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DEPARTMENT OF
MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD 1974/54

ARCHAEAN TO EARLY PROTEROZOIC SHIELD STRUCTURES: RELEVANCE OF PLATE TECTONICS

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ABSTRACT

It is suggested that an interpretation of early Precambrian history in terms of small-scale plate tectonics and shield growth in-situ is more consistent with present evidence than a uniformitarian projection of modern large-scale plate tectonics. Greenstone belts are regarded as ensimatic arc-trench type structures founded on oceanic crust; however, a correlation with circum-Pacific or Alpine domains juxtaposed with continent-ocean interfaces is considered unlikely, and there is no evidence for large-scale continents before about 2.6 b.y. ago. The nucleation of early granites is interpreted in terms of active cycling and partial melting of oceanic crust by means of subduction and/or downbuckling about small-scale cells. Remnants of this crust are believed to be represented by the lower ultramafic-mafic units of greenstone belts in Western Australia, Transvaal and Rhodesia. An upper, tholeiitic to calc-alkaline, volcanic assemblage erupted during and after the nucleation of the early sodic granites. The lower greenstones of pre-granite age and the upper greenstones of syn- to post-granite age are separated by major unconformities. Widely scattered nucleation of protocontinents - each limited by the scale of the corresponding plate and cycling cell - are believed to have taken place. The distribution of early granites and greenstone belts was controlled by early linear structures of the oceanic crust. The diapiric granites and arcuate greenstone belts of the Rhodesian and Pilbara cratons reflect the exposure of crustal levels deeper than those of linear granite-greenstone systems. A still deeper crustal level is represented by Archaean gneiss-granulite suites. The parallel orientation of Archaean trends in North America, South Africa, India and Australia on a Gondwanaland reconstruction may imply that the agglomeration of a Proterozoic megacontinent took place in situ, rather than by long range drift. Palaeomagnetic data render long range drift of some crustal segments in the early Proterozoic unlikely. An ensialic origin of at least some Proterozoic mobile belts, possibly according to a rift valley or aulacogene model is favoured. Evidence for the existence of oceanic crust in the Proterozoic is scarce. Clifford's concept of a secular growth in the size of stable crustal cells is upheld. Modern plate tectonic patterns are to a major extent inherited from Proterozoic patterns.

(1) INTRODUCTION

A search for manifestations of plate tectonic processes in the Precambrian is a logical extension of modern continental drift theories. Palaeomagnetic data suggest that independent drift of continent-size plates occurred in the Late Precambrian (e.g., Spall, 1972; 1973). On the other hand, there is good palaeomagnetic evidence suggesting that individual cratons in Africa and Australia have maintained constant relative positions, and that a supercontinent encompassing Africa, South America and North America could have existed before about 1000 m.y., and possibly as far back as 2200 m.y. (McElhinny et al., 1968; Piper et al., 1973).

Few palaeomagnetic pole data have been recorded in Archaean terrains, where metamorphism and strong deformation render such measurements difficult. Pending further palaeomagnetic work therefore, geological considerations are the only means by which the plausibility of plate tectonics for the isotopically recorded range of 3.8 - 2.5 b.y. can be examined. In the bid to correlate Precambrian features with elements of modern plate boundaries references have been made to a variety of features, including faults, shears, elongated intrusions, volcanic belts, metamorphic isograds, geochemical variations, magnetic lineaments, and gravity anomalies (see Gibb & Walcott, 1971; Katz, 1972; Condie, 1972; Thorpe, 1972; Davidson, 1973; Chase & Gilmer, 1973). The assumption of a plate tectonics model is also implicit in uniformitarian extrapolations to the Precambrian of Mesozoic-Cainozoic tectonic regimes, such as Alpine geosynclines, arc-trench systems, and cordillera systems (see Engel & Engel, 1964; Wilson et al., 1965; Glikson, 1970; White et al., 1971; Hoffman, 1973). In testing the uniformitarian assumption, however, Precambrian geologists were equally impressed by what were shown to be fundamental differences between modern tectonic domains and their assumed Precambrian analogues (see Engel, 1968; Viljoen & Viljoen, 1969a; Anhaeusser et al., 1969; Clifford, 1970; Glikson, 1971, 1972; Engel & Kelm, 1972; Mason, 1973; Fyfe, 1973a; b; Glikson & Lambert, 1973).

The possible role of plate tectonics during the Early Precambrian cannot be meaningfully considered in isolation from a discussion of such fundamental questions as the origin and nature of the primitive crust, the genesis of early granites, the evolution of greenstone belts, crustal metamorphic zonation, the relationships between low- and high-grade Archaean cratons, granite-granulite relations, the cyclicity of tectonic and thermal events, and the secular chemical evolution of the crust. In this paper I will attempt to appraise possible evidence for plate tectonic processes in the Archaean* and the earliest Proterozoic**, and to discuss their significance in terms of some of the above-listed questions. This discussion leads to a tentative hypothesis of a global system of co-axial small crustal cycling*** cells in the Archaean.

(2) NATURE AND ZONATION OF THE PRIMITIVE ARCHAEAN CRUST.

An elucidation of the sequence of events inherent in the evolution of greenstone belts and protocontinents must precede and places constraints on any discussion of Archaean plate tectonics. The starting point for many models has been an assumed sialic crust (e.g. MacGregor, 1951; Ramberg, 1964; Goodwin and Ridler, 1970; Sutton, 1971; Windley and Bridgwater, 1971; Windley, 1973), presumably accreted upon the cooling of the outer shell of the Earth. Others postulated a primitive sima from which acid rocks were derived through either exogenic processes (Wilson, 1959) or downbuckling and/or subduction (Glikson, 1970; Hart et al., 1970; Anhaeusser, 1973; Glikson & Lambert, 1973). According to the latter school of thought, no sialic basement existed beneath the lower ultramafic-mafic units of Archaean greenstone belts in the Transvaal, Rhodesia, and Western Australia. Instead, these units are regarded as remnants of a once extensive crust which predated the nucleation of granites. Isotopic age data show that the formation of granites has not been simultaneous in different regions of the Archaean globe, with the exception of a major global event about 2.6 b.y. ago (see below). An emplacement of early Na-granites into the ultramafic-mafic crust was accompanied and followed by tholeiitic, calc-alkaline and minor ultramafic volcanism, with the result that in some

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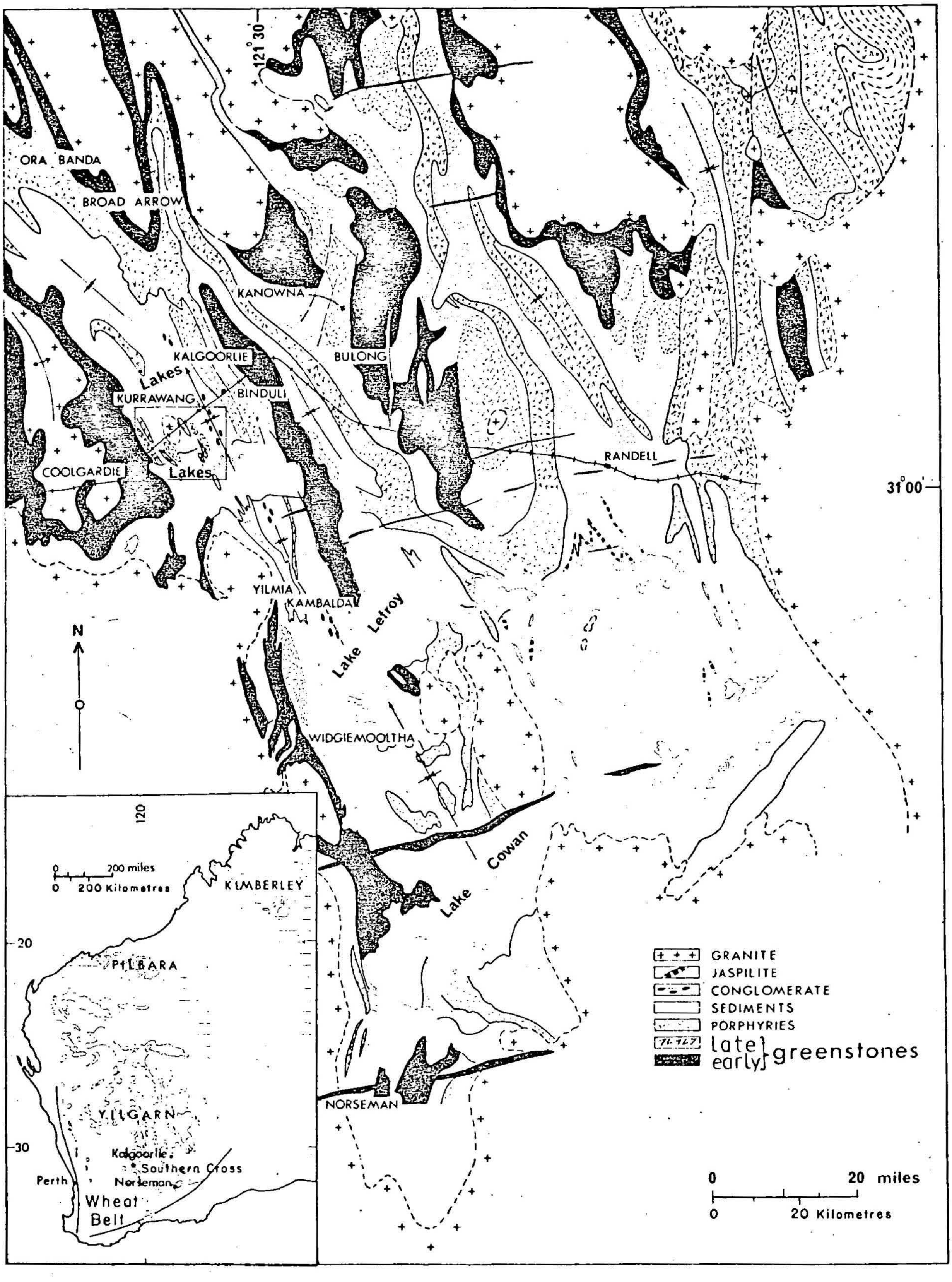
* Referring to the eon preceding 2.6 b.y. ago

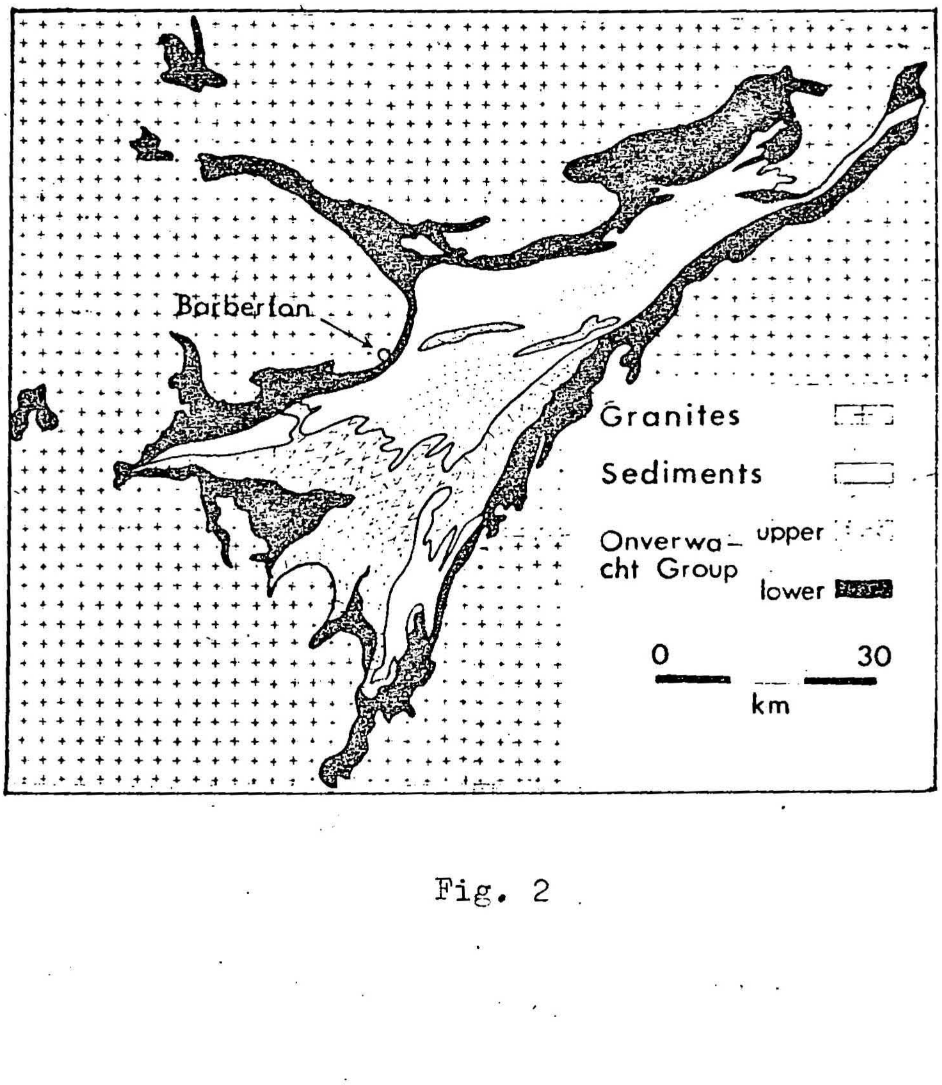
** Referring to the time span 2.6 - 1.8 b.y. ago.

*** The term crustal cycling is preferred to the term convection, as the question of the existence of mantle convection is outside the scope of this paper.



121°30'
ORA BANDA
BROAD ARROW
KANOWNA
KALGOORLIE
BULONG
Lakes
KURRAWANG
BINDULI
COOLGARDIE
Lakes
RANDELL
31°00'
YILMIA
KAMBALDA
Lake Lefroy
N
WIDGIEMOOLTHA
Lake Cowan
NORSEMAN
GRANITE
JASPILITE
CONGLOMERATE
SEDIMENTS
PORPHYRIES
late
early
greenstones
0 20 miles
0 20 Kilometres
120
0 200 miles
0 200 Kilometres
KIMBERLEY
20
PILBARA
YILGARN
30
Kalgoorlie
Southern Cross
Norseman
Perth
Wheat Belt

Fig. 1


Barberton
Granites
Sediments
Onverwa-
cht Group
upper
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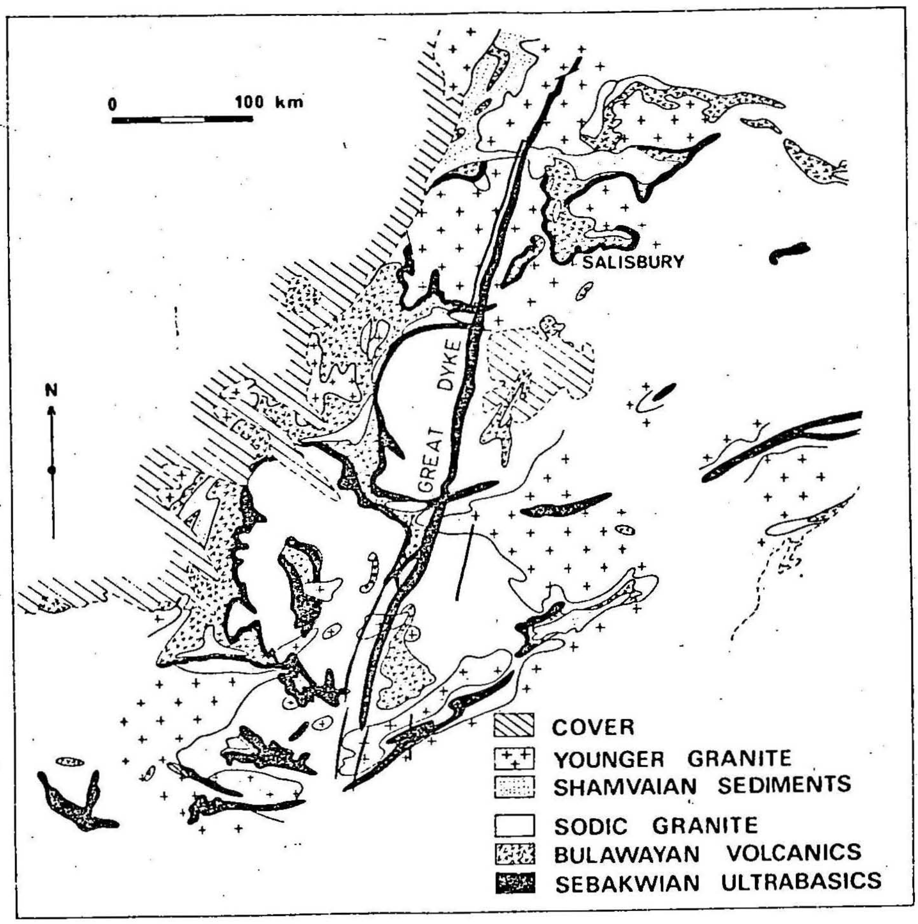
0
30
km

Fig. 2


0
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N
SALISBURY
GREAT DYKE
COVER
YOUNGER GRANITE
SHAMVAIAN SEDIMENTS
SODIC GRANITE
BULAWAYAN VOLCANICS
SEBAKWIAN ULTRABASICS

Fig. 3

Table 1 - Tentative classification of sedimentary and igneous stages and rock units* from Archaean terrains in Africa, India Australia, Canada, and Greenland, in terms of evolutionary stages suggested in this paper (see also Glikson 1972). The major assemblages of Viti-Levu, Fijian Archipelago, are listed for comparison

Stage	Principal Characteristics	Swaziland Systems eastern Transvaal	'Ancient Gneiss Complex' and other units in Swaziland	Rhodesia	Southern India	Kalgoorlie System, Yilgarn craton	Wheat Belt Yilgarn craton	Pilbara System	Southwestern Greenland	Superior Province	Slave Province	Viti Levu, Fiji
Earliest Proterozoic volcanism and deposition	Craton-wide; sandstone conglomerate, jaspilite, siltstone, continental basic and acid volcanics	Witwatersrand System: Dominion Reef F. ca 2600 m.y.		Piriwiri Lomagundi, Deweras 1950-1600 m.y.	Kaladgi Group (equated with the Cuddapah Group) ca 1500 m.y.		Cardup, Moora and Badgeradda Groups, and Billeranga Beds	WylooGroup Hamersley Group Fortescue Group		Huronian sediments	Aphebian Cover	
Basic dykes	Basaltic to doleritic dykes, noritic dykes, occasionally highly banded and layered	Basaltic to doleritic some parallel to the fold axes		Great Rhodesian Dyke		Widgiemooltha dyke suite ca 2400 m.y. at high angles to fold axes			Ameralik dykes			
K-granites	Granite, adamellite, granodiorite, pegmatites	Hood Granite, Nelspruit migmatite ca 3000 m.y.		2700-2600 m.y. 2900 m.y.	Peninsular gneiss ca 2600 m.y. ?Closepet Granite ?Chitradurga Granite	Mungari Granite 2615 ± 15 m.y.	Rb-normal granitic gneisses. 2700-2550 m.y.	Moolyella Granite 2670 ± 95 m.y.	Amitsoq Gneiss ca 3750 m.y.	Kenoran ca 2600 m.y.	K-granite 2575 ± 25 m.y.	
Molasse-type stage	Conglomerate, sandstone (cross bedded), greywacke minor acid and alkaline volcanics, chert.	Moodies Group Basal conglomerate derived from underlying units.				Kurrawang Beds basal unconformity in places						
Turbidite Stage	Greywacke, feldspathic sandstone, siltstone, acid volcanic and pyroclastic rocks, chert, jaspilite	Fig Tree Group	Pongola System	Shamvaian Group	Dharwar sediments and acid volcanics	Mungari Beds, Association 4 (Kurnalpi Sheet)		Mosquito Creek Succession		Timiskaning	Yellowknife Super-group	
Late greenstones (island-arc-type)	Calc-alkaline basalt-andesite-rhyolite cycles, tholeiite-rhyolite cycles, minor ultramafics	Onverwacht Group, upper part: Hooggenoeg F, Kromberg F., Swartkoppie F.,		Bulawayan	Dharwar greenstones	At Red Lakes, Yilmia, Association 3 (Kurnalpi Sheet) Mulgabbie Formation			Isua greenstones 3750 m.y. possibly also Malene Supracrustals	Keewatin, Abitibi, Cross Lake Group		Late Miocene-Pliocene calc-alkaline volcanics: mainly andesite granite-derived sediments
Unconformities	Angular unconformities, paraconformities	Middle Marker, Carbonate, acid volcanics and chert. 3375 ± 20 m.y.		Basal Bulawayan unconformity, overlain by conglomerate with granite pebbles	Unconformity	At Jones Creek, Mungari, Mount Monger, and other places		Unconformity at the base of the Mosquito Creek Sequence	?Possibly reflected by granite clasts inthe Isua sequence	Inferred from the occurrence of granite pebbles	Inferred from granite clasts in the Yellowknife Group	major unconformity
Na-granites	Tonalite, trondhjemite, granodiorite, porphyries	'Ancient tonalites' ca 3400-3200 m.y.	tonalite gneiss ca 3340 m.y.	'Gregarious batholiths' ca 3300 m.y.	?Champion Gneiss and metamorphism ca 2800 m.y.	Sodic granite intruded into the Kambalda greenstones 2900 ± 250 m.y.	Rb-low granitic gneisses 3100-2900 m.y.	Plagioclase-high granites 3125 ± 366 m.y.	?	Granodiorite	Granodiorite 2640-2610 m.y.	quartz tonalite, olivine gabbro 10 m.y.

Stage	Principal Characteristics	Swaziland System eastern Transvaal	'Ancient Gneiss Complex' and other units in Swaziland	Rhodesia	Southern India	Kalgoorlie System, Yilgarn craton	Wheat Belt Yilgarn craton	Pilbara System	Southwestern Greenland	Superior Province	Slave Province	Viti Levu, Fiji
Early greenstones (oceanic-type)	Ultramafic to mafic volcanic and hypabyssal rocks, chert, jaspilite, pelitic sediments, minor acid volcanics	Onverwacht Group, lower part: Sandspruit F. Theespruit F. Komati F.	amphibolites	Sebakwian Group	Ultramafic volcanic enclaves in gneiss of the Dharwar dome	At Coolgardie, Kalgoorlie, Ora Banda, Bulong; Association 1 (Kurnalpi Sheet) 'western greenstones' (Jones Creek) 2900 m.y.	Basic granulite enclaves in gneiss	Warrawoona succession	?	?	?	Upper Eocene-Middle Miocene; Oceanic tholeiite, intermediate to acid volcanics, pelagic sediments

* This is <u>not</u> a stratigraphic correlation chart

Principal references:- South Arica: Anhaeusser, 1973; Hunter, 1970; Rhodesia: Bliff and Stidolph, 1969; India: Sarkar, 1972;
Western Australia: Arriens, 1971; Turek and Compston, 1971; DeLaeter and Blockley, 1972; Prider, 1965; Williams, 1968
Greenland: Bridgwater et al., 1973. Canada: Goldich, 1968; Green and Baadsgaard, 1971.
Fiji: Gill, 1970

areas these volcanics unconformably overlie granites. A distinction is thus made between lower greenstones and upper greenstones, respectively corresponding to the pre-granite ultramafic-mafic units and the syn- to post-granite volcanic sequences (Table 1, Figs. 1, 2, 3). The two sequences are separated by major unconformities believed to reflect movements related to the emplacement of the early Na-granites.

A classification of elements of Archaean systems in the Transvaal, Swaziland, Rhodesia, India, Western Australia, Canada, and Greenland according to the proposed model is attempted in Table 1. A diagrammatic representation of Archaean shield evolution is attempted in Fig. 5. It is pertinent to summarize here the principal lines of evidence which suggest that a primitive ultramafic-mafic oceanic-type crust existed before granites appeared:

(1) No sialic basement is known to occur beneath the lower ultramafic-mafic units in Western Australia, eastern Transvaal and Rhodesia.

(2) No sial-derived detritus is known to be associated with the lower greenstones, however, granite-derived sediments abound as intercalations in the upper greenstones.

(3) Early Na-granites in the greenstone belts commonly contain ultramafic and mafic inclusions, whereas the lower greenstones do not contain sialic inclusions.

(4) The youngest age limits for the lower greenstones are defined by the oldest intrusive granites, however, because of metamorphic resetting of the isotopic ratios no older age limits have been placed on these rocks by geochronological studies.

(5) Experimental petrology shows that acid sodic melts cannot form by direct partial melting of mantle peridotite, even under high H_2O partial pressures (Nicholls & Ringwood, 1972; Green, 1973), but can be produced by partial melting of basic rocks. Derivation of acid melts by fractional crystallization of basic magma is considered unlikely to have been responsible for the formation of the large Archaean plutons, because of the relatively small volumes of acid liquid produced in this manner*. It follows that basic rocks must have been common before the appearance of granites.

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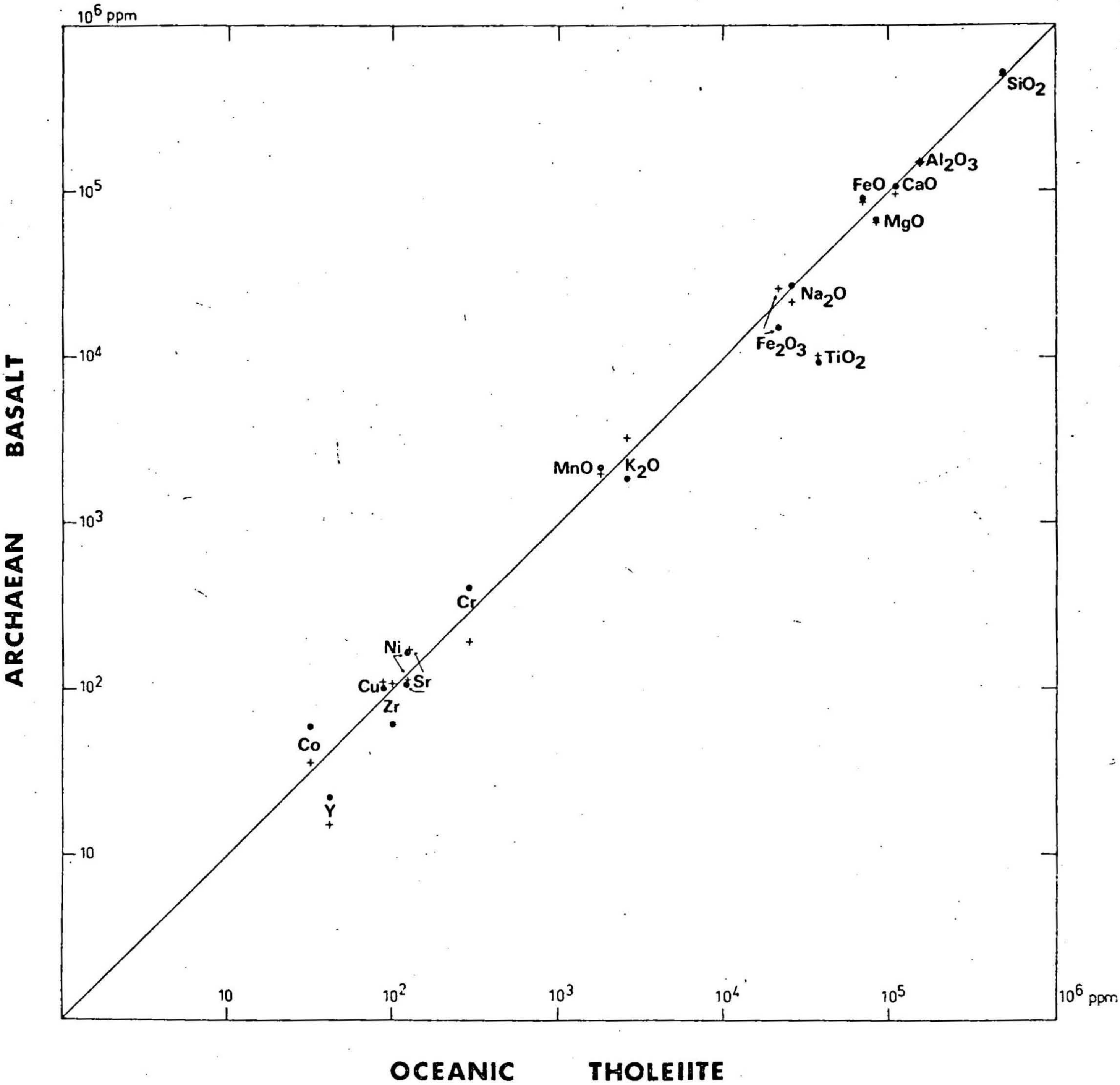
* Fractional crystallization is possible, however, in connection with acid volcanic piles which overlie individual greenstone cycles.

(6) Both the <u>lower</u> and the <u>upper greenstones</u> contain metabasalts whose chemical characteristics are in most respects compatible with modern ocean-floor tholeiites (Glikson, 1970, 1971, 1972; Hallberg, 1972) (Fig. 4). Such rocks are rare in Proterozoic and Phanerozoic continental domains**.

Two principal objections have been raised against the postulated existence of a primitive oceanic crust in the Archaean. The first is based on the occurrence of some granites unconformably beneath greenstones in Rhodesia (Bliss and Stidolph, 1969), Canada (McGlynn and Henderson, 1970; Bell, 1971; Baragar, 1972; F.J. Elbers, pers. comm., 1973) and Western Australia (Durney, 1972), as well as the occurrence of cross-bedded quartzites at the base of greenstone sequences in India (Srinivasan and Srinivas, 1972) and in Manitoba (F.J. Elbers, pers.comm., 1973). The second objection refers to the relatively older ages of some high-grade Archaean terrains as compared to ages recorded in low-grade granite-greenstone terrains, particularly the very old ages of granitic gneisses in southwestern Greenland Minnesota (Windley, 1973) and the eastern Labrador coast (K.D. Collerson, pers. comm., 1974).

The first objection is apparently founded on the assumption that within each particular terrain the greenstones represent an essentially continuous volcanic sequence. However, as suggested above two major volcanic cycles can be recognized, representing oceanic-type and island-arc-type volcanism respectively. Such relationships are well established in the Kaapvaal, Rhodesian, and Yilgarn cratons (Table 1). In southern India possible pre-Dharwar <u>lower greenstones</u> are represented by occasionally-pillowed ultramafic and mafic enclaves in the Dharwar gneiss dome (R. Srinivasan, pers. comm., 1972). No pre-Keewatin volcanic rocks have been yet proven to exist in the Canadian Shield; however, the possibility that such rocks occur cannot be excluded. A recent report on ultramafic and mafic inclusions in quartz diorites in the Sachigo and Berens River areas of the northwestern part of the Superior Province may furnish a clue in this regard (Ermanovics, 1974).

** Low-K tholeiitic basalts of post-basement age are known in some Proterozoic terrains, including the Labrador trough, eastern Greenland and northwestern Queensland.



10^6 ppm
10^5
10^4
10^3
10^2
10
10
10^2
10^3
10^4
10^5
10^6 ppm
SiO_2
Al_2O_3
FeO
CaO
MgO
Na_2O
Fe_2O_3
TiO_2
MnO
K_2O
Cr
Ni
Cu
Sr
Zr
Co
Y
ARCHAEAN BASALT
OCEANIC THOLEIITE

Fig. 4

As for the second objection: that high-grade metamorphic rocks occur in depth beneath low-grade granite-greenstone systems is evident from both geological and geophysical data. Thus, seismic data indicate that upper crustal layers of the Yilgarn craton are tilted eastward (Mathur, 1973; Glikson & Lambert, 1973). The Dharwar synclinoria in southern India plunge at low angles northward (Pichamuthu, 1967), and the Superior Province is probably tiled eastward (Bell, 1971). The eastern Transvaal (Kaapvaal) shield may be tilted westward. In each case, high-grade metamorphic rocks crop out towards the uptilted and more deeply eroded structural level. However, instead of interpreting these features in terms of basement-cover relationships between an early sial and greenstones, it is suggested here that the high-grade rocks represent exposed coeval roots of low-grade granite-greenstone suites. Thus the transitions between the low- and high-grade Archaean terrains in Western Australia, India and Canada are continuous. Moreover, isotopic age data from several Archaean cratons can be interpreted in terms of simultaneous episodes in their low- and high-grade sectors. Thus, 2.9 - 3.1 b.y. old and 2.6 - 2.7 b.y. old granites in Western Australia occur in the high-grade Wheat Belt terrain, the low-grade Pilbara system, and possibly also the Kalgoorlie System (Glikson & Sheraton, 1972; Glikson & Lambert, 1973). In South Africa, the 'ancient tonalites' of the Kaapvaal craton and the amphibolite-facies 'ancient gneiss complex' in Swaziland (Hunter, 1970), both yield ages of about 3.2 - 3.4 b.y. (see data in Anhaeusser, 1973). In Manitoba, the ages of the Laurentian granites which intrude Keewatin greenstones and of granulites of the Pikwitonei Province (Superior-Churchill boundary zone) centre on 2.6 b.y. (see data in Bell, 1971). In India, the age of supposed pre-Dharwar gneisses and granulites (3.0 - 2.8 b.y.) and of lower Dharwar metamorphism and plutonism (ca 2.8 b.y., data from Sarkar, 1972) almost coincide.

The great antiquity of some granitic gneisses cannot by itself imply that they are older than the greenstones (see Black et al., 1971). This conclusion is clearly demonstrated by the recent discovery at Isua, southwestern Greenland, of a ca 3750 m.y. old sequence of mafic to ultramafic rocks, quartzites, carbonates, jaspilites and agglomerates (Moorbath et al., 1973b) intruded by gneisses correlated with the equally old Amitsoq Gneiss (Bridgwater et al., 1974). Because quartzites are abundant in this sequence, and as the intrusive Amitsoq Gneiss has a potassium content normal for calc-alkaline granites, the Isua rocks could perhaps be compared to <u>upper greenstones</u> as classified above.

If this inference is correct, and if the mode of Archaean evolution in Greenland was similar to that in low-grade granite-greenstone systems, still older greenstones may occur in this region. In this respect, it should be pointed out that the relationships between the Malene Supracrustals (mafic-ultramafic) and the Amitsoq Gneiss cannot be regarded as established on present evidence, and that these rocks could correspond to lower greenstones. The data from Greenland are thus not necessarily inconsistent with the primitive ultramafic-mafic crust theory.

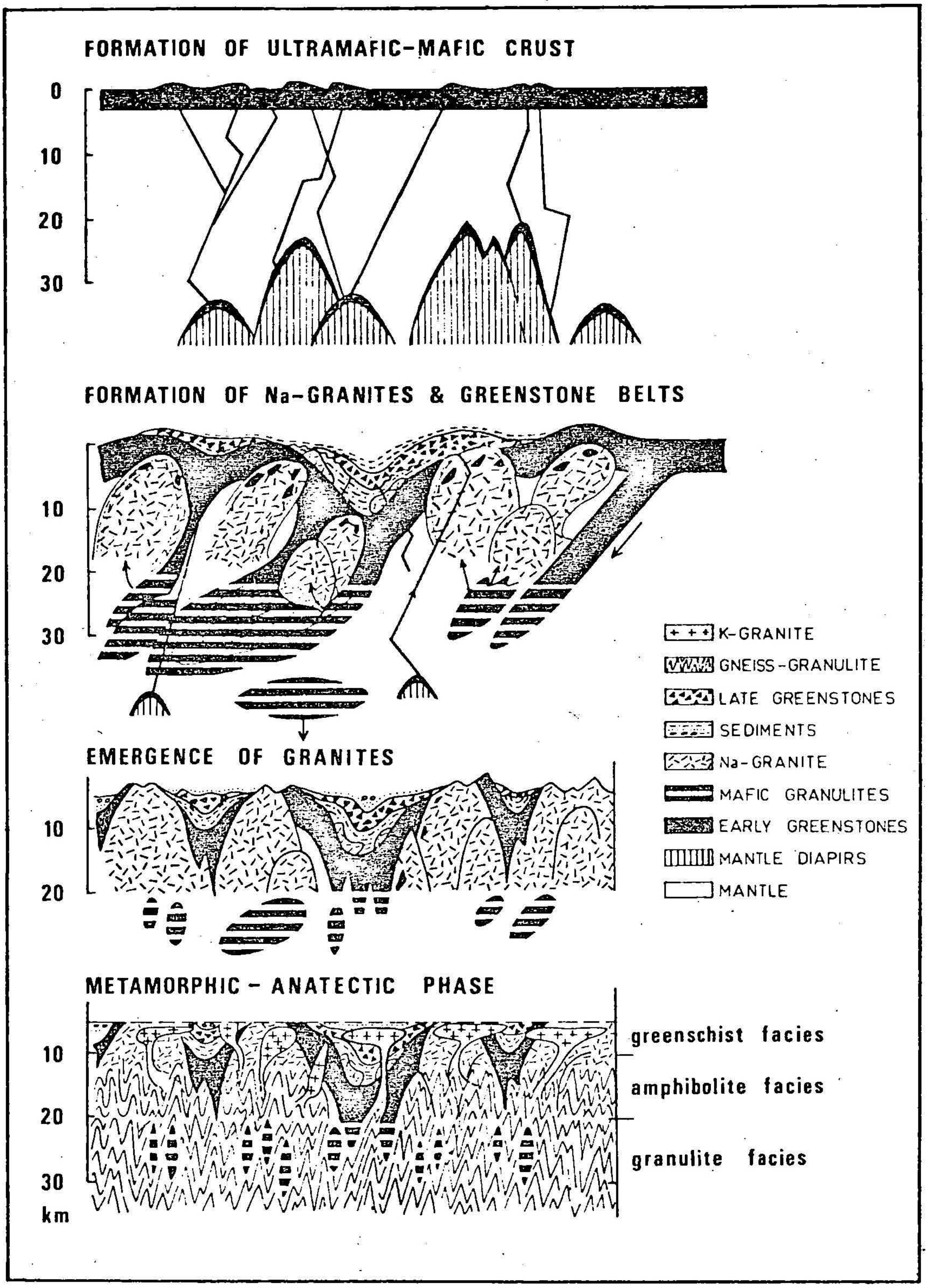
(3) PLATE TECTONICS AND THE ORIGIN OF CRATONS.

If it is accepted that, within each individual crustal ~~regions~~ region, the evolution of sial commenced with an oceanic-type crust, a consideration of plate tectonics can be made in two different senses:

(1) In terms of the origin and distribution of the early nuclei of Na-granite (this section)

(2) In terms of the interaction between simatic regions (? plates), regions characterized by different stages of cratonization, and sialic plates (section 4).

In considering the origin of granites in the Archaean, two principal observations are pertinent. Firstly, the oldest granites intruded into greenstone belts typically include tonalite, trondhjemite, granodiorite and diorite (Viljoen and Viljoen, 1969c; Glikson and Sheraton, 1972; Anhaeusser, 1971). Secondly, as pointed out above, the generation of large volumes of acid melts is likely to be the product of partial fusion of metamorphosed basic rocks, i.e., eclogite, basic granulite, or amphibolite. Derivation from amphibolite is favoured here, as the existence of large bodies of eclogite in the Archaean is inconsistent with a high geothermal gradient inferred by Fyfe (1973a,b) and Glikson and Lambert (in prep.). A lack of eclogite could explain the scarcity of andesites in the South African and Western Australian greenstone belts (see Hallberg, 1972), andesites being the first partial melting products of eclogite. On the other hand, andesites can also form by high degrees of partial melting of amphibolite. The abundance of andesites in Canadian greenstone belts (Baragar and Goodwin, 1969) could either be attributed to the latter process, or could imply formation of eclogite due to a decline in the geothermal gradient during the upper greenstones phase, with which the Canadian Keewatin greenstones may compare (Table 1).



FORMATION OF ULTRAMAFIC-MAFIC CRUST
0
10
20
30
FORMATION OF Na-GRANITES & GREENSTONE BELTS
10
20
30
K-GRANITE
GNEISS-GRANULITE
LATE GREENSTONES
SEDIMENTS
Na-GRANITE
MAFIC GRANULITES
EARLY GREENSTONES
MANTLE DIAPIRS
MANTLE
EMERGENCE OF GRANITES
10
20
METAMORPHIC - ANATECTIC PHASE
10
20
30
km
greenschist facies
amphibolite facies
granulite facies

Fig. 5

Implicit in such a process of granite formation is the downbuckling or subduction of a mafic crust which must be actively cycled to account for the very high ratio of granites to greenstones in Archaean cratons. Whether the oceanic crust subsided by means of subduction or downbuckling however, is open to different interpretations. Subduction and progressive melting of amphibolite should result in acid to andesitic melts - the latter being relatively rare in South Africa* and Western Australia (Hallberg, 1972). On the other hand, it is difficult to conceive downbuckling as an efficient mechanism inducing crustal circulation. Possibly subduction occurred, and the refractory residues of low degrees of partial fusion of amphibolite were not capable of yielding andesites under the prevailing conditions.

Talbot (1968) suggested that the unique small-scale spacing pattern of the oval 'gregarious Batholiths' in Rhodesia (Fig. 3) reflects a corresponding thermal convection system in the Archaean. This concept was also favoured by Fyfe (1973a, b), who related the short wave-lengths of pluton spacings to a shallow-level anatectic zone. Thus, a low-density viscous layer underlying a higher density viscous layer would give rise to diapirs whose spacing is a function of pressure differences in the source layer. Talbot and Fyfe related their model to the anatectic remobilization of a granitic basement supposedly underlying greenstones, following MacGregor (1951). As argued above, however, an assumption of a sialic basement cannot be justified in connection with granite-greenstone systems. Instead, if transient and very high geothermal gradients are assumed, segregation of relatively small volumes of acid magma could be consequent on low degrees of partial melting of basic rocks downbuckled or subducted to a depth of over 20 km (Glikson and Lambert, in prep.), giving rise to relatively small granite plutons.

The well pronounced parallel linear pattern of greenstone belts in the Superior Province, Slave Province, South India, Yilgarn craton (Fig. 1), and to a lesser extent Kaapvaal craton (Fig. 2), yields a vital clue for Archaean tectonic models. In these terrains, the long axes of the granitic plutons mostly parallel fold axes, major faults and metamorphic foliations

* However the tonalites of the Kaapvaal Shield can be classified as intermediate rocks, as SiO_2 values are as low as 60% (see Viljoen and Viljoen, 1969c).

within the greenstone belts, thus implying a genetic relationship between deformation, metamorphism, and plutonic activity. Thus, the downbuckling of linear synclinal troughs could result in partial melting along parallel infracrustal synclinal root zones. Furthermore, there is good evidence that the linear structures antedated the intrusion of granites. Thus, lateral flexures clearly related to granite emplacement are superposed on isoclinal folds coaxial with the greenstone belts (Anhaeusser et al., 1969; Glikson, 1971) (Figs. 1, 2). In some terrains this structural overprinting has all but obliterated possibly pre-existing linear structures, as in the Rhodesian (Fig.3) and Pilbara cratons. Characteristic of these two cratons is the arcuate form, narrowness and small size of the greenstone belts, and the high ratio of granite to greenstone, as compared to linear granite-greenstone terrains. The reported occurrence of high-grade rocks in some Rhodesian greenstone belts (Stowe, 1968), and the great width of assimilated aureoles around granites in the Pilbara craton (Noldart & Wyatt, 1961), suggests a deeper-seated origin than that of the Kaapvaal and Yilgarn cratons. In Western Australia this inference is supported by the occurrence of two greenstone cycles in the linear Kalgoorlie System, and preservation of only the lower cycle in the arcuate Laverton, Southern Cross and Pilbara granite-greenstone terrains (see Williams, 1973). The implication follows that "gregarious" (MacGregor, 1951) granite-greenstone patterns may reflect a relatively deep crustal level, where the tectonic pattern was controlled by granite intrusion. According to this interpretation, linear co-axial systems correspond to higher supracrustal levels where an axial stress field affecting the layered sequence resulted in more uniform deformation.

An analysis of global Archaean trends on a reconstructed Gondwanaland map was conducted by Dearnley (1966) and Engel and Kelm (1972) (Fig. 6). Dearnley obtained a linear pattern converging toward the Arctic and along the 30°N parallel, which he interpreted in terms of a global 2-cell convection system. Implicit in this model is a progressive continental accretion process presumably associated with major subduction zones. An interpretation consistent with this possibility was developed by Talbot (1973), who conceived a concomitant development of meridional island arc chains, subsequently accreted into a supercontinent. However, no isotopic age data consistent with lateral accretion are at hand, nor is there evidence for an existence of major continents in the Archaean - the oldest extensive platform-cover deposits being those of the 2600 m.y. old Witwatersrand System. Though future geochronological work may

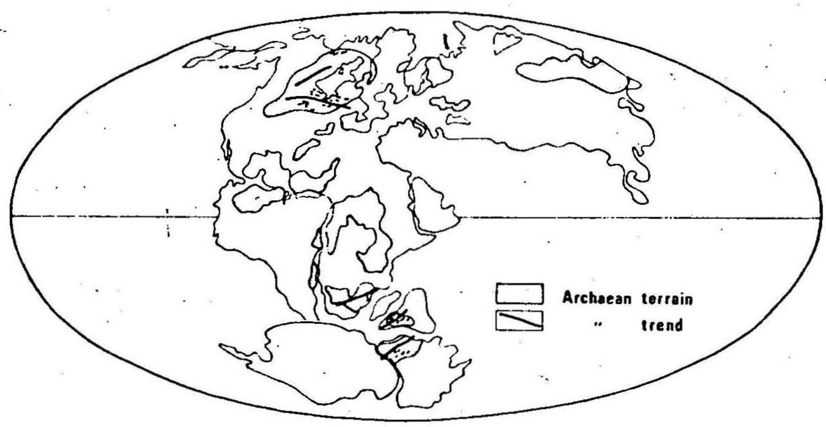


Fig. 6

support lateral age variations across greenstone belts, the present data can be equally well interpreted in terms of ~~a~~ broadly simultaneous cratonization episodes on a shield-wide scale. Thus, the 2.6 b.y. old Kenoran event is recorded over most of the Canadian Archaean shield (e.g., Goldich, 1968; Green and Baadsgaard, 1971). A 3.4 - 3.2 b.y. old granite phase affected most the Kaapvaal and Rhodesian cratons, and 3.1 - 3.9 b.y. old and 2.8 - 2.6 b.y. old events are widespread in the Archaean terrains of Western Australia (Arriens, 1971; De Laeter and Blockley, 1973; Glikson and Sheraton, 1972). Admittedly these intervals are wide enough to conceal considerable lateral age zonations.

These considerations lead to a two-stage model of sial derivation (Ringwood and Green, 1966), whereby ensimatic arc-trench-like systems evolved over large tracts of linearly deformed or rippled oceanic crust (see also Hart et al., 1970; Talbot, 1973). It will be suggested later that these parallel trends may reflect a global system of multiple small-size cells of crustal cycling. Unlike Mesozoic-Cainozoic orogenic belts, the Archaean basins were not related to continent-ocean interfaces as is the circum-Pacific belt, or to intercontinental gaps as is the Alpine-Himalayan belt. This is implied by the lack of both geological and isotopic evidence for the existence of major sialic continents in the Archaean. However, the suggested model has an important analogy with intra-oceanic island arcs, in particular the Fijian archipelago, whose evolution shows a remarkable similarity to that of Archaean granite-greenstone systems (Table 1). Successive stage of evolution according to this model are portrayed in Fig. 5, which is based on petrogenetic considerations developed elsewhere (Glikson and Lambert, in prep).

(4) PLATE TECTONICS AND THE FORMATION OF A PROTEROZOIC SUPERCONTINENT

Age data from Archaean terrains indicate that, at any point in time within the isotopically recorded interval of 3.8 - 2.6 b.y., crustal regions in which different stages of cratonization were achieved co-existed simultaneously. Whereas the nature of the boundaries between Archaean proto-shields and oceanic crust is little understood, the lack of evidence for early sialic crust in the vicinity of greenstone belts suggests that such boundaries did not serve as sites of development of such belts. In searching for the contacts of distinct Archaean crustal plates, one possibility is that Proterozoic mobile belts represent the successors of such geosutures (see Mason, 1973). This view may be supported by the structural differences between granite-greenstone cratons which occur on either side of mobile belts. Examples of such pairs are the Kaapvaal and Rhodesian cratons, the Yilgarn and Pilbara cratons, and possibly the Brazilian and Guiana cratons. In each case the first craton is characterized by linear parallel structures and by a high greenstone/granite ratio, and the second craton by arcuate and smaller greenstone belts. Alternatively, however, these differences can be due to the erosion of the respective cratons to various crustal levels, as argued above. In the latter case, strong vertical movements between adjacent cratons must have occurred, presumably along the major boundary faults juxtaposed with the intervening mobile belts (see Mason, 1973; McConnell, 1972). According to this model cratonic drift and convergence are not necessarily implied by structural differences between adjacent cratons.

Major thermal events, which include intrusion of granite and regional metamorphism about 2.6 b.y. ago were recorded in Canada (e.g. Goldich, 1968; Green and Baadsgaard, 1971), India (e.g. Sarkar, 1972), eastern Transvaal (data cited in Anhaeusser, 1973), the North Atlantic Craton (data cited in Bridgwater et al., 1973), Western Australia (Arriens, 1971; Turek and Compston, 1971; De Laeter and Blockley, 1972) and other Archaean terrains. This phase clearly represents a thermal peak in several continents, which resulted in extensive metamorphic age resettings masking earlier events. Thus, the geochronological sequence in the Kalgoorlie greenstone belts of the Yilgarn craton is partly masked by a regional metamorphic event about 2675 m.y. ago (see Turek and Compston, 1971), which affected plutonic, volcanic and sedimentary rocks to various degrees. Younger granites postdating this metamorphism are typically high-level K-rich types, and are believed to be the product of anatexis of older sodic granites and high-grade roots of the Kalgoorlie greenstone belts (Glikson and Sheraton, 1972). Thus, notwithstanding doubts expressed regarding the significance of the 2.6 b.y. date for the definition of the Archaean-Proterozoic boundary (e.g., Rankama, 1971), the importance of this break in several continents is evident. This break was marked by two major developments: first, the termination of the era of greenstone belt evolution**, and secondly, the onset of deposition of continental sedimentary and volcanic blankets on a shield-wide scale.

** With the possible exception of late stages of the Dharwar belts, India.

Had extensive shields existed before ca 2.6 b.y. ago similar deposits should have been formed earlier. However, the only continental sediments known from the Archaean are represented by the uppermost units of greenstone belts, and have participated in the major tectonic movements which affected these belts. Examples are the Moodies Group, Sharmvaian Group, Timiskaming series, and Kurrawang Conglomerates (Table 1). It follows, therefore, that either large-scale continental environments did not exist in the Archaean, or that the continental deposits were completely eroded following major epeirogenesis about 2.6 b.y. ago. In the latter instance, a special reason must be adduced to explain why such units were nowhere retained within structural depressions. Perhaps a unique tectonic stability of Archaean protocontinents prevented extensive continental deposition. This problem remains as one of the major dilemmas of Archaean geology.

In view of the age difference between greenstone belts of geographically distinct Archaean terrains, the 2.6 b.y. old episode cannot be regarded as representing a simultaneous culmination of greenstone belt evolutionary cycles world-wide. Instead, it is suggested that the 2.6 b.y. old event was independent of and superposed on the cyclic evolution of the greenstone belts, resulting in continental conditions where the development of greenstone belt-type basins was no longer possible.

The question must now be asked whether the ca 2.6 b.y. old thermal episode signifies the convergence and fusion of distinct Archaean cratons into the Early Proterozoic supercontinent suggested by palaeomagnetic data (Piper et al., 1973). Only palaeomagnetic studies of rocks older than 2.6 b.y. can throw further light on this question. However, it is suggested that the parallel trends of greenstone belts in South Africa, India and Australia on a pre-drift Gondwanaland map (Fig. 6), renders long-range drift and rotation of individual Archaean cratons unlikely. Had individual Archaean cratons merged through drift and subsequent collisions, the parallel trends of greenstone belts world-wide would be difficult to understand, bearing in mind the antiquity of these trends. According to this line of evidence, the fusion of Archaean cratons into a Proterozoic supercontinent must have taken place in situ or through minor, short-range drift. The implication follows that the distribution of Archaean isotopic ages on the reconstructed Gondwanaland should be meaningful for the secular lateral migration of Archaean tectonic patterns. Many more isotopic age data are needed, however, before a clear pattern may emerge.

(5) A RIFT VALLEY MODEL FOR PROTEROZOIC MOBILE BELTS.

Large-scale fracturing and the intrusion of basic dyke swarms about 2.6 - 2.4 b.y. ago are known from Western Australia and Rhodesia, and similar dyke systems occur in the Pilbara and Kaapvaal cratons (Table 1). No obvious consistent relationships appear to exist between these dykes and axes of greenstone belts which they transect, nor between dyke orientations in different shields on a Gondwanaland reconstruction map. The major taphrogenic events which, as suggested below, are believed to have initiated the evolution of mobile belts, must have postdated the intrusion of dykes, as indicated by the truncation of the latter along mobile belts in Rhodesia (Great Rhodesian Dyke), South Africa and Western Australia. These dykes hold therefore much promise in unraveling, by means of future palaeomagnetic studies, the Early Proterozoic geotectonic pattern prior to the evolution of mobile belts.

McConnell (1972) emphasized the coincidence between rift structures and Precambrian mobile belts in eastern and southern Africa, and suggested that the long-term evolution of these taphrogenic features may reflect repeated high heat-flow events in the underlying mantle. The origin of major faults which define craton-mobile belt boundaries can in some cases be traced back to the Lower Proterozoic, as suggested for the Limpopo belt (Mason, 1973) and for some mobile belts in Western Australia (Glikson and Lambert, 1973). A further extension of this concept gives rise to an ensialic rift model as suggested by Windley (1973), which is capable of explaining the following features:

(1) The common occurrence of continental-type deposits, including cross-bedded quartzites, within mobile belts.
(2) The scarcity of deposits typical of modern oceanic, island-arc or cordillera environments, i.e. ophiolites, andesites, turbidites, and melange-type sediments.
(3) The abundance of high-K tholeiites in mobile belt sequences, implying continental-type volcanism (see Baragar, 1969; Glikson et al., in prep.)
(4) The major boundary faults and shear zones in mobile belts.
(5) There is some evidence that, like the east African rift valleys, the margins of cratons are uplifted or domed along mobile belt boundaries. Thus, partly reworked Archaean granulites crop out along the northern and southern flanks of the Limpopo belt (Mason, 1973), and though age data are insufficient to determine whether these rocks are confined to the mobile belt or also occur

in depth beneath the Rhodesian and Kaapvaal cratons, the gradual transitions between the granulites and these granite-greenstone terrains (Mason, 1973) favour the latter possibility. If this is correct, it would follow that both cratons are strongly uplifted along and tilted away from the Limpopo mobile belt. Likewise the Kaapvaal craton is tilted away from the Mozambique mobile belt. Further, as argued above, the Yilgarn and Superior Cratons are probably tilted away from the Darling and Pikwitonei high-grade belts, respectively.

(6) The occurrence of alkaline intrusions in the Limpopo, Grenville and other mobile belts in similarity to the occurrence of such rocks along modern rift valleys.

A rift valley model is capable of explaining the evolution of ensialic mobile belts in terms of a subsidence of downfaulted troughs and concomitant advection of subjacent mantle diapirs, in analogy with relationships demonstrated by geophysical surveys in the east African rift system (Baker et al., 1972). The ensuing metamorphism, anatexis, and palingenesis at the roots of the downfaulted supracrustal column accounts for acid igneous activity, whereas the subsequent ascent of mantle diapirs may be reflected by basic volcanism and dyke intrusion. This is the sequence of events in the Proterozoic terrain of northwestern Queensland, where acid volcanism precedes basic volcanism (Glikson et al., in prep.). Early faulting is believed to have taken place along the Proterozoic Mount Isa fault trough, regarded as an ensialic structure limited by major boundary faults. This was followed by acid volcanism and then by eruption of continental flood tholeiites. Subsequent vertical up-faulting may well result in patterns observed in Proterozoic belts in central Australia. For example,,in the Arunta Complex, major faults separate parallel belts which are characterized by different grades of metamorphism, different ratios of metamorphic rock to granite, and different ratios of basic to acid igneous rocks. Some of these faults were shown to be at least 1070 m.y. old (Marjoribanks and Black, 1974). In both examples an ensialic rift model can explain a number of observations. In the present state of knowledge, however, the rift model must remain tentative.

(6) SECULAR CHANGES IN PLATE TECTONIC PATTERNS

The preceding discussion can be summarized in the following hypothesis for the origin of Archaean shields and Proterozoic continents:

(1) The primitive Archaean crust consisted of an ultramafic-mafic volcanic assemblage represented by the lower greenstones, and including tholeiites analogous in most respects to modern ocean-floor tholeiites.

(2) The development of subduction and/or downbuckling, controlled by early linear trends, gave rise to sodic granites and to tholeiitic to calc-alkaline upper greenstones, forming protocontinental granite-greenstone shields.

(3) The aggregation of the protocontinents into a major Proterozoic continent probably coincided with the major thermal event about 2.6 b.y. ago, and possibly involved little continental drift.

(4) Precambrian ensialic mobile belt systems could have evolved from circum-cratonic rift-valley-systems. Probably no large-scale relative drift of individual cratons has taken place during the Lower and Middle Proterozoic.

The geological evidence, augmented from about 2200 m.y. ago by palaeomagnetic data, therefore suggests that, until about 2.6 b.y. ago, geological processes took place within ensimatic to partly cratonized environment, whereas in the Proterozoic the focus of activity shifted to ensialic environments. Little or no evidence is at hand regarding the nature and evolution of ensimatic domains or sial-sima boundaries in the Proterozoic. Had oceanic regimes been widespread during this eon, it is difficult to understand why clear relics of such systems have not been recognized at the margins of Proterozoic sial shields, and why greenstone belts are unknown after about 2.6 b.y. ago. The scarcity of evidence for oceanic crust in the Proterozoic would clearly suit proponents of the expanding Earth hypothesis (e.g. Carey, 1958; Heezen, 1960; Wilson, 1960). However, further studies of possible marginal mobile belts are needed to throw light on this problem.

It has been suggested that some mobile belts ~~in Canada~~, such as the Labrador trough (Dimroth et al., 1970) and the Coronation geosyncline (Hoffmann, 1973) in the Canadian Shield display analogies with Alpine-type systems, and represent Proterozoic continental margins. If this is correct, it would follow that there are 'mobile belts and mobile belts', and criteria for their separation from each other must be developed. These examples may furnish the first clue for Proterozoic oceanic crust, which however must await confirmation by further palaeomagnetic studies.

Clifford (1968, 1970), on the basis of a comparison between the sizes of African cratons and modern crustal plates, suggested that a secular increase had taken place in the size of convection cells (Fig.7). If the scale and geometry of Archaean granite-greenstone patterns reflect corresponding features of crustal cycling cells, then these cells were developed on an even smaller scale than those reflected by Proterozoic craton-mobile belt systems. An assumption of small-scale cells or plates in the Archaean is compatible with the following considerations:

(1) If the size of stable crustal cells increased between the Proterozoic and the Mesozoic (see Clifford, 1968), and assuming a secular irreversible change in the internal thermal regime of the Earth, it appears plausible that Archaean cell dimensions should have been even smaller than in the Proterozoic.

(2) If a higher geothermal gradient is assumed for the Archaean (e.g., Fyfe, 1973a, b; Windley, 1973; Glikson and Lambert, in prep.), a shallower level of the partial melting zone would apply. This should have resulted in a closer spacing of advecting mantle diapirs according to the calculations of Elssaser (1963) and Ramberg (1967).

(3) The evidence for cycling and subduction of a mafic crust on the one hand, and the lack of evidence for major continents in the Archaean on the other hand, can be reconciled if small crustal cycling cells are invoked. Such a pattern would result in numerous scattered centres of cratonization, rather than lateral accretion of a major continent by large-scale sea floor spreading (Fig. 7).

(4) As argued above, the parallel orientation of greenstone belts in Canada, South Africa, India and Australia on a Gondwanaland reconstruction renders an aggregation of the Proterozoic super-continent through drift unlikely. Small crustal cycling cells, and restriction of plate motions to areas overlying these cells, could explain this feature. According to this interpreation, about 2.6 b.y. ago subautochthonous fusion of neighbouring cratonized domains took place.

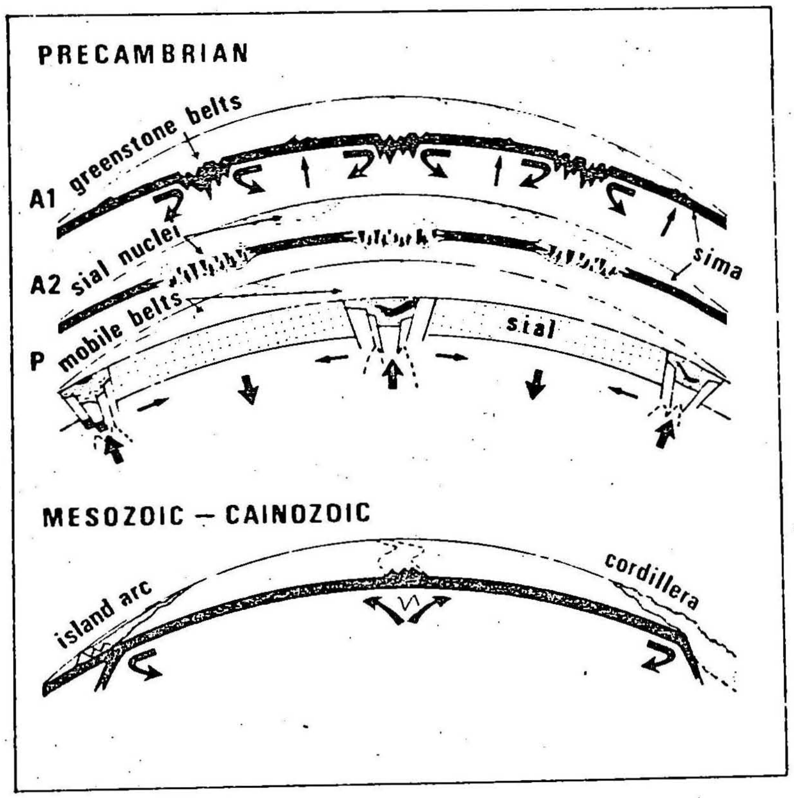

PRECAMBRIAN
A1 greenstone belts
A2 sial nuclei
sima
P mobile belts
sial
MESOZOIC – CAINOZOIC
island arc
cordillera

Fig. 7

(5) A small size of plates or cells can explain the spatial juxtaposition within greenstone belts of mantle-derived lower greenstones, oceanic crust-derived granites, and calc-alkaline volcanics, in terms of spatial superposition of the different processes due to the small plate sizes (Fig. 5); possibly mantle diapirs could rise even beneath subduction zones, which could explain the abundance of ultramafic volcanics in the upper greenstones in Western Australia.

Small-scale crustal cycling cells, aligned in a co-axial pattern about parallel Archaean tectonic trends (Figs. 6, 7), are thus consistent with spatially restricted plate motions. This gives rise to the tentative conclusion that long-range plate movements were of relatively minor importance in the Archaean.

The major change in the global geotectonic system between the Archaean and the Proterozoic (see Runcorn, 1962; Dearnley, 1966) may well have coincided with and been responsible for the agglomeration of individual sialic shields into the supercontinent indicated by palaeomagnetic evidence (Piper et al., 1973). The modern plate tectonic pattern appears to be at least partly inherited from early Proterozoic and possibly even Archaean structural patterns. This is suggested by the coincidence of modern continental margins in Africa, India, and Western Australia with Precambrian mobile belts (Hurley, 1972; Glikson and Lambert, 1973), and by the analogy between Archaean global trends and great meridional circles (Engel and Kelm, 1973). It is also suggested by the superposition on Precambrian mobile belts in Africa of Cainozoic rift structures - a feature which may signify a renewal of the processes which gave rise to the mobile belts in the first place (McConnell, 1972). One possible explanation of the long-term activity in the pan-African-type mobile belts is that their inherited fundamental weakness resulted in repeated igneous activity owing to pressure releases and partial melting at the base of the crust. Alternatively, these geosutures overlie high heat flow zones or advective mantle, in which case a long-term coupling of crust and upper mantle is implied, rendering drift of the lithosphere relative to the asthenosphere less likely. Though it is possible to draw further inferences along these lines, clearly our understanding of the relationships between crust and mantle in the Precambrian is still in its infancy.

ACKNOWLEDGMENT

I wish to thank the organizers of the GAC/MAC conference, and in particular Professor D.F. Strong, for his invitation to prepare and present this paper. In a discussion of this nature it has proved impossible to give full credit to all relevant earlier contributions, nor do I wish in any way to belittle those contributions whose conclusions are questioned in this review. Grateful acknowledgment is due to Dr I.B. Lambert, Mr W.B. Dallwitz, Dr B.J.J. Embleton, Dr. M.W. McElhinny, Mr R. Tingey and Mr B. Duff for their comments and criticism. The permission by Mr I. Gemuts and Mr A. Theron to cite their manuscript and base Fig. 1 on their unpublished map of the Kalgoorlie-Norseman area is gratefully acknowledged. This paper is published with the permission of the Director, Bureau of Mineral Resources, Geology and Geophysics.

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Captions

Fig. 1 - Geological sketch map of the Kalgoorlie-Norseman area, Eastern Goldfields of Western Australia, showing the distribution of lower greenstones and upper greenstones as interpreted by Gemuts and Theron (in prep.) (by permission of the authors)

Fig. 2 - Geological sketch map of the Barberton Mountain Land, after Viljoen and Viljoen (1969a).

Fig. 3 - Geological sketch map of the Rhodesian Shield, after Bliss and Stidolph (1969). The distribution of the Sebakwian Group is after an interpretation by Viljoen and Viljoen (1969a).

Fig. 4. - Major and trace element correlation plots between average metabasalt of the Kalgoorlie System (Hallberg, 1972) (solid circles), average Archaean metabasalt of the Canadian Shield (Baragar and Goodwin, 1969) (crosses) and average oceanic tholeiite (Engel et al., 1965).

Fig. 5 - A diagrammatic representation of the evolution of shields in the Archaean, based on petrogenetic considerations made elsewhere (Glikson and Lambert, in prep.)

(1) Formation of ultramafic-mafic crust: Partial melting within rising mantle diapirs and an Archaean low-velocity zone yields ultramafic and mafic magmas, whose eruption results in a volcanic oceanic-like crust.

(2) Formation of Na-granites and greenstone belts: Downbuckling and subduction of hydrated ultramafic-mafic crust, and its partial melting below about 20 km depth - assuming a very high geothermal gradient - result in formation of acid sodic melts. Segregated acid magma rise up as progressively accreting plutons which pierce the overlying ultramafic-mafic crust. Synclinal zones in the deformed crust evolve into greenstone belts, where sedimentation, calc-alkaline volcanism, and volcanism related to continuing, but less frequent, activity in the subjacent mantle, takes place, resulting in the formation of upper greenstones.

(3) Emergence of granites: Further rise and exposure of granites, accompanied by subsidence of intervening greenstone belts.

(4) Metamorphic-anatectic phase: A rise in the geothermal gradient, resulting in vertically zoned regional metamorphism, anatexis, and formation of high-level K-granites.

Fig. 6 - Distribution of Archaean tectonic trends on a reassembled Gondwanaland model (after Engel and Kelm, 1973).

Fig. 7 - Hypothetical crustal cycling cell systems and sial-sima distribution patterns in the Archaean, Lower to Middle Proterozoic, and post-Permian.

A1 - Small crustal cycling cells, forming a co-axial system. Evolution of greenstone belts.

A2 - Nucleation of protocontinents.

P - Rifting of a Proterozoic sial crust and evolution of mobile belts, related to medium-size crustal cycling cells.