusting. However, basement-cover relations were suggested by McGregor (1973) on the basis of the intrusion into the Amitsoq Gneiss of the Ameralik basic dykes, which are absent from the Malene greenstones, from associated anorthosite sills, and from the younger Nuk gneiss (3084 $\mp$ 46 m.y., cited in McGregor, 1973). We suggest here that dykes cannot be used as an absolute field reference marker because their intrusion can be controlled by differential mechanical properties of the country rocks. Thus, a lesser degree of fracture development in supracrustal rocks in relation to more rigid plutonic rocks may well result in the termination of dykes along granite-greenstone contacts. Thus, the Malene greenstones could be older than the Amitsoq Gneiss. Nor can a lower geochronological limit be placed on the Malene supracrustals, which in the Fiskanaesset area (south of Godthabfjord) are intruded by ca. 3600 m.y. old anorthosites (Evensen et al., cited in Windley, 1973). The similar ages of the Malene greenstones and the Amitsoq gneisses and the occurrence within the latter of ultramafic and mafic xenoliths (Windley, 1973, D. Bridgwater, pers. comm., 1972) suggest to us that the alternative suggestion of McGregor (1973), namely tectonic juxtaposition of oceanic crust and infracrustal gneisses, should be preferred. Such an interpretation is clearly in agreement with the evidence cited above from low-grade granite-greenstone systems.

Evidence substantiating the above model of crustal evolution is forthcoming from isotopic studies. It is apparent that the early Na-granite phase, and in particular the late K-rich anatectic phase of shield evolution should have caused significant increases in the $Sr^{87}/86$ ratios of sea water relative to those of the upper mantle. Such a divergence has been noted at about 3.0 b.y. on the basis of $Sr^{87}/86$ ratios of sea water relative to those of the upper mantle, and on the basis of $Sr^{87}/86$ ratios of carbonate sediments and basaltic rocks of various ages (Hedge & Walthall, 1963). Furthermore, Pb isotope data (Patterson & Tatsumoto, 1964) can be interpreted in terms of a major fractionation of sialic crust around 3.0 b.y.

8. ARCHAEAN GEOTHERMAL GRADIENTS, WITH PETROGENETIC IMPLICATIONS

It is widely believed that higher geothermal gradients prevailed in the Archaean relative to the present (Viljoen & Viljoen, 1969c; 1971; Saggerson & Owen, 1969; Hart et al., 1970; Saggerson & Turner, 1972; Fyfe, 1973a, 1973b; Dickinson & Luth, 1971). In this section we attempt to place constraints on the basis of geological data on the geothermal gradients during the ocean crust-forming stage, the early Na-granite nucleation stage, and the late K-rich granite metamorphic-anatectic stage. These gradients do not necessarily reflect long-term average values, and will be tentatively related here to spatially and temporally distinct thermal events of a transient nature.

Oceanic crust-forming stage: Peridotitic flows, high-Mg basalts, and low-K tholeiites abound within basal ultramafic-mafic associations, and in the Kalgoorlie System commonly occur in this stratigraphic order (Viljoen & Viljoen, 1971; Nesbitt, 1971; Hallberg & Williams, 1972). Green (1972) noted that the peridotites imply 60-80 percent melting of mantle pyrolite, and extrusion temperatures of about 1600-1650°C (anhydrous melts). The origin of these rocks necessitates rapid upwelling of little-fractionated ultramafic melts, a condition unknown in younger geological systems.* To account for this phenomena, two possible mechanisms will be considered:

(a) Mantle diapirism and adiabatic melting triggered by pressure-release consequent on cratering of the crust by extra-terrestrial impact (Green, 1972);

(b) Extensive melting of mantle peridotite as the result of very high geothermal gradients and considerable amount of diapiric uprise.

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*However, Gale (1973) has reported the occurrence of high-Mg basalts from the Palaeozoic ophiolites of Newfoundland.

Possibility (a)

Green (1972) suggested, by analogy with the lunar maria, that mantle diapirism could be triggered by deep cratering as the result of meteorite impact. This mechanism, however, is faced with a difficulty arising from the occurrence of high-Mg and peridotitic extrusives within the upper as well as the lower greenstone sequences of the Kalgoorlie System, in the upper Onverwacht Group in the Barberton Mountainland (Viljoen & Viljoen, 1971), and in Canadian belts (Pyke et al., 1973) which are correlated here with the upper greenstone units. It is not possible to relate the ultramafic volcanism to the same event which caused the volcanism of the lower greenstone belts because of the considerable time gap between them evidenced by sediments. Neither the sequences which underlie the upper greenstone units nor the granitic plutons which are known to antedate these units display any impact effects such as shatter cones, large-scale brecciation, shock-induced cleavage, shock-melting, or high-pressure mineral phases. It is apparent, therefore, that only endogenic processes could have given rise to the upper ultramafics, and thus there is no reason to appeal to extra-terrestrial impact in connection with the genesis of ultramafics of the lower greenstone sequences.

Possibility (b)

It appears that many petrogenetic features of Archaean ultramafic-mafic associations can be understood if high heat flows and considerable amounts of mantle diapirism are invoked. Variations in these parameters must have been inter-related. For instance, adiabatic diapiric uprise, possibly resulting from influx of water and/or gravitational instability, would lead to regional rises in the geotherms. Furthermore, elevated geothermal gradients, perhaps a function of intense convection current activity and/or crustal rifting, could lead to diapiric ascent by causing onset, or increased degrees, of melting in the mantle.

The low to upper greenschist facies metamorphism of the approximately 8 km thick lower Onverwacht Group in South Africa (Viljoen & Viljoen, 1971) and the 11 km thick Coolgardie Mount Robinson greenstones in the Kalgoorlie System (Glikson, 1971a), help to place an upper limit on the geothermal gradient at the stage during which these ultramafic-mafic units formed. Assuming a thickness of about 10 km, and an upper greenschist facies boundary at about 400 ^{o}C (Turner, 1968), a maximum gradient of 40^{o}C/km is obtained. If this maximum is assumed as the actual figure, such a geotherm would cause incipient melting in wet (P_{H_2O} = P total) and dry peridotite at depths in the vicinity of 30 km and 80 km, respectively (Fig. 8). Only small amounts of melting would occur in the vicinity of the wet pyrolite solidus, unless there was considerable influx of water; with traces of water, magmas would not segregate until temperatures approaching the dry peridotite solidus are reached. Experimental data indicate that up to about 20 percent melting in this depth interval would generate alkaline basaltic magmas, and about 30 to 40 percent melting would give rise to low-Al olivine tholeiites (Green & Ringwood, 1967). Greater degrees of melting would progressively result in high-Mg basalt and peridotitic melts (Green, 1972).

Hallberg & Williams (1972) and Williams & Hallberg (1973) documented the coexistence in the Kalgoorlie System of high-Mg basalts showing considerable variation in Mg and Al, and low-K tholeiites of uniform composition. Within individual sequences the latter are mostly located at stratigraphically higher positions than the ultramafic extrusives, a trend representing a decline from ca. 80 to ca. 30 percent melting of pyrolite. Conceivably, the high-Mg basaltic to peridotitic volcanism ensued from variable degrees of melting within and immediately around rising mantle diapirs; according to this model the apparent lack of fractionation of the peridotites (Green, 1972) could be related to superheating. In contrast, the low-K tholeiitic melts would be produced from lower degrees of partial melting within a constantly located mantle source layer, as well as in mantle zones adjacent to diapirs or at waning stages of melting within the latter. The constant chemical composition of the tholeiites further indicates that they represent the minimal amount of liquid which segregated and reached the surface under the prevailing conditions. The conspicuous absence of alkaline basalts in Archaean greenstone sequences* can be explained as due to consistently high degrees of partial fusion (above 30%). The rarity of high-Al tholeiites (Glikson, 1970) suggests that melting and/or fractionation have not occurred within the depth interval of 15-35 km (Green & Ringwood, 1967). The alternative possibility, namely melting at depths of less than 15 km (Glikson, 1972b), appears be less likely because 30 - 40 percent partial melting at this depth would imply gradients as high as 80°C/km. Such high heat flow,

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*With the exception of trachytic flows in the Moodies Group (Anhaeusser et al., 1968) and the Timiskaming Series (Goodwin, 1968).

operative over long periods as required by the long-term basic volcanism, should have been indicated by extensive high-grade metamorphism of at least the lower ultramafic-mafic assemblages.

As transient high geothermal gradients decreased, the depth of the magma source layer would increase and lesser degrees of partial melting would ensue. There would be a parallel crystallization of eclogite interstitially and as segregation pods within the peridotite. This is consistent with geophysical models suggesting an abundance of eclogite within the uppermost mantle (see review by Wyllie, 1971).

<u>Early Na-granite phase</u>: We consider that deformation, metamorphism, downbuckling, and partial melting of extensive regions of the primitive oceanic crust were responsible for the formation of Na-granite protocontinental nuclei. If geothermal gradients in the vicinity of 40°C/km are assumed, as for the oceanic crust-forming stage, partial melting of hydrated basic rocks within downbuckled crust should have commenced at depths as shallow as 20 km, and magma segregation and upward migration would have been widespread at levels less than about 30 km (Fig. 8). Plagioclase would be the first phase to melt, with consequent formation of Na to Na + Ca-rich liquids (Lambert & Wyllie, 1970, 1972). In the Western Australia region this stage occurred about 2.9 - 3.1 b.y. ago. The generation of syn-depositional Na-rich acid rhyolites and porphyries which overly ultramafic-mafic cycles in the Kalgoorlie System (O'Beirne, 1968; Williams, 1969; Glikson, 1970), may well represent surface manifestation of this plutonism. That the eruption of the porphyries closely followed mantle melting episodes may indicate that the latter events triggered crustal subsidence and downbuckling, possibly associated with intensive convection currents and/or gravitative subsidence at the base of the accumulating volcanic piles. Persistence of this gradient in depth would have lead to further partial melting in the mantle.

The Na-granite plutons are typically small as exemplified by the 'gregarious batholiths' in Rhodesia, where the mean diameter is about 65 km and the mean distance between batholith centres is about 90 km (Talbot, 1968). This could perhaps be the function of a shallow depth of partial melting of the oceanic crust, which resulted in smaller magma volumes than accumulative segregation at greater depths.

Metamorphic-anatectic stage: The very gradual variations in metamorphic grade within Archaean cratons such as the Yilgarn and peninsular India, as contrasted with high thermal gradients in orogenic zones (see Turner, 1968, p. 359), justify their examination with reference to the problem of the Precambrian regional geothermal gradient. Thus, in India and the Yilgarn craton isograds are spaced several hundred kilometres apart (Pichamuthu, 1967; Wilson, 1958). It was argued above that, in view of the eastward tilting of the Yilgarn craton revealed by seismic refraction studies (Mathur, 1973), the change in grade across this block reflects its vertical metamorphic zonation. Because no major faulting is known to occur across the Coolgardie-Boorabbin-Southern Cross-Hundaring seismic traverse, an estimate of the geothermal gradient can be made on the basis of the indicated vertical interval between the greenschist-amphibolite and the amphibolite-granulite isograds, and the temperatures of these transitions (taken as 400°C and 650°C, after Turner, 1968, p. 366). Thus, the vertical distance between the greenschist-amphibolite and amphibolite-granulite facies isotherms at Boorabbin is calculated as 5.3 km (Figs. 3 and 6). The calculated vertical metamorphic gradient of approximately 45°C/km probably represents a transient geothermal gradient which caused the regional metamorphism dated as 2675 ± 35 m.y. at Kalgoorlie (Turek & Compston, 1971); the latter is also reflected by the predominance of gneisses of a similar age in the Wheat Belt. This value is in agreement with the estimate of the Archaean geothermal gradient in India by Ray (1·970), and suggests that the 40°C/km gradient assumed earlier for the ocean crust-forming and Na-granite-forming stages is reasonable. It accounts for the low-pressure facies of regional metamorphism developed in the greenstone belts of the Kalgoorlie System and in the Wheat Belt gneiss-granulite suite. Furthermore, it is adequate to cause granulite facies metamorphism and anatexis of the Na-granitic rocks at depths around 15 km, with consequent upward migration of K-rich granitic magmas and aqueous fluids. It should be noted that such a high thermal gradient could not have continued far down into the mantle without resulting in the generation of considerable amounts of basic and ultrabasic magmas within the upper mantle.

CONCLUSIONS

(1) No lower age limits have been determined for such ultramafic-mafic assemblages as the lower greenstones of the Kalgoorlie System, the lower part of the Onverwacht Group (Transvaal), the Sebakwian Group (Rhodesia), ultramafic enclaves in the Dharwar anticlinorium in southern India, and the Malene volcanics in southwestern Greenland. Nor are basal unconformities nor pre-lower greenstone sialic rocks known to occur within these geological systems.

(2) In contrast to the lower ultramafic-mafic assemblages, upper greenstone belts either have lower proportions of ultramafic to mafic material, (e.g. upper greenstones of the Kalgoorlie System) or consist of basalt-andesite-rhyolite cycles (e.g. Canadian greenstones). These later greenstones postdated the early sodic granites which intrude the lower volcanic belts. Major unconformities or discontinuities are invariably present between the lower and upper greenstones, signifying the termination of the oceanic crust stage and onset of basinal greenstone-belt evolution.

(3) A stratification of granitic rocks is suggested for the Yilgarn and eastern Kaapvaal cratons, with older sodic granites occurring at depth, and younger high-K granites at shallow crustal levels. Variations in metamorphic grade, geochemistry, and isotopic age between the low-grade granite-greenstone Kalgoorlie System, the Pilbara System, and the Wheat Belt gneiss-granulite terrain are explicable in terms of origin at different crustal depths. Changes in the geometry of the batholiths and the greenstone belts, in the width of contact aureoles, and in degree of penetrative deformation are probably related to the depth of emplacement and density of distribution of the early Na-rich granitic plutons.

(4) The evidence from Western Australia is consistent with a model of evolution starting with a primitive ultramafic-mafic oceanic crust which resulted from high degrees of melting in rising mantle diapirs. Sodic granites formed at about ca. 3 b.y. as a result of downbuckling and subduction of the oceanic crust, and K-rich granites formed at ca. 2.6 b.y. owing to metamorphism and anatexis of the early sodic granites. Data from India support this model, and the field evidence and isotopic ages reported from the Transvaal and from southwestern Greenland are shown to be consistent with the existence of an early basic crust in these areas.

(5) A vertical metamorphic gradient of about 45°C/km is calculated for the Yilgarn craton, and is tentatively regarded as a transient gradient associated with the 2.6 b.y. regional metamorphic event. Similar gradients may have existed during the ocean crust-forming stage and Na-granite forming stage. Application of this parameter to PT phase diagrams suggests that a zone of partial melting has existed in hydrated ($H_2O = 0.2\%$) mantle at depths of about 30 km, and that Na-rich acid melts could arise through partial melting of hydrated basic crust at depths of about 20 to 30 km.

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Figure captions

Fig. 1 - Geological sketch map of Archaean terrains in Western Australia (after the Tectonic Map of Australia, Geological Society of Australia, 1971). P - Perth; MU - Mundaring; A - Albany; S - Southern Cross; B - Boorabbin; K - Kalgoorlie; N - Norseman; L - Leonora; LA - Laverton; M - Meekatharra; W - Wiluna; PH - Port Hedland.

Fig. 2 - Simplified Bouguer anomaly map for the southwestern and western parts of Western Australia. Countour interval 20 mgl. (after Fraser, 1973). Place name abbreviations as for Fig. 1.

Fig. 3 - Seismic crustal structure and gravity profile between Perth, Boorabbin and Coolgardie, Yilgarn craton (after Mathur, 1973).

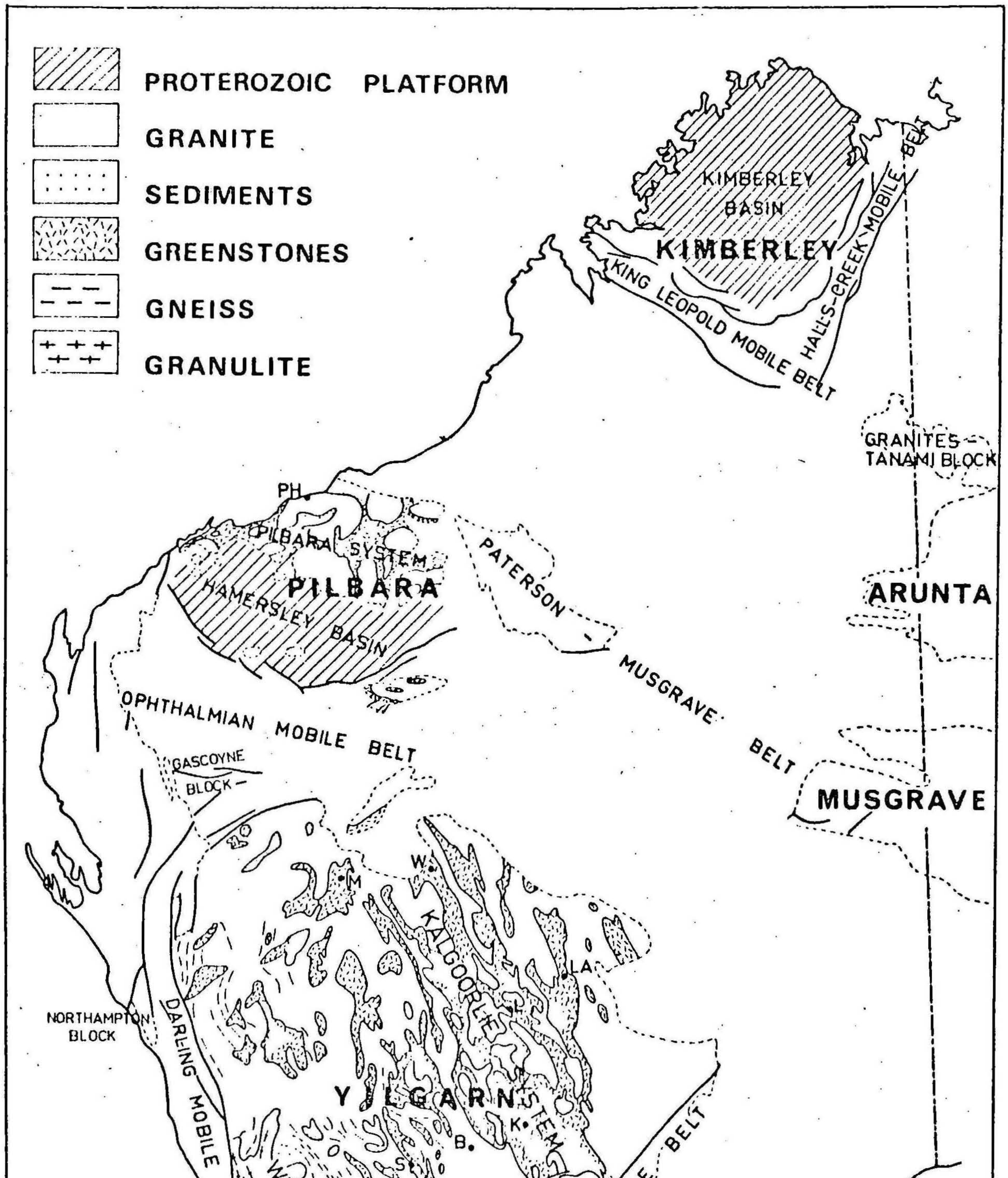
Fig. 4 - Heat production and calculated distribution (average) of Th, U and K in the Yilgarn craton, Western Australia (after Hyndman et al., 1968).

Fig. 5 - Frequency distribution of Rb in granites of different ages in the Yilgarn craton (based on data from Arriens, 1971).

Fig. 6 - A hypothetical cross-section across the Yilgarn craton. Surface geology after Wilson (1958) and interpolated. Seismic boundaries after Mathur (1973).

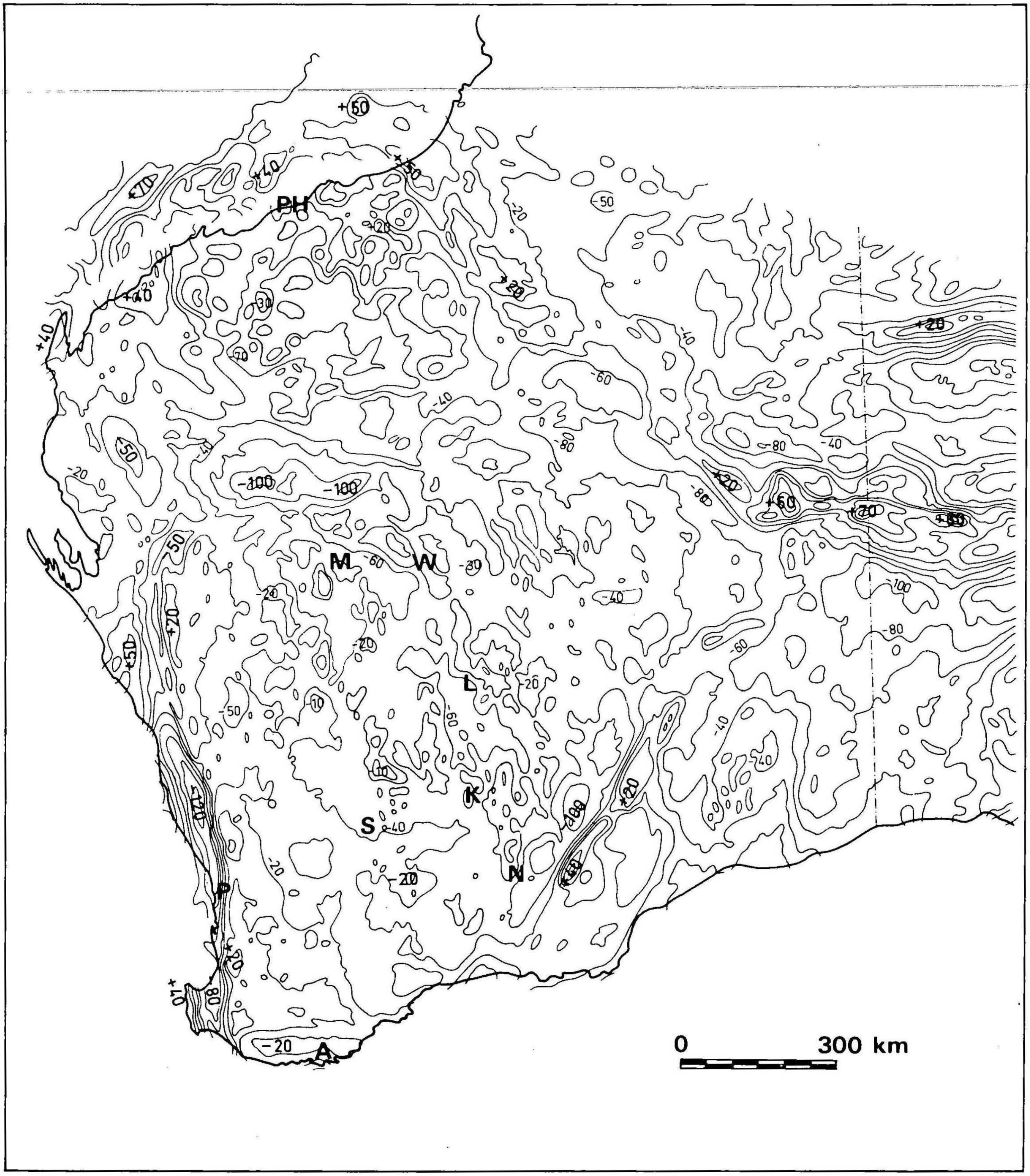
Fig. 7 - Relations between major rock units in the Yilgarn craton and relations between the structural levels of the Pilbara and Yilgarn cratons, as interpretaed in this paper. EG - early granites; LG - late granites; LU - lower ultra-mafic-mafic units; UU - upper ultramafic-mafic units; PS1 - lower porphyries and acid sediments; PS2 - upper porphyries and acid sediments; Ucg - upper conglomerate; un - unconfor-mity; GGU - gneiss, granulite and ultramafic-mafic enclaves.

Fig. 8 - Pressure-temperature diagram portraying the relations between a hypothetical Archaean geothermal gradient of 40 - 50°C/km and solidus curves for pyrolite (after Green, 1973) and olivine tholeiite (Lambert & Wyllie, 1972). Also shown are metamorphic facies boundaries after Turner (1968)



To accompany Record 1972/141

W/A 245


PH
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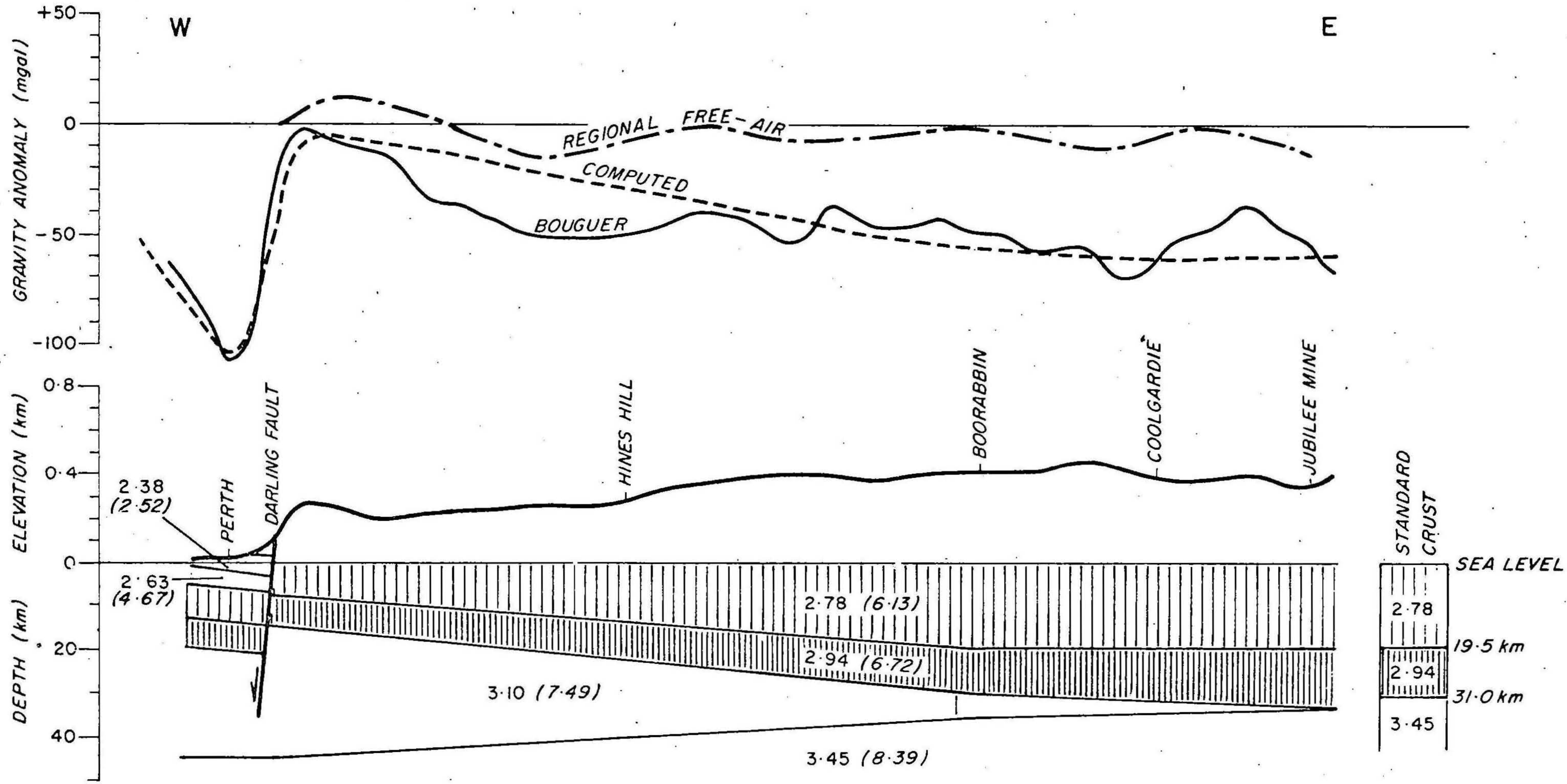
300 km

GEOTRAVERSE W.A.

Fig. 3



LEGEND

2·78 Density (g/cm³)

(6·13) Seismic velocity in formation (km/s)

GRAVITY PROFILES AND SEISMIC CRUSTAL STRUCTURE BETWEEN PERTH AND THE JUBILEE MINE

To accompany Record 1972/141

M(G) 268

Fig. 4

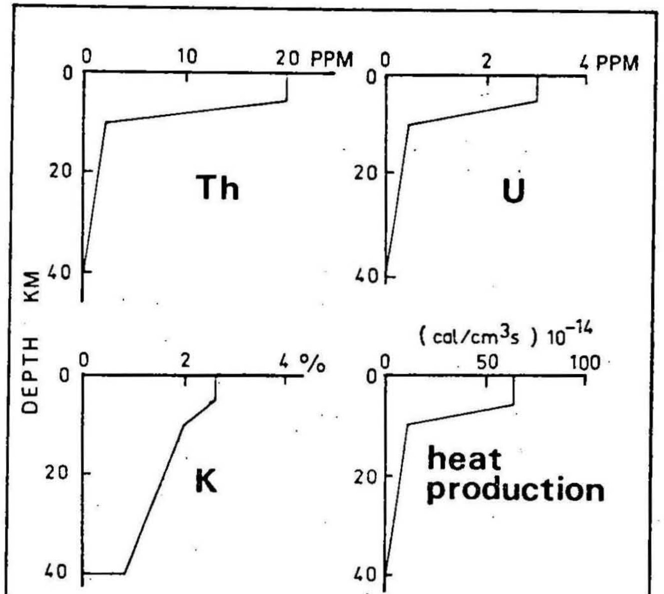


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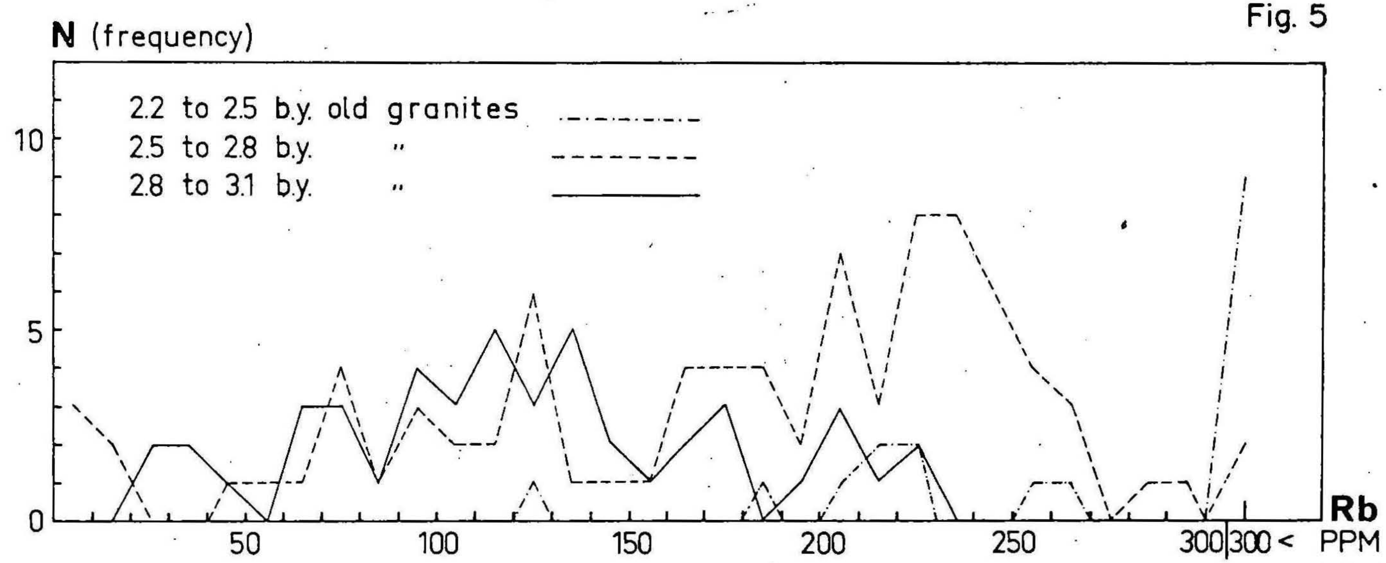
Fig. 5



To accompany Record 1972/141

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Fig. 6

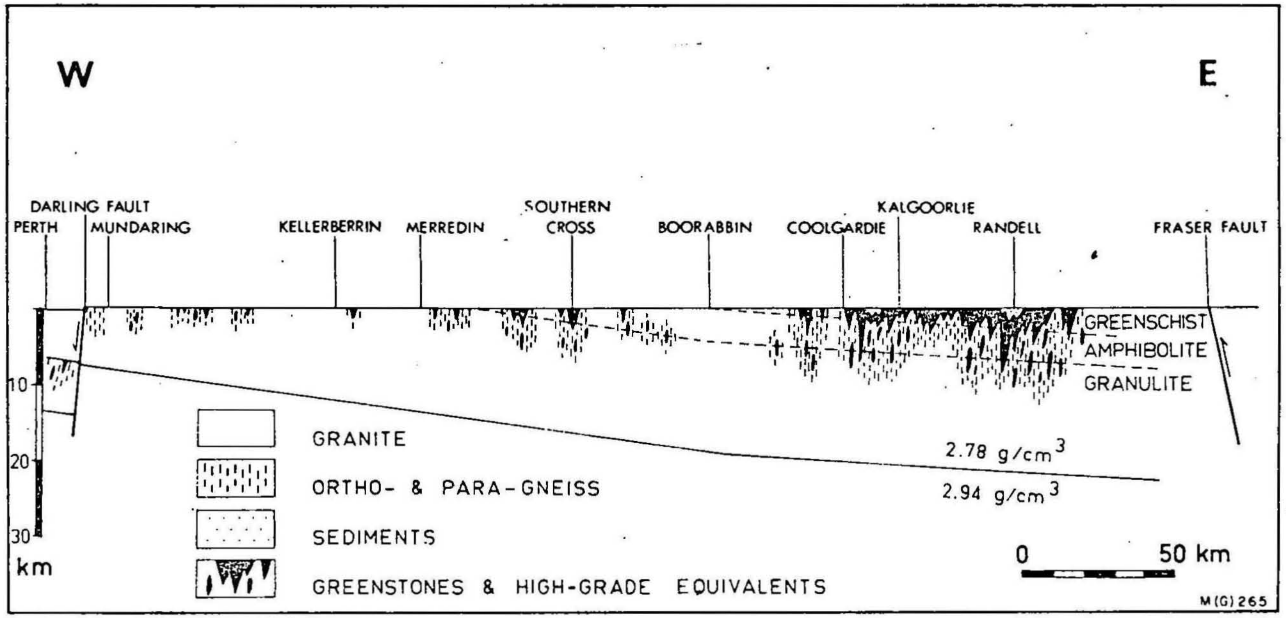

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Fig.7

ROCK UNITS RELATIONS ; YILGARN & PILBARA CRATONS

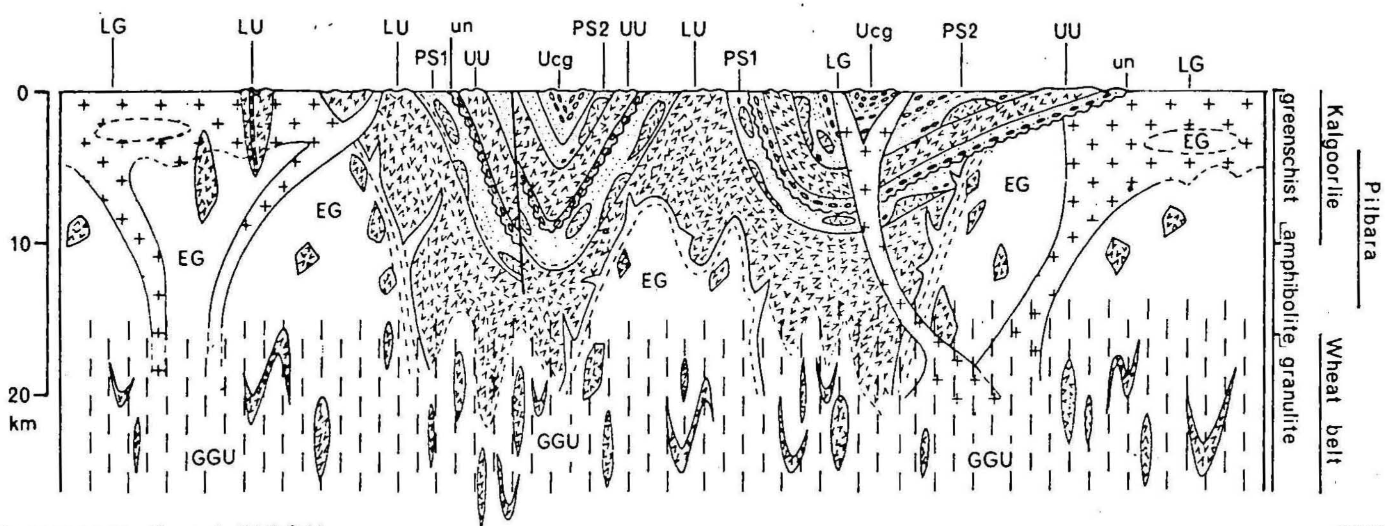

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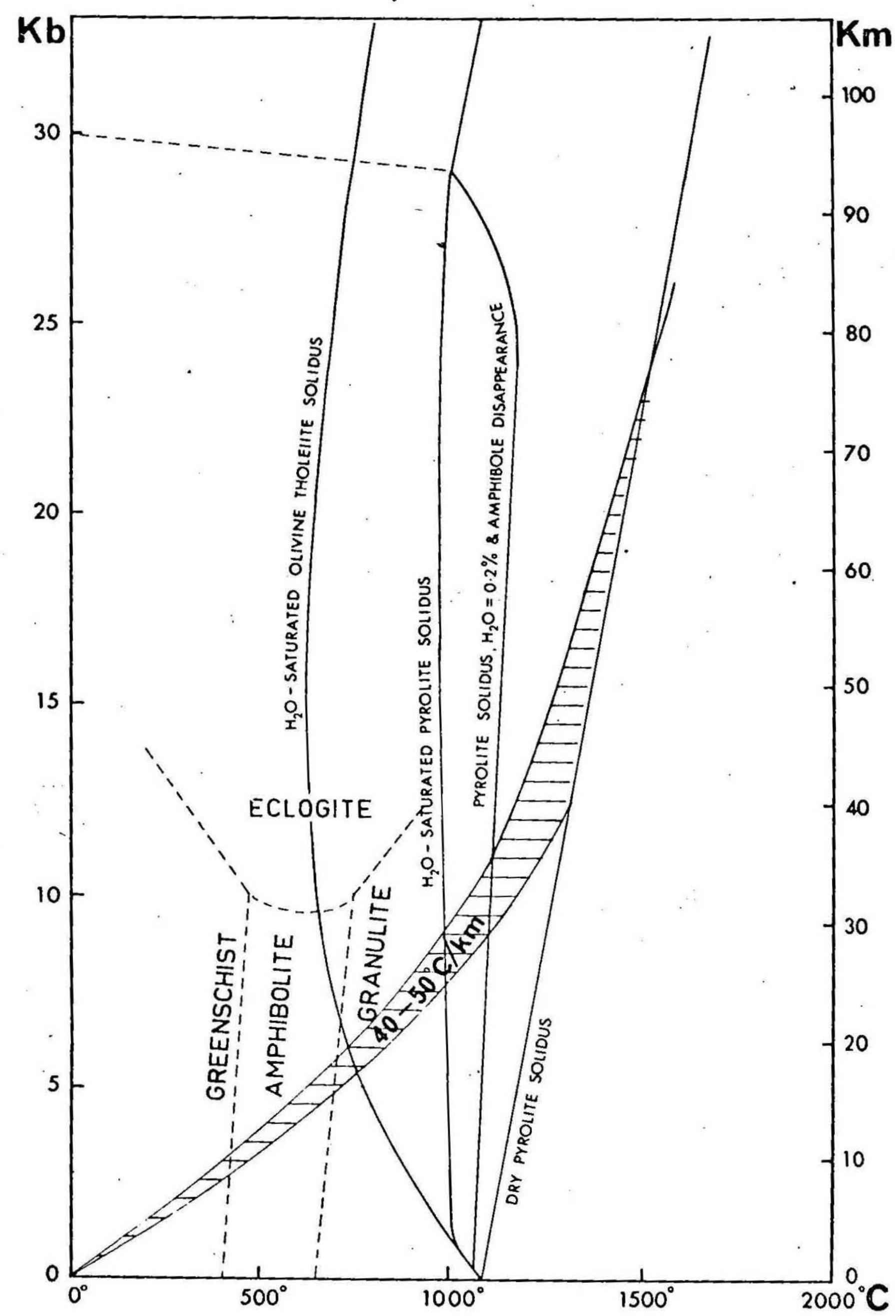
Fig. 8



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