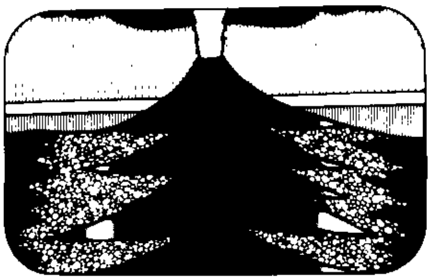

Some Aspects of the Evolution of the Archean Crust

G. M. Young
Department of Geology
University of Western Ontario
London, Ontario N6A 5B7

Summary
The geologic record of the Archean in the Superior Province of Canda is divisible into two major portions: an older, high grade basement (>3.5 Ga), and younger (3.0 Ga to 2.6 Ga) rocks that are arranged in easterly-trending zones (Ga, Gigayear, is used to mean 10^9 years). The younger rocks comprise alternating volcanic (low grade greenstone superbelts) and sedimentary (paragneiss superbelts) terrains. The contrasting lithologic and metamorphic nature of the superbelts is tentatively explained in terms of a mantle convection cell system. Closely analogous Archean assemblages of southern Africa developed about 0.5 Ga earlier, attesting to the heterogeneous nature of the Archean crust and its diachronous evolution in different parts of the world.

Introduction

In recent years there has been considerable revival of interest in Precambrian problems. This is due, in part, to the discovery of plate tectonics and increasing efforts to apply some of these new ideas to old rocks. It is impossible, in a short article to cover all aspects of Archean geology (it is probably also impossible in a long article!) and it will be obvious to the specialised reader that many important facets of the Archean have received scant attention. It is hoped that omissions and errors will stimulate others to write complementary articles.

By many, though not all, definitions, the Archean begins with the oldest preserved rocks. In Canada the boundary between Archean and Proterozoic is generally placed at about 2.6 Ga (Stockwell, 1973). There are problems in defining the upper boundary, however. Cloud (1976) introduced the idea of a highly diachronous wave of cratonization, bringing an end to Archean-style crustal conditions. To accommodate the diachroneity, he introduced the concept of the Zuluan Wedge (Fig. 1) to explain the early (3.5 Ga to 2.6 Ga) advent of Proterozoic-style sedimentation in southern Africa. Many of the events that appear, in our foreshortened view, to punctuate geologic history (e.g., orogeny, glaciation) may in fact be quite diachronous. Cloud (1976) aptly described this as "more illuminating than troublesome". Part of the purpose of this article is to suggest that there is an equally diachronous evolution of Archean-style terrains.

The Oldest Archean Rocks

Many Precambrian regions contain rocks that, because of geologic relationships or geochronology, or both, are considered to be older than adjecent greenstones or paragneisses. Such rocks have been intensively studied in west Greenland (Bridgwater *et al.*, 1973; McGregor, 1973; Bridgwater *et al.*, 1974; Tarney, 1976) where they have been shown to be about 3.7 Ga old (Moorbath *et al.*, 1977). Similar gneisses in eastern Labrador were probably once contiguous with those of west Greenland. They have yielded almost equally old radiometric ages (Hurst *et al.*, 1977). Myers (1976) interpreted the rocks of the Fiskenaesset region of western Greenland as amphibolites (volcanics) that were intruded by anorthosite sheets. After intense deformation, they underwent pervasive intrusion by granitic sheets. The original nature of many of these gneissic rocks remains enigmatic.

Geologic relationships between such high grade ancient gneiss complexes, and greenstone belts such as those of the Superior Province of Canada are unknown, but current radiometric data suggest that the gneissic rocks are significantly older. In some small areas, such as the northwestern margin of the Superior Province, geologic relationships can be observed (Rousell, 1965, Bell, 1971; Ermanovics and Davidson, 1976) between granulitic gneisses of the Pikwitonei sub-province and unconformably-overlying, greenstone-belt rocks of the Sachigo belt.

Other examples of ancient gneiss terrains in the Superior Province include the Kapuskasing Belt (Thurston *et al.*, 1974), and the rocks of the Minnesota River Valley region (Goldich *et al.*, 1970; Morey and Sims, 1976; Hurst *et al.*, 1977). Some of these regions are oulined in Figure 2.

Similar ancient gneisses are widely represented in the U.S.S.R. (Salop, 1977) where they are considered to be older than 3.5 Ga The special lithologic, metamorphic and structural attributes of these rocks led Salop (1977) to infer a unique phase in the evolutionary development of the Earth's crust. It was to this part of Precambrian history that the term "permobile" was originally applied (Salop, 1977, p. 92). Salop (1977) stressed the absence of rigid blocks or cratons that might have controlled fold directions to produce a tectonic "grain". To date there is no evidence of greenstone belt assemblages in Canada comparable in age to ancient gneisses such as those of

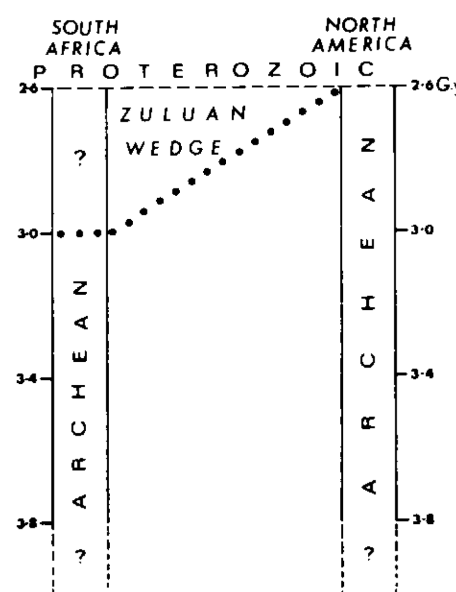

Figure 1
Comparison of some aspects of the Archean-Proterozoic boundary in South Africa (after Cloud, 1976) and in the Canadian Shield (after Stockwell, 1973). The Zuluan Wedge was proposed by Cloud (1976) to accommodate stable shelf-type depositsof the Kaapvaal craton, between 3.0 Ga and 2.6 Ga ago. The figure demonstrates the diachronous development of end-Archean cratonization and some of the problems in establishing the Archean-Proterozoic boundary.

eastern Labrador and the Minnesota River Valley. Such assemblages are, however, known from southern Africa.

Greenstone Superbelts: Volcanic Rocks.
There is a voluminous literature concerning the nature of volcanic rocks in Archean greenstone belts. In addition to intensive field and petrographic studies most investigations have leaned heavily on major element geochemistry (e.g., Wilson *et al.*, 1965; Goodwin, 1968; Glikson, 1976). Recent research is becoming increasingly involved with trace element studies (Condie, 1975; Winchester and Floyd, 1976).

Published thicknesses for supracrustal rocks in greenstone belts are up to 20 km. Goodwin and Ridler (1970) estimated the Abitibi superbelt (Fig. 2) to be underlain by about 60 per cent volcanic rocks, 10 per cent sedimentary rocks and 30 per cent granitic rocks. Some of these volcanic rocks have undergone only a very mild burial metamorphism (Jolly, 1974).

The volcanic rocks are commonly organized into mafic-felsic cycles. The lower parts of some greenstone belt assemblages contain ultramafic rocks, including some that are interpreted as lavas. These have been reported from South Africa (Viljoen and Viljoen, 1969), Australia (Nesbitt, 1971), Canada (Pyke *et al.*, 1973) and elsewhere. These unusual lavas have been interpreted to indicate a high degree of melting of the mantle at shallow depths, perhaps related to high heat-flow rates and steep geothermal gradient (Green, 1975; Brooks and Hart, 1974; Cawthorn and Strong, 1974). The extensive lower, mafic part of the typical Archean volcanic sequence has been compared geochemically to both modern island arcs and ocean tholeiites (White *et al.*, 1971). Many authors have interpreted the low-K tholeiites of the Archean as oceanic tholeiites, but, as was pointed out by Brooks and Hart (1974) and others, low-K tholeiites could have been generated in a variety of tectonic settings related to a shallow depth of mantle melting.

Higher in the typical Archean volcanic pile the lavas are more differentiated and there is a gradual transition to more felsic volcanics (including pyroclastic rocks). These suites are attributed by most to the calc-alkaline series and

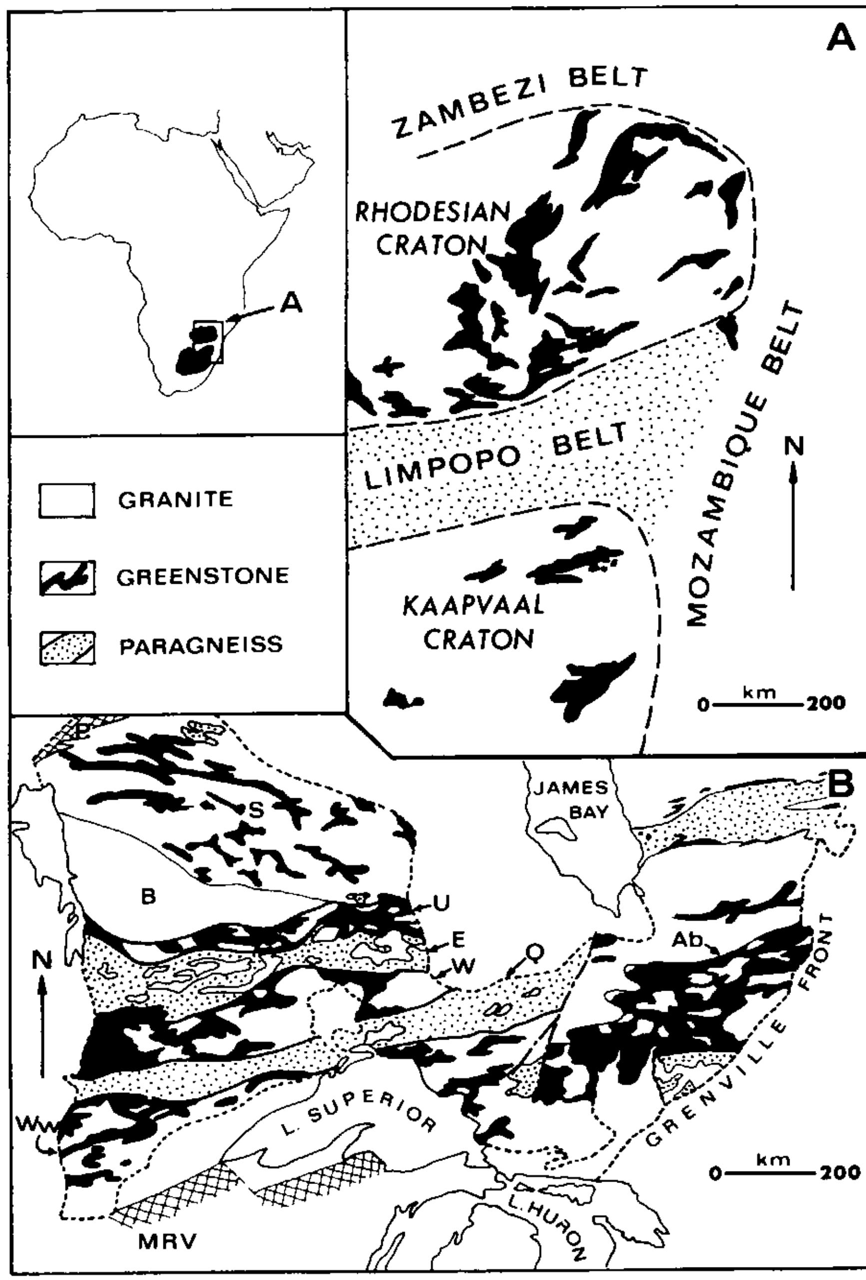

Figure 2
Sketch Maps at approximately the same scale, to show a simplified comparison of the Archean geology of southeast Africa (after Windley, 1977) and part of the Superior Province of Canada (after Baragar and McGlynn, 1976; Ermanovics and Davison, 1976; Goodwin, 1977). Note the alternating linear zones (superbelts) of greenstones (mostly of low metamorphic grade) and paragneiss (high metamorphic grade). In both southern Africa (Part A of the Figure) and in the Superior Province (Part B of the Figure) rocks of the two types of superbelt appear to be approximately contemporaneous. Note the parallelism between the tectonic "grain" in the greenstone belt terrains and contacts with the paragneiss superbelts. Cross-hatching represents rocks interpreted as ancient gneiss terrains. P - Pikwitonei belt; U - Uchi; E - English River; W - Wabigoon; Q - Quetico; Ab - Abitibi; B - Berens; S - Sachigo; MRV - Minnesota River Valley region.

have many chemical attributes similar to those of modern island arc volcanics (Wilson *et al.*, 1965; Goodwin, 1968; Anhaeusser, 1973). There are, however, some significant differences, notably the general (though not complete) absence of alkaline volcanic rocks from the Archean Successions.

Gélinas *et al.* (1977) compared a section of the Abitibi volcanics to those of modern continental island arcs.

At a very early stage in the understanding of Archean greenstone belts, Lawson (1888) noted the possibility of at least two ages of greenstones in Northern Minnesota: those that preceded intrusion of the "Laurentian" granites and those that were formed later. Subsequent age determinations have failed to show significant age differences among these rocks so that the Laurentian granites are now considered to be consanguineous with the lavas.

Published radiometric age determinations suggest that the greenstones of the southern part of the Superior Province were extruded between about 2.7 Ga and 2.8 Ga (Krogh and Davis, 1972) but these limits will probably be expanded as more and better data become available.

Greenstone Superbelts: Sedimentary Rocks

Sedimentary rocks can provide important clues concerning conditions at the Earth's surface in Archean time. In the following section they are treated under a number of sub-headings.

Turbidites and Associated Facies. The most common and best-studied of Archean sedimentary rocks are turbidites and associated coarser grained rocks that have a close temporal and spatial relationship with the volcanic rocks of the greenstone belts.

The high percentage of sand-size quartz grains in some Archean turbidites (Donaldson and Jackson, 1965; Henderson, 1975a; Walker and Pettijohn, 1971) was interpreted to mean that some granitic rocks were exposed to erosive processes in Archean time. In other studies (e.g., Ojakangas, 1972) the provenance of some Archean sedimentary accumulations was found to be exclusively volcanic. Ayres (1969) proposed that the sand-size quartz might have been derived from porphyritic lavas.

The origin and significance of Archean conglomerates have been debated for over 50 years. They contain granitoid clasts which some people regarded as fragments of an older sialic basement.

Another perplexing aspect of Archean conglomerates is the lack of good evidence for unconformities. If some of the clasts are in fact older sialic basement, then unconformities should be present in the shield. Some granitoid clasts (and possibly also a local unconformity) may be related to exposure and erosion of synvolcanic intrusive rocks (the "Laurentian problem" of Lawson). A summary of evidence from the Canadian shield was recently published by Baragar and McGlynn (1976).

Donaldson and Ojakangas (1977) reported orthoquartzite clasts in an Archean conglomerate of the North Spirit Lake area.

Conglomerates associated with the greenstone superbelts are of at least two types. Some appear to be deeper water, resedimented conglomerates (Henderson, 1975b; Ojakangas, 1972; Walker and Pettijohn, 1971). But others are associated with abundantly cross-bedded, shallow water sandstones of fluvial aspect (Henderson, 1975a; Boutcher *et al.*, 1966). McGlynn and Henderson (1970), Henderson (1975a), Baragar and McGlynn (1976) and Pettijohn (1972) all invoked a mixed source terrain, involving older sialic basement, penecontemporaneous volcanics and hypabyssal intrusions for the sedimentary rocks associated with the greenstones of the Canadian shield.

The linear distribution of conglomerates along the borders of the greenstone superbelts suggests intermittent tectonic activity, probably faulting, along or close to the margins of the superbelts.

Greenstone Superbelts: Iron Formations

Most iron formations in Archean rocks occur in the greenstone superbelts. They are mostly of Algoman type (Gross, 1965). The volcanic association of these iron formations has been considered to be a genetic one (Goodwin, 1970), the iron and silicon, and possibly other elements, being exhaled from a volcanic source. Alternatively, Cloud (1973, 1976) proposed that some of the banded iron formations formed from iron dissolved in oceanic waters under conditions less oxidizing than at present. He considered deposition of iron formation to be associated with metabolic activity of primitive micro-organisms. The iron was considered to have acted as a sink for oxygen produced by metabolic processes. If Cloud's speculation is correct, then the presence of iron formation in some of the oldest rocks on Earth (Isua supracrustals of western Greenland) would indicate the presence of organisms at that time.

Dunbar and McCall (1971) recognized an intimate association between turbidites and oxide-facies iron formation. The iron-rich rocks occupy the "e" position in the Bouma sequence, so that the iron-oxide was interpreted as background sedimentation in the basin. Deposition of relatively pure iron formation could only take place during periods of clastic starvation. This idea was also applied by Shegelski (1975) to Archean turbidites in the Savant Lake area in the northern part of the Wabigoon superbelt (Fig. 2) and by Beukes (1973) to the Sheba and Belvue Road Formations of the Fig Tree Group in South Africa.

Many examples of sulphide and carbonate iron formations are closely related to submarine volcanic exhalation of H_2S and CO_2 (White and Waring, 1963; Schidlowski, 1976). The sulphide and carbonate facies iron formations may have formed, in part at least, by combination of these volcanic exhalative products with iron already present in abundance in sea water. Part of the iron may also have been derived from the volcanic activity.

Chert is also a common constituent of iron formations in Archean rocks. This may reflect the abundance of dissolved silica in the world oceans at that time, caused by the ubiquitous volcanic centres and lack of silica-secreting micro-organisms.

The major deposits of sulphide facies appear to have a close spatial relationship with volcanic centres, particularly those with a strong felsic component (Goodwin and Ridler, 1970). These felsic centres probably formed significant topographic highs in Archean depositional basins so that the sulphide facies iron formations might be considered as a proximal facies, some oxide facies iron formations being the deposits of the corresponding deeper water distal facies.

Widespread submarine volcanism and lesser amounts of oxygen in the Archean atmosphere and hydrosphere may both have contributed to the abundance of iron in the oceans. Silica may have been abundant because of a dearth of silica-secreting organisms. Sulphur and carbon dioxide could have been derived largely from volcanic exhalations.

Greenstone Superbelts: Orthoquartzites and Carbonates
Dearth of these rock types is ascribed to the general lack of stable shelf environments during the Archean. Some areas, however, clearly had depositional conditions that permitted accumulation of quartzites and carbonates. For example, the quartzite occurrences in the Prince Albert Group in the northern part of the Churchill province (Schau, 1977). Carbonates also form a minor part of many Archean sedimentary assemblages. In some cases they are iron-rich and constitute a special facies of iron formation (Goodwin and Ridler, 1970). Other occurrences take the form of thin stromatolitic units (Henderson, 1975b).

The Paragneiss Superbelts
Stockwell (1964, Fig. 1) subdivided the western part of the Superior province into several subprovinces. These included the English River and Quetico belts which were distinguished mainly on the basis of their easterly trends. These belts were considered to consist mainly of highly metamorphosed sedimentary rocks and abundant granitic intrusions. Wilson (1971) also subdivided the western part of the Superior province into a series of separate regions and emphasized the importance of fault boundaries. The elongate, easterly trending alternating zones of greenstone-dominated and paragneiss-dominated terrain are referred to in this paper as greenstone superbelts and paragneiss superbelts (following Goodwin, 1977).

The paragneiss superbelts in Canada have received much less study than the greenstone superbelts. Recent work in the Quetico paragneiss superbelt by Mackasey *et al.* (1974), Kehlenbeck (1976) and Blackburn and Mackasey (1977) has documented the presence of metasedimentary rocks, migmatites and granitoid rocks of both magmatic and anatectic origin. The contacts in some areas are affected by major faults (e.g., Quetico Fault), but, as emphasized by Blackburn and Mackasey (1977), the faulting appears to be a late, superimposed feature affecting a boundary that elsewhere is a wide, diffuse zone representing a facies change from dominantly volcanic to dominantly sedimentary rocks. Harris and Goodwin (1976) proposed a basement-cover relationship between ortho-and paragneiss in part of the English River belt. Some of the orthogneisses have yielded a U-Pb age of about 3.0 Ga (Krogh *et al.*, 1976). The relatively poorly studied paragneiss superbelts of the southern part of the Superior province are characterized by a preponderance of highly altered sedimentary rocks. In the marginal zones of some paragneiss belts the altered sedimentary rocks appear to pass by transition into typical low grade assemblages of the neighbouring greenstone superbelts. There is some evidence (Harris and Goodwin, 1976) that the high grade terrains also include older sialic basement material.

A Tectonic Model for the Upper Archean (3.5 Ga to 2.6 Ga)
In the past, many models have been suggested to explain the greenstone belts of Canada and elsewhere, but most models have ignored, or downplayed the importance of, the high grade Archean terrains (paragneiss superbelts of this discussion). In recent years, interpretations of high grade terrains in the Archean have included the following: 1) They are older basement on which, or adjacent to which, greenstone belts and superbelts developed (Binns *et al.*, 1976; Rutland, 1976; Morey and Sims, 1976). 2) They are a deep infrastructure, coeval with the development of the greenstone superbelts (Glikson, 1972; Goodwin, 1977). 3) They are high grade terrains formed by metamorphism of sediments deposited contemporaneously with extrusion of lavas in adjacent greenstone terrains (Mackasey *et al.*, 1974; Blackburn and Mackasey, 1977; Shackleton, 1976).

Controversies over the origin of such high grade terrains probably reflect confusion of one type with another and the possibility that two or even three types may occur within one region. If an "ancient gneiss" basement of type 1 is involved in intensive reworking during a later orogenic episode, it could be transformed, in a sense, into a type 2, deep "coeval" infrastructure. If a type 3 terrain were made up of both an older basement and a thick sedimentary cover, and the two were tectonically stacked and interleaved, accompanied by metamorphism, anatexis and intrusion, then separation of basement and cover would be difficult. Thus, there are difficulties, not only in the interpretation of field data, but in the concepts themselves. Ideas concerning origins of the rocks become blurred and there may be overlap or merging of the concepts themselves. Some of the models that have been proposed are reviewed briefly in the following section.

Goodwin and West (1974) explained the Canadian greenstone belts by some form of plate tectonics and included a time sequence from an oceanic crustal stage, through an island-arc stage to a final stage in which greywacke-type sediments accumulated in foreland basins (to become the paragneiss superbelts after metamorphism). None of the proposed models adequately explains the high grade metamorphism of the paragneiss superbelts in relation to adjacent greenstone-rich areas.

Figure 3 shows the main aspects of the model presented here to explain the close juxtaposition of high and low grade Archean terrains. It differs from the models presented by Windley (1977) in that subduction of crustal plates is not invoked. It has been suggested (Richter, 1973; Baer, 1977) that subduction of this kind was not possible in Archean times because of steep thermal gradients and high heat flow rates. The subduction model of Windley would also impart a stong asymmetry to the high grade terrains but this has not been reported in the literature. The model represented in Figure 3 also differs from that of Windley in assuming an almost continuous, thin, older sialic crust as proposed by Hargraves (1976), Fyfe (1974) and Baragar and McGlynn (1976). This old sialic crust is considered to be a complex "ancient gneiss" terrain similar to those of western Greenland and the Aldan Shield of the Soviet Union. Vigorous mantle convection is envisaged as being responsible for development of a system of relatively small convection cells (Elder, 1968; Clifford, 1970; Fyfe, 1974). The greenstone belts are considered to have formed above rising cells or "hot lines" (Sun and Hanson, 1975)

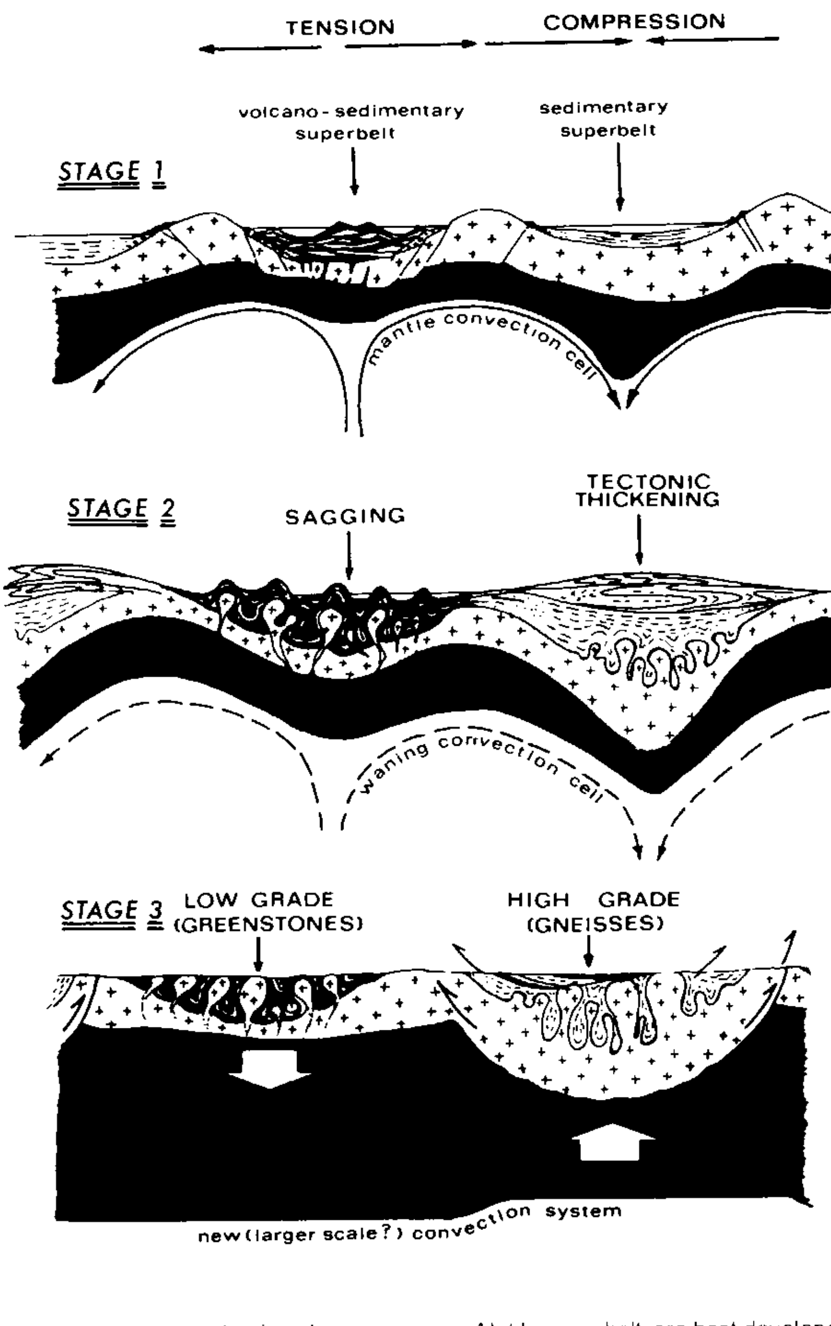

Figure 3
Schematized model to explain the close juxtaposition of low grade (greenstone superbelt) and high grade (paragneiss) terrains in the Archean crust. The sketches are not to scale, but horizontal dimensions of the greenstone and paragneiss superbelts at stage 3 are meant to be comparable to width of the corresponding terrains of part B of Figure 3.

Stage 1. *The "ancient gneiss complex" of the text is represented by the ornament consisting of crosses. A system of small scale convection cells in the mantle (100 km to 300 km across) is envisaged as setting up a state of tension in areas of thermal upwelling, and of compression in areas overlying descending currents. These became the sites of volcanic activity and sediment accumulation respectively. The sediments of the compressive zone are considered to have been derived mainly from the uplifted margins of the adjacent volcanic basin, but in the third dimension transition from the dominantly volcanic regime to the sedimentary one is possible. Some volcanic rocks are present in the sedimentary basins, particularly near the margins.*

Stage 2. *Extrusion of great thicknesses of relatively dense volcanics (and associated sediments) leads to subsidence of the volcanic basin. With decay of the thermal cells, the greenstone terrain subsides still farther, giving rise to the younger granites by melting of the depressed crust. In the sedimentary basin, considerable crustal thickening is achieved by sediment loading and the compressive effects of the sub crustal convection system. As the convection system decays, the thickened part of the crust is affected by rising isotherms and undergoes considerable thermal reworking.*

Stage 3: *With inception of a new (larger scale?) convection system, the greenstone superbelt subsides to be preserved at a low metamorphic grade. These rocks have undergone little erosion because of subsidence related to both loading factors and removal of the local heat source. Uplift of the sedimentary basin, due to isostatic rebound, was accomplished in part by movements along large scale faults at, or close to the margins of the superbelts. Subsequent erosion leads to exposure, at surface, of high grade metamorphic rocks, comprising both paragneisses and older basement rocks.*

and the sedimentary basins above converging, descending cells. The model provides an explanation for the development of the two contrasting types of superbelt.

1. *History of a typical greenstone superbelt.* The greenstone superbelts are considered to have formed above thermal plumes or "hot lines" which caused distention, fracturing and possibly local separation of the thin sialic crust. Extrusion of ultramafic and mafic lavas (mostly subaqueously) was followed, in many cases, by mafic-felsic differentiated sequences that, in the Abitibi superbelt, are best developed near the margins (Goodwin and Ridler, 1970; Goodwin, 1977). These dominantly volcanic assemblages appear to have achieved remarkable thicknesses, although tectonic stacking may have led to exaggeration in some cases (Gorman *et al.*, 1978). Accumulation of such great thicknesses of relatively dense rocks would have caused depression of the already thinned sialic substrate (Hargraves, 1976; Baragar and McGlynn, 1976). At the same time isostatic considerations suggest that such volcanic accumulations would eventually have risen above sea level (Hargraves,

1976) to produce the clastic detrital sedimentary rocks that are typical of the upper parts of greenstone belt assemblages. Depression of the sialic substrate, of the volcanic pile itself, below the appropriate isotherm (Fyfe, 1974; Baragar and McGlynn, 1976; Hargraves, 1976) would have produced crustal melting and intrusion of the ubiquitous post-greenstone granitic rocks. These granites commonly separate the greenstone assemblage from rocks suspected to be older gneissic basement.

Preservation of the high level greenstone assemblage at a relatively low metamorphic grade is explained, in the model, by slow subsidence following waning of the subcrustal heat source (mantle convection cells). The greenstone belts have not undergone intense erosion and are not the deep roots of ancient mountain systems.

The common vertical tectonic style and "keel-like" form of many greenstone belts may be due in part to settling of the denser volcanic rocks into a sialic substrate (Ramberg, 1967; Gorman *et al.*, 1978). Emplacement of late potassic granites may also have contributed locally to the tectonic style. In some areas early deformation of greenstone belts has been interpreted as involving horizontal tectonics (Ramsay, 1963; Stowe, 1974). Such recumbent folding and nappe-style tectonics may be high level expressions of the proposed sagging stage, as illustrated by Gorman *et al.* (1978). Preservation of such "high level" zones may be another reflection of the general subsidence of greenstone terrains as the heat source waned. Some deformation, usually at a late stage, has been attributed to transcurrent faulting along boundaries between high and low grade terrains (Coward and James, 1974; Coward *et al.*, 1976).

2. History of a typical paragneiss superbelt. Goodwin (1977) interpreted the paragneiss superbelts of the southern part of the Superior province as an integral part of the crustal superstructure, but did not provide a detailed mechanism to explain their origin. Katz (1976) and Windley (1977) also recognized these terrains as being contemporaneous with the greenstone belts and their models were discussed above. Recently Harris and Goodwin (1976) and Krogh *et al.* (1976) described parts of the English River gneiss belt in terms of an older ($\sim$ 3.0 Ga) sialic basement and a younger, highly metamorphosed, sedimentary cover.

Contacts between the paragneiss superbelts and greenstone superbelts are commonly described as being faulted (Wilson, 1971; Kehlenbeck, 1976). Others have reported an increase in the amount of greenstone remnants in the paragneisses towards the outer margins of the belt and have emphasized the transitional nature of the boundaries between paragneiss and greenstone terrains (Pettijohn, 1972; Blackburn and Mackasey, 1977). The observed field relations (cf. Shackleton's 1976, description of similar relationships in southern Africa) support interpretation of these high grade paragneiss superbelts as comprising both an older basement, and a thick sedimentary cover of approximately the same age as adjacent greenstones.

The general arrangement that applies to Archean terrains of Canada, the U.S.S.R., southern Africa and western Australia is one of local areas of complex high grade ancient gneiss (basement) exposed adjacent to both high grade younger paragneiss and greenstone superbelts. The ancient gneiss complexes are here interpreted to underlie large portions of the paragneiss and greenstone superbelts.

The younger high grade terrains (paragneiss superbelts) of many regions contains some rocks that suggest stable shelf conditions and granitoid source terrain (e.g., the thick quartzites and marbles of the Limpopo Belt). The shelf-type sediments in some belts appear to be best developed near the margins. The paragneiss superbelts are interpreted as having formed by accumulation of a thick sedimentary succession in subsiding troughs formed above a zone of convergent, descending convection cells (Fig. 3). Subsidence, particularly near the margins of such belts, must have been slow enough to permit accumulation of shelf type sediments.

The provenance of the sedimentary rocks in paragneiss belts is, in most cases, impossible to determine. Conglomerates along the margins of the greenstone superbelts of the western Superior Province (Pettijohn, 1972) might reflect early or late faulting along the contact zones between the two different types of Archean terrains.

The proposed convergent cell system beneath the sedimentary basin, together with the weight of accumulating sediment, would have led to crustal thickening by folding and possibly tectonic interleaving. It has recently been proposed (Richter, 1973; Forsyth and Uyeda, 1975) that mantle convection does not provide the necessary force to drive the huge plates that currently constitute the Earth's crust. Richter (1973) suggested that convection cells may cause the break-up of plates, but because of the small size of the cells relative to the plates and because of a lack of strong coupling between plate and cell it was proposed that the cells did not provide a viable plate-moving mechanism. With a crust that was at least locally thinner than at present, with higher heat flow and steeper thermal gradient in the Archean (see Burke and Kidd, 1978 for an opposing view) it is suggested that tectonic movement of crustal elements was much more strongly linked to the convection process than is currently thought to be the case.

Following decay of the proposed thermal system there would have been significant uplift (isostatic rebound) of the thickened crust. Deep erosion took place to expose high grade metamorphic rocks comprising both paragneisses and their basement. Part of the isostatic readjustment could have taken place along major faults situated at, or close to, the boundaries of the paragneiss superbelts.

Comparison with Southern Africa

In southern Africa, two major Archean cratons (Anhaeusser, 1976) are separated by the dominantly high grade paragneisses and associated rocks of the Limpopo Belt. For comparative purposes a simplified version of the stratigraphy of the Kaapvaal Craton, the Limpopo Belt and the Rhodesian Craton is given in Figure 4. Two remarkable features of the Rhodesian Craton are the very ancient greenstones of the Sebakwian Group (Wilson *et al.*, 1978) and the fact that there are greenstone assemblages (including ultramafic lavas) ranging from older than 3.5 Ga to about 2.7 Ga. Both the "Sebakwian group" and the "Lower Bulawayan Group" are older than any greenstone belts presently known in Canada.

To the south, in the Kaapvaal Craton, the Swaziland Supergroup of the Barberton Mountainland consists of about 16 km of dominantly volcanic rocks (including ultramafic varieties) overlain by

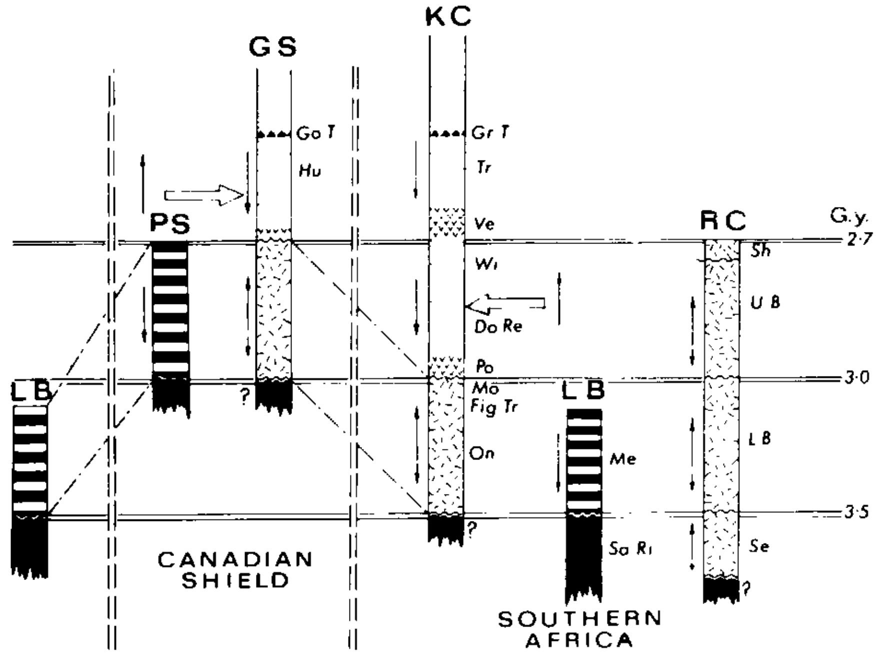

Figure 4.
Schematic representation of early Precambrian statigraphy of the Superior Province and southern Africa. Time lines are drawn at approximately 2.7 Ga, 3.0 Ga and 3.5 Ga (Note: G.y. = Ga). Ornamentation is as follows: black-gneissic basement, dashed ornament - greenstone belt assemblage; stripes-paragneiss, dots - cratonic sedimentary rocks; "v" ornament - volcanics in cratonic cover rocks, triangles - tillites. For southern Africa three columns are shown representing the Kaavaal Craton **(KC)**, *Limpopo Belt* **(LB)** and the Rhodesian Craton **(RC)**. *Abbreviations on column* **KC** *are as follows: Gr T - Griquatown Tillite, Tr - Transvaal, Ve - Ventersdorp, Wi - Witwatersrand, Do Re - Dominion Reef, Po - Pongola, Mo - Moodies; Fig Tr - Fig Tree, On - Onverwacht. Those on column* **LB** *are: Me - Messina Fm., Sa Ri - Sand River gneisses. Letters on column* **RC** *are as follows: Sh - Shamvaian, UB - "Upper Bulawayan", LB - "Lower Bulawayan", Se - "Sebakwian". For the Superior Province, abbreviations on column* **GS** *(greenstone superbelt) are as follows: GT - Gowganda Tillite; Hu - Huronian. Column* **PS** *represents a paragneiss superbelt. Arrows to left of columns inferred crustal movements, double-headed arrows represent build-up of volcanics, with concomitant basinal subsidence. Open arrows show major paleocurrent directions in cratonic cover rocks. Dot-dash lines show major age differences in comparable facies between southern Africa and the Superior Province. The Limpopo Belt is represented twice to facilitate this comparison.*

about six km of sedimentary rocks. This thick greenstone assemblage is also older than those of the Superior Province, but younger than the oldest greenstones of the Rhodesian Craton. Following an orogenic event at about 3.0 Ga ago, the thick cratonic sequence comprising the Pongola, Dominion Reef and Witwatersrand was deposited. These were followed by the Venterdorp Lavas and the Transvaal Supergroup which includes the Griquatown tillite of comparable age to those of the Huronian of Canada.

The Limpopo Belt comprises mainly highly metamorphosed fine grained clastic sedimentary rocks, together with some carbonates. At least some of these rocks appear to have accumulated in a relatively stable shelf-type environment (James, 1975; Shackleton, 1976). High grade of metamorphism is typical of the Limpopo Belt, in contrast to the low grade rocks of the adjacent greenstone belts. Rocks of the Limpopo Belt and those of the greenstone belts have been affected by the same late fold phases (Coward and James, 1974; James, 1975) but a basement (older than 3.6 Ga) has recently been defined beneath paragneisses of the Limpopo Belt (Barton *et al.*, 1977).

As shown in Figure 4, the paragneisses of the Limpopo Belt probably formed at the same time as volcanic and sedimentary rocks of the adjacent "cratons". This major facies change is comparable in style to that shown by the *much younger* rocks of the Canadian Superior Province. In western Australia (Rutland, 1976) it is possible that the Wheat Belt zone of high grade rocks (including a high proportion of shelf-type sedimentary rocks), together with the greenstone belts of the Eastern Goldfields region, may provide another example of penecontemporaneous development of high grade paragneisses and low grade volcano-sedimentary terrains in the Archean.

The succession of events on the Kaapvaal Craton is closely comparable to that in the Superior Province, including the development of a younger cratonic sequence (rocks of the Zuluan Wedge) comparable in facies to, but much older than the corresponding rocks (Huronian) at the southern margin of the Superior Province. The greenstone belts of the Kaapvaal Craton, together with the high grade paragneisses of the Limpopo Belt, provide a close analogue for the alternating greenstone and paragneiss belts of the much younger Superior Province. The model suggested here for development of these contiguous high and low grade terrains is in keeping with an Archean crust of highly variable thickness. Crustal heterogeneity is also indicated by the clearly diachronous development of the greenstone-paragneiss superbelts, in addition to the diachronous development of the overlying cratonic sequences noted by Cloud (1976). A third type of Archean terrain, giving further support to the concept of crustal heterogeneity, is exemplified by the rocks of the Rhodesian craton, where volcanic conditions persisted intermittently from about 3.6 Ga to about 2.6 Ga.

Conclusions

Current geologic and geochronological results from North America support the concept of a two-fold subdivision of the Archean into ancient gneiss complexes, the exact origin of which remains obscure, the younger supracrustal assemblages (with associated intrusive rocks) of two contrasting types. The younger rocks are preserved as adjacent greenstone and paragneiss superbelts of generally low and high metamorphic grade respectively. These rocks are succeeded unconformably by the cratonic assemblages of the early Proterozoic.

A closely similar evolutionary pattern is evidenced by the Archean crustal rocks of southern Africa. In southern Africa, however, some parts of the Archean crust appear to have gone through stages comparable to those of the Canadian Shield about 0.5 Ga earlier. Greenstone superbelts are considered to have formed above rising mantle convection cells, whereas the paragneiss superbelts are interpreted as having formed above descending cells. The contrasted metamorphic grades of the two types of superbelts indicate differences in vertical elevation and an Archean crust of highly variable thickness. The main characteristics of the Archean crust were its heterogeneity and its highly diachronous evolutionary pattern. Even in the oldest greenstone belts of southern Africa there is evidence of a still older sialic component, but the nature and origin of the "oldest rocks" are still conjectural.

Acknowledgements

I would like to thank C. W. Jefferson, G. M. Yeo, S. M. McLennan and G. Delaney for discussions on problems of Archean geology. P. Thurston and B. E. Gorman assisted me in literature search. C. W. Jefferson and G. M. Yeo provided helpful comments on an earlier version of the manuscript, as also did G. V. Middleton and an anonymous Associate Editor. To all of these people, and to National Research Council of Canada I would like to express my thanks. T. N. Clifford deserves special mention for assistance in clarifying some of the mysteries of south African geology.

References

Anhaeusser, C. R., 1973, The evolution of the early Precambrian crust of southern Africa: Phil. Trans. Royal Soc. London, v. 273A, p. 359-388.

Anhaeusser, C. R., 1976, The nature and distribution of Archaean gold mineralisation in southern Africa: Minerals Sci. Engng. v. 8, p. 46-84.

Ayres, L. D., 1969, Early Precambrian metasandstone from Lake Superior Park, Ontario, and implications for the origin of the Superior Province (Abst.): Geol. Soc. Amer., Abstracts with Programs, 1969.

Baer, A. J., 1977, Speculations on the evolution of the lithosphere: Precamb. Research, v. 5, p. 249-260.

Baragar, W.R. A. and J. McGlynn, 1976, Early Archean basement in the Canadian Shield; a review of the evidence: Geol. Survey Canada, Paper 76-14, 20 p.

Barton, J. M., Jr., R. E. P. Fripp, and B. Ryan, 1977, Rb/Sr ages and geologic setting of ancient dykes in the Sand River area, Limpopo mobile belt, South Africa: Nature, v. 267, p. 487-490.

Bell, C. K., 1971, Boundary geology, Upper Nelson River area, Manitoba: *in* Geoscience Studies in Manitoba and Northwestern Ontario: A. C. Turnock, ed., Geol. Assoc. Canada, Spec. Paper No. 9, p. 11-39.

Beukes, N. J., 1973, Precambrian iron-formations of southern Africa: Econ. Geol., v. 87, p. 601-611.

Binns, R. A., R. J. Gunthorpe and D. I. Groves, 1976, Metamorphic patterns and development of greenstone belts in the eastern Yilgarn block, Western Australia: *in* B. F. Windley, ed., The Early History of the Earth. London, Wiley, p. 303-313.

Blackburn, C. E. and W. O. Mackasey, 1977, Nature of the Quetico-Wabigoon boundary in the de Courcey-Smiley Lakes area, northwestern Ontario discussion. Can. Jour. Earth Sci., v. 14, p. 1959-1961.

Boutcher, S. M. A., A. S. Edhorn and W. W. Moorehouse, 1966, Archean conglomerates and lithic sandsto es of Lake Timiskaming, Ontario. Proc. Geol. Assoc. Canada, v. 17, p. 21-42.

Bridgwater, D., V. R. McGregor, and J. S. Myers, 1974, A horizontal tectonic regime in the Archean of Greenland and its implications for early crustal thickening: Precamb. Research, v. 1, p. 179-198.

Bridgwater, D., J. Watson, and B. F. Windley, 1973, The Archean craton of the North Atlantic region: Phil. Trans. Royal Soc., London, v. 273A, p. 493-512.

Brooks, C. and S. R. Hart, 1974, On the significance of komatiite. Geology, v. 2, p. 107-110.

Burke, K. and W. S. F. Kidd, 1978, Were Archean continental geothermal gradients much steeper than those of today?: Nature, v. 272, p. 240-241.

Cawthorn, R. G. and D. F. Strong, 1974, The petrogenesis of komatiites and related rocks as evidence for a layered upper mantle: Earth Plan. Science Letters, v. 23, p. 369-375.

Clifford, T. N., 1970, The structural framework of Africa: *in* T.N. Clifford and I. G. Glass, eds., African Magnetism and Tectonics: Edinburgh, Scotland, Oliver and Boyd, p. 1-26.

Cloud, P. E., 1973, Paleoecological significance of the banded iron-formation: Econ. Geol., v. 68, p. 1135-1143.

Cloud, P. E., 1976, Major features of crustal evolution: Geol. Soc. South Africa, Annexure to v. LXXIX, 33 p.

Condie, K. C., 1975, A mantle plume model for the origin of greenstone belts based on trace element distributions: Nature, v. 258, p. 2981-2992.

Coward, M. P., and P. R. James, 1974, The deformation pattern of two Archean greenstone belts in Rhodesia and Botswana. Precamb. Research, v. 1, p. 235-258.

Coward, M. P., P. R. James, and L. Wright, 1976, Northern margin of the Limpopo Belt, Southern Africa: Geol. Soc. Amer. Bull., v. 87, p. 601-611.

Donaldson, J. A. and G. D. Jackson, 1965, Archean sedimentary rocks of North Spirit Lake area, northwestern Ontario: Can. Jour. Earth Sciences, v. 2, p. 622-647.

Donaldson, J. A. and R. W. Ojakangas, 1977, Orthoquartzite pebbles in Archean conglomerate, North Spirit Lake, northwestern Ontario: Can. Jour. Earth Sci., v. 14, p. 1980-1990.

Dunbar, G. J. and G. J. H. McCall, 1971, Archean turbidites and banded ironstones of the Mt. Belches area (Western Australia): Sedimentary Geol., v. 5, p. 93-133.

Elder, J. W., 1968, Convection - key to dynamical geology: Sci. Progress, London, v. 56, p. 1-33.

Ermanovics, I. and W. L. Davison, 1976, The Pikwitonei granulites in relation to the Northwestern Superior province of the Canadian Sheild. *in* B. F. Windley, ed., The Early History of the Earth: London, Wiley, p. 331-347.

Forsyth, D. and A. Uyeda, 1975, On the relative importance of the driving forces of plate motion: Geophys. Jour. Royal Astronom. Soc., v. 43, p. 163-200.

Fyfe, W. W., 1974 Archean tectonics. Nature, v. 249, p. 338.

Gelinas, L., C. Brooks, G. Perrault, J. Carignan, P. Trudel, and F. Grasso, 1977, Chemostratigraphic divisions within the Abitibi volcanic belt, Rouyn-Noranda district, Quebec: *in* W. R. A. Baragar, L. C. Coleman and J. A. Hall, eds., Volcanic Regimes in Canada: Geol. Assoc. Canada, Spec. Paper 16, p. 265-295

Glikson, A. Y., 1972, Early Precambrian evidence of a primitive ocean crust and island nuclei of sodic granite: Geol. Soc. Amer. Bull., v. 83, p. 3323.

Glikson, A. Y., 1976, Earliest Precambrian ultramafic-mafic volcanic rocks: ancient oceanic crust of relic terrestrial maria? Geology, v. 4, p. 201-205

Goldich, S. S., C. E. Hedge, and T. W. Stern, 1970, Age of the Morton and Montevideo gneisses and related rocks southwestern Minnesota: Geol. Soc. Amer. Bull., v. 81, p. 3671-3696

Goodwin, A. M., 1968, Archaean protocontinental growth and early crystal history of the Canadian Shield: 23rd Internatl. Geol. Cong., Part 1, p. 69-89

Goodwin, A. M., 1970, Archean volcanogenic iron-formation of the Canadian Shield: Proc. Kiev Symposium on genesis of Precambrian iron and manganese deposits, UNESCO, p. 23-24

Goodwin, A. M., 1977, Archean basin-craton complexes and the growth of Precambrian shields: Can. Jour. Earth Sci., v. 14, p. 2737-2759

Goodwin, A. M. and R. H. Ridler, 1970, The Abitibi Orogenic Belt: *in* A. E. Baer, ed., Symposium on Basins and Geosynclines of the Canadian Shield: Geol. Surv. Canada, Paper 70-40, p. 1-24

Goodwin, A. M. and G. F. West, 1974, The Superior Geotraverse Project: Geosci. Canada, v. 1, no. 3, p. 21-29

Gorman, B. E., T. H. Pearce, and T. C. Birkett, 1978, On the structure of Archean greenstone belts: Precambrian Research, v. 6, p. 23-41

Green, D. H., 1975, Genesis of Archean peridotitic magmas and constraints on Archean geothermal gradients and tectonics: Geology, v. 3, p. 15-18

Gross, G. A., 1965, Geology of iron deposits in Canada. I. General geology and evalutation of iron deposits: Geol. Surv. Can. Econ. Geol. Report 22, 181 p.

Hargraves, R. B., 1976, Precambrian geologic history: Science, v. 194, p. 363-371.

Harris, N. B. W. and A. M. Goodwin, 1976, Archean rocks from the eastern Lac Seul region of the English River gneiss belt, northwestern Ontario, Part 1. Petrology, chemistry and metamorphism: Can. Jour. Earth Sci., v. 13, p. 1201-1211

Henderson, J. F., 1975a, Sedimentology of the Archean Yellowknife Supergroup at Yellowknife, District of Mackenzie: Geol. Surv. Can. Bull. 246, 62 p.

Henderson, J. F., 1975b, Archean stromatolites in the northern Slave Province, Northwest territories, Canada: Can. Jour. Earth Sci., v. 12, p. 1619-1630

Hurst, R., J. Farhat, and G. Wetherill, 1977, Very old (>3100 m.y.) rocks in North America: *in* C. Ponnamperuna, ed., Chemical Evolution of the Early Precambrian, London, Academic Press, p. 25-26

James, P. R., 1975, A deformation study across the northern margin of the Limpopo belt: Res. Instit. African Geol., Leeds Univ. Ann. Rept. No. 19, p. 66-67

Jolly, W. T., 1974, Regional metamorphic zonation as an aid in study of Archean terrains: Abitibi regions, Ontario: Can. Mineral., v. 12, p. 499-508

Katz, M. B., 1976, Early Precambrian granulites - greenstones, transform mobile belts and ridge rifts on early crust? *in* B. F. Windley, ed., The Early History of the Earth: London, Wiley, p. 147-155

Kehlenbeck, M. M., 1976, Nature of the Quetico-Wabigoon boundary in the de Courcey-Smiley area, Northwestern Ontario: Can. Jour. Earth Sci., v. 13, p. 737-748.

Krogh, T. E. and G. L. Davis, 1972, Zircon U-Pb ages of Archean metavolcanic rocks in the Canadian Shield: Carnegie Instit. Washington, Yearbook, v. 70, p. 241-242.

Krogh, T. E., N. B. W. Harris, and G. L. Davis, 1976, Archean rocks from the eastern Lac Seul region of the English River gneiss belt, northwestern Ontario, Part 2, Geochronology: Can. Jour. Earth Sci., v. 13, p. 1212-1215

Lawson, A. C., 1888, Report on the geology of the Rainy Lake region, Canada: Geol. Hist. Survey Ann. Rept. n.s. v. 3, Pt. F, 182 pp.

Mackasey, W. O., C. E. Blackburn, and N. F. Trowell, 1974, A regional approach to the Wabigoon-Quetico Belts and its bearing on exploration in northwestern Ontario, Ontario Div. Mines, Miscell. Paper, 58, 29p.

McGregor, V. R., 1973, The early Precambrian gneisses of the Godthaab district, west Greenland: Phil. Trans. Roy. Soc. London, v. 273A, p. 343-358.

McGlynn, J. C. and J. B. Henderson, 1970, Archean volcanism and sedimentation in the Slave structureal province, *in* A. J. Baer, ed., Symposium on Basins and Geosynclines of the Canadian Shield: Geol. Surv. Canada, Paper 70-40, p. 31-44.

Moorbath, S., J. H. Allaart, D. Bridgwater and V. R. McGregor, 1977, Rb-Sr ages of Early Archean supracrustal rocks and Amitsoq gneisses at Isua: Nature, v. 270, p. 43-45

Morey, G. B. and P. K. Sims, 1976, Boundary between two Precambrian W terranes in Minnesota and its geologic significance: Geol. Soc. Amer. Bull., v. 87, p. 141-152.

Myers, J. S., 1976, Granitoid sheets, thrusting and Archean crustal thickening in West Greenland: Geology, v. 4, p. 265-268

Nesbitt, R. W., 1971, Skeletal crystal forms in the ultramafic rocks of the Yilgarn block, Western Australia: evidence for an Archean ultramafic liquid, Geol. Soc. Australia, Spec. Publ. No. 3, p. 331-350.

Ojakangas, R. W., 1972, Archaean volcanogenic graywackes of the Vermilion District, northeastern Minnesota: Geol. Soc. Amer. Bull. v. 83, p. 429-442.

Pettijohn, F. J., 1972, The Archean of the Canadian Shield: a resume: Geol. Soc. Amer. Mem. 135, p. 131-149

Pyke, D. R., A. J. Naldrett, and O. R. Eckstrand, 1973, Archaean ultramafic flows in Munro Township, Ontario: Geol. Soc. Amer. Bull., v. 84, p. 955-978

Ramberg, H., 1967, Gravity deformation and the Earth's crust: Academy Press, New York, 214 p.

Ramsay, J. G., 1963, Structural investigations in the Barberton Mountain Land, eastern transvaal: Trans. Geol. Soc. South Africa, v. 66, p. 353-398

Richter, F. M., 1973, Dynamical models for sea floor spreading: Research in Geophysics and Space Physics, v. 11, p. 223-287

Rousell, D. H., 1965, Geology of the Cross Lake area: Mines Branch, Manitoba, Publ. 62-4

Rutland, R. W. R., 1976, Orogenic evolution of Australia, Earth Science Reviews, v. 12, p. 161-196.

Salop, L. J., 1977, Precambrian of the Northern Hemisphere: Developments in Palaeontology and Stratigraphy, #3, Amsterdam, Netherlands, Elsevier, 378 p.

Schau, M., 1977, "Komatiites" and quartzites in the Archean Prince Albert Group, *in* W. R. A. Barager, L. C. Coleman, and J. M. Hall, eds., Volcanic Regimes in Canada, Geol. Assoc. Canada, Spec. Paper 16, p. 341-354

Schidlowski, M., 1976, Archaean atmosphere and evolution of the terrestrial oxygen budget: *in* B. F. Windley, ed., The Early History of the Earth: London, Wiley, p. 525-535

Shackleton, R. M., 1976, Shallow and deep level exposures or Archaean crust in India and Africa; *in* B. F. Windley, ed., The Early History of the Farth, London, Wiley, p. 317-321.

Shegelski, R. J., 1975, Geology and geochemistry of iron-formation and their host rocks in the Savant Lake-Sturgeon Lake greenstone belts; a progress report: *in* Geotraverse Workshop, 1975, Univ. Toronto, p. 34-1 - 34-21.

Stockwell, C. H., 1964, Fourth Report on structural provinces, orogenies and time classification of rocks of the Canadian Precambrian Shield: Geol. Surv. Can., Paper 64-17, Part II, 26 p.

Stockwell, C. H., 1973, Revised Precambrian time scale for the Canadian Shield: Geol. Surv. Canada, Paper 72-52, 4 p.

Stowe, C. W., 1974, Alpine-type structures in the Rhodesian basement complex at Sebukwe: Jour. Geol. Soc., London, v. 130, p. 411-426.

Sun, S. S. and G. N. Hanson, 1975, Evolution of the Mantle: geochemical evidence from alkali-basalt: Geology, v. 3, p. 297-302.

Tarney, J., 1976, Geochemistry of Archaean high grade gneisses with implications as to the origin and evolution of the Precambrian crust: *in* B. F. Windley, ed., Early History of the Earth, London, Wiley, p. 405-417.

Thurston, P. C., G. M. Siragusa, and R. P. Sage, 1974, Geology of the Chapleau area, Districts of Algoma, Sudbury and Cochrane: Ontario Ministry Nat. Resources, Open File Rept. 5079 (2).

Viljoen, M. J. and R. P Viljoen, 1969, A collection of 9 papers on many aspects of the Barberton granite-greenstone belt, South Africa. Geol. Soc. South Africa, Spec Pub. No. 2, 295 p.

Walker, R. G. and F. J. Pettijohn, 1971, Archean sedimentation: analysis of the Minnitaki basin, northwestern Ontario, Canada: Geol Soc. Amer Bull., v. 82, p. 2099-2130.

White, A. J R., P. Jales, and D. M. Christie, 1971, Composition of greenstones and the hypothesis of sea-floor spreading in the Archaean: Geol. Soc. Australia Spec. Publ. 3, p. 47-56.

White, D. E. and G. A Waring, 1963, Volcanic emanations: U S. Geol. Survey Prof. Paper 440-K.

Wilson, H. D. B., 1971, The Superior province in the Precambrian of Manitoba: *in* A. C. Turnock, ed., Geoscience Studies in Manitoba Geol. Assoc. Canada, Spec. Paper 9, p. 41-49.

Wilson, H. D. B., P. Andrews, R. L. Moxham and K. Ramlal, 1965, Archaean volcanism in the Canadian Shield: Can. Jour. Earth Sci., v. 2, p. 161-175.

Wilson, J F., M. J. Bickle, C J Hawkesworth, A. Martin, E. G. Nisbet, and J. L. Orpen, 1978, Granite-greenstone terrains of the Rhodesian craton: Nature, v. 271, p. 23-27.

Winchester, J. A. and P. A. Floyd, 1976, Geochemical magma type discrimination: application to altered and metamorphosed basic igneous rocks: Earth Plan. Sci. Letters, v. 28, p. 459-469.

Windley, B. F., 1977, Timing of continental growth and emergence: Nature, v. 270, p. 426-427.

MS received March 17,
revised May 25, 1978