Mem. Natl Inst. Polar Res., Spec. Issue, **53**, 8-28, 1998

TECTONIC DEVELOPMENT OF EARLY PRECAMBRIAN OROGENS

Brian F. WINDLEY

Department of Geology, Leicester University,
Leicester LE1 7RH, U.K.

Abstract: A review of recent literature shows that Archaean and Early Proterozoic orogens developed by tectonic processes that were largely comparable to those in operation today. During the Archaean the earliest crust segregated from the mantle, and greenstone belts largely formed as accretionary collages of oceanic crust, island arcs, accretionary prisms, and possible plateaus. Calc-alkaline magma genesis was controlled by slab melting without dehydration leading to common tonalite-trondhjemite-granodiorite suites, which are widely preserved today in Archaean granulite-gneiss belts. Rapid crustal growth and coalescence of terranes in the late Archaean led to formation of one or more supercontinents at *ca.* 2.5 Ga, the breakup of which gave rise to extensive passive continental margins and shelf sequences in the Early Proterozoic. The widespread development by subduction processes of island arcs and of magmatic arcs in active continental margins aids in demarcating Early Proterozoic suture zones within accretionary and collisional orogens which are comparable with those of the present-day.

key words: Archaean, Proterozoic, greenstone belts, arcs, plumes

1. Introduction

The bulk of the continental crust is made up of Precambrian rocks situated within orogenic belts, the formation of which took place during the greater part of geological time. There is increasing evidence from a multi-disciplinary databank that the lithological associations, tectonic arrangements and geochemical signatures of rocks in these belts are remarkably similarly to their modern analogues, and therefore it is commonly concluded that the tectonic processes that were responsible for the development of Early Precambrian orogens, even in the Archaean, were approximately akin to those of today (KRÖNER, 1991; CONDIE, 1997a; SENGÖR and NATAL'IN, 1996; WINDLEY, 1995; PERCIVAL *et al.*, 1997). However, other viewpoints by well-known authorities are still being proposed, in particular for the Archaean. For example, "the operating Archaean processes were... non-actualistic" (GOODWIN, 1996), "plate tectonic processes were not then operating (in the Archaean)", and "no diagnostic indicators of plate tectonics have been found in Archean terrains" (HAMILTON, 1998), and plume tectonics were more important than plate tectonics in the early Precambrian (DAVIES, 1993; PARK, 1997). So, who is correct ? What is the relative merit of these ideas ?

The aim of this paper is review some important relationships in key Early Precambrian orogens in order to deduce the most likely responsible tectonic regimes. But, firstly, what do we mean by orogens and plates in this context ?

2. Orogens and Plates

There are two contrasting types of orogens, which both develop at convergent plate boundaries, collisional and accretionary (SENGÖR *et al*., 1993; WINDLEY, 1993); these are comparable with the internal and external orogens of MURPHY and NANCE (1991).

Collisional orogens are generated by the collision between two continental plates; modern examples are the Alps and Himalayas, the Hercynian of western Europe, and the northern Scottish side of the British Caledonides. They commonly retain a record of the successive stages of the Wilson Cycle through which they have been, such early rifts, passive continental margins, and Andean-type batholiths. They are typically long and narrow, and contain much evidence of reworking of older continental crust, and relatively little juvenile crustal material. They may, but not necessarily, include some diagnostic terranes which docked as a result of subduction, and which were trapped between the two main colliding continental plates *e.g*. the Kohistan arc terrane in the western Himalayas.

Accretionary orogens are an accumulated collage of terranes accreted to a continental margin, that may include island arcs, accretionary prisms, oceanic plateaus, ophiolites and continental blocks. They have been called Turkic-type orogens by SENGÖR and NATAL'IN (1996). They are typically very wide, have a long history, and contain much new juvenile crust, but relatively little reworked continental crust. Phanerozoic examples include Japan (midPalaeozoic to Recent), the Cordillera of western North America (Early Palaeozoic to Recent), and the early to late Palaeozoic Altaid collage of Central Asia (SENGÖR *et al*., 1993), and Proterozoic examples are the Pan-African collage of the Saudi Arabian Shield, and the 2.1 Ga Birimian of West Africa.

When discussed in the context of Palaeozoic and Precambrian orogenic belts, the term 'plates' usually refers to relatively rigid continental lithospheric blocks, which either were able to drift and so collide with other plates to form collisional orogens, or which acted as a backstop against which allochthonous terranes could accumulate to form accretionary orogens. This point is important when considering two commonly-discussed questions; firstly whether oceanic and continental plates existed in the Archaean, and secondly, does the Archaean-Proterozoic boundary represent the time when continental plates were first able to act as relatively large and independent blocks which were able to rift, drift and collide with other continental blocks to form collisional orogenic belts.

We can bear these points in mind when reviewing the geology of Archaean and Early Proterozoic orogens below.

3. The Early Crust

The Archaean eon lasted from the age of the oldest rocks at 4.17 Ga to 2.5 Ga, about a third of geological time. Primarily the Archaean was the period when the earliest crust segregated from the mantle, when the first cratons and terranes amalgamated by accretionary processes, and when the first orogens, continents and even supercontinents evolved (ROGERS, 1996).

The oldest rocks on Earth are deep crustal gneisses or granites in granulite-gneiss belts (Bowring *et al*., 1989). The oldest upper crustal rocks in any greenstone belt are 3.5–3.7 Ga at Barberton, South Africa (Kröner *et al*., 1996). Segregation of crustal or sialic material from the earth's mantle was already advanced by 4.0–3.8 Ga, but it may have been sporadic. The existence of extremely positive initial $^{\varepsilon}$Nd values in 3.7–3.8 Ga ultramafic rocks from Greenland and Labrador demonstrates the presence of a highly LREE-depleted and fractionated mantle reservoir prior to 3.8 Ga (Collerson *et al*., 1991). The presence of these Nd isotope ratios higher than that of the bulk Earth suggests that by 3.8 Ga the volume of the crust was as large as 40% of the present value. The fact that only a minute fraction ($<1\%$?) of that crust is preserved may be an indication of removal by mantle recycling, possibly therefore by subduction processes. According to Chase and Patchett (1988) the temporary storage of that subducted mafic-ultramafic oceanic crust was responsible for the high $^{\varepsilon}$Nd values. The first continents to form in the early Archaean may have been generated by collision of ocean ridge/plateau crustal blocks with each other, followed by subduction zones developing around their margins leading to the production of felsic upper crust (Condie, 1997b).

The reason for only localised development of very early crust may have been because mid-oceanic ridges before 4.0 Ga stood above sea-level, preventing interaction between the mantle and hydrosphere, and efficient production of continental crust. Not until 4.0–3.6 Ga were ridges drowned, allowing appreciable continental crust to evolve (De Wit *et al*., 1992; De Wit and Hynes, 1995). However, De Wit *et al*. (1992) suggested that the period 4.0–3.6 Ga was one of intraoceanic obduction, and that modern-style processes of subduction did not start until 3.0 Ga when the volume of low-density serpentinite had decreased, because of the decline of the Mg content of oceanic crust. This last point seems unlikely in view of geochemical and isotopic evidence from regions such as West Greenland for the production of widespread tonalite-trondhjemite-granodiorite (TTG) suites by 3.7 Ga interpreted as the result of melting of subducted mafic oceanic crust (Nutman *et al*., 1993).

4. Archaean Orogens

Many Archaean terranes, generally termed greenstone belts (De Wit and Ashwal, 1997) contain rocks that come from oceanic crust, oceanic plateaus, island arcs, fore-arcs, back-arcs, continental arcs, and accretionary wedges (*e.g.* the Superior Province, Williams *et al*., 1992). In contrast, many terranes, generally termed granulite-gneiss belts, contain rocks that have been deformed and metamorphosed in the deep continental crust. However, the presence of meta-supracrustal rocks shows that upper crustal material has been transported to the deeper parts of continental terranes, where they were tectonically intercalated with rocks that had formed in the deep crust.

A key problem concerns the tectonic relationship between upper and lower crustal belts. Only rarely do we find evidence of a complete crustal section from the upper to the lower Archaean crust, as seen in the Kapuskasing Uplift in Ontario and confirmed by the LITHOPROBE seismic reflection profile (Ludden *et al*., 1993; Percival and West, 1994). High-precision U-Pb ages of Krogh (1993) demonstrate a progressive downward younging of crustal growth. According to Percival *et al*. (1997) the greenstone lavas formed in an island arc, and the deeper crustal gneisses were generated underneath the lavas in a slightly younger Andean-type continental margin.

The development of extensive sedimentary basins in the late Archaean indicates that the continental crust had locally attained sufficient rigidity to sustain the load of sedimentary piles many kilometres thick. Examples include: the 11 km-thick, 3.1–2.7 Ga Witwatersrand Supergroup, the 8 km-thick, 2.7 Ga Ventersdorp Supergroup, and the 15 km-thick, 2.56 Ga Transvaal Supergroup all in southern Africa, the 3.5–5 km-thick, 2.77–2.70 Ga Fortescue Group in NW Australia, and the 3 km-thick, 2.79 Ga Oraniemi Group in Finland (WINDLEY, 1995).

From their exhaustive survey ERIKSSON *et al.* (1994) concluded that Archaean greenstone belts contain six lithological associations that can be matched with the following Phanerozoic depositional environments: 1. barred lagoons and bays around oceanic volcanic islands and sediment-starved platforms adjacent to coalesced volcanoes in inter-arc, intra-arc and back-arc basins. 2. forearc trenches and marine volcano-plutonic arcs. 3. cratonic extensional basins in arc-continent and intracontinental rifts. 4. continent-adjacent syn- to post-rift stable shelves and arc-adjacent post-rift stable shelves. The proportion of these sedimentary successions increased from 4.0 to 2.5 Ga in response to the progressive growth of the continents (ERIKSSON and FEDO, 1994). 5. compressional foreland basins of arc-continent collisional and compressional-arc tectonic basins. 6. strike-slip collisional graben in hinterland tectonic-escape and terrane-accretion orogens.

5. Plumes and Plateaus

The total heat flux of the Earth and the heat production from the breakdown of radiogenic isotopes were two to three times greater in the Archaean than today. Some sixty-five percent of the heat loss from the Earth today is used in oceanic crust creation and cooling, and thus, predictably, the production of Archaean oceanic crust was higher than today.

However, oceanic plateaus, generated from hot mantle plumes, could have provided an important additional mantle contribution of heat to early crustal growth. As STEIN and HOFMANN (1994) proposed, the evolution of the earth may have been punctuated by periods of increased plume activity, of which the Archaean was the first and most prominent. NISBET *et al.* (1993) calculated that Archaean mantle jets were 300°C hotter than the ambient Archaean mantle temperature. PARMAN *et al.* (1997) estimated that komatiite mantle source temperatures were 200°C higher than the hydrous mantle melting temperatures estimated in modern subduction zones, and only 100°C higher than mean mantle melting temperatures at mid-oceanic ridges, and they suggested that komatiites were generated from an Archaean mantle that was wetter than the modern MORB source, the early mantle contained high abundances of volatiles inherited from accretion, and that the komatiites could be an expression of an irreversible early degassing period of the Earth. The most likely regime was a hydrous mid-oceanic ridge, and if mantle plumes were involved, they must have contained significantly more water than modern plumes. The volcanology of a 150 km by 30 km cumulate komatiite unit in the Yilgarn block of Western Australia shows the presence of large thermal erosion channels developed by turbulent lava rivers, the size of the channels requiring very rapid eruption rates comparable to those in Phanerozoic plume-generated flood basalt provinces (HILL *et al*., 1995).

Modern oceanic crust is typically 6-10 km thick, and oceanic plateaus are up to 32 km thick. Archaean oceanic crust has been commonly calculated to have been about 20-22 km thick, and Archaean oceanic plateaus would have been even thicker (50 km?). Therefore, accretion of Archaean oceanic crust would have been close in tectonic style to that of modern oceanic plateaus (KIMURA *et al*., 1993). Because Archaean oceanic lithosphere was very chemically depleted (CHASE and PATCHETT, 1988), it is likely that oceanic plateaus would have been buoyant and thus would have accreted rather than subducted, like the Mesozoic Bolivar plateau in SW Columbia (NIVIA, 1996).

The tholeiitic lavas in greenstone belts, which have high Fe, Ni and Cr, low Al, and depleted incompatible trace elements, are comparable geochemically to modern flood basalts which are widely recognised as having been generated by plume-lithosphere interaction (TARDUNO *et al*., 1991). These geochemical similarities suggest that magmas derived from mantle plumes may have been important in building Archaean crust (HILL, 1993; CHOUKROUNE *et al*., 1997).

The bimodal volcanic rocks in Archaean greenstone belts could have been produced from mantle plumes, the abundant tholeiitic basalts from melting in the cool head of the plume, and the relatively rare komatiites by melting in the hot conduit axial jet (CAMPBELL *et al*., 1989; ARNDT *et al*., 1997). Modern hot spots and MORB share a common depleted source and thus Archaean komatiites appear to have come from the same deep depleted reservoir as modern picrites and MORB (ANDERSON, 1994). KRÖNER (1991) proposed that in the early pre-plate tectonic Earth islands of Iceland-type, thick, plume-induced crust gave rise to the basaltic-komatiitic volcanism. In contrast, MORB-like greenstone lavas underlain by tonalitic-trondhjemitic plutons could have formed as a consequence of subducting a ridge segment within 500 km of a hotspot located beneath a continent, as happened 3-6 Ma ago in the Taitao Peninsula in Chile (NELSON and FORSYTHE, 1989; ABBOTT, 1996).

Most debate about modern analogues of ancient plateaus has concerned the voluminous upper lavas, such as the tholeiitic-komatiitic suites of the Malartic-Val d'Or area in the Canadian Superior Province, which are comparable geochemically to Tertiary lavas of the oceanic plateau on Gorgona island (STOREY *et al*., 1991; KIMURA *et al*., 1993). The Malartic block in the Abitibi greenstone belt was envisaged by DESROCHERS *et al*. (1993) as resulting from the amalgamation of fragments of oceanic plateaus upon which was superimposed extension-related calc-alkaline volcanism. In the Vizien greenstone belt a 2786 Ma mafic-ultramafic sequence is an allochthonous package of pillowed basaltic andesite, komatiite, and volcaniclastic rocks cut by peridotite and gabbro sills; the sequence is interpreted by SKULSKI and PERCIVAL (1996) as a sliver of plume-related oceanic plateau crust. Also in the Abitibi belt the association of calc-alkaline rhyolites with rifted arc-related basalts passing upward into MORB-like basalts, which in turn are capped by komatiites, reflects an evolution in magma genesis from crustal melting (rhyolites) and arc rifting to melting of a mantle plume; the plume rose below an arc, the MORB-like basalts being produced from the cooler plume head at a shallower depth (DOSTAL and MUELLER, 1997).

But what about the deeper parts of plateaus ? Based on the account of NIVIA (1996) of the Bolivar mafic-ultramafic complex in Columbia, as the obducted lower crust of the

Caribbean-Columbian oceanic plateau, Kent *et al.* (1996) suggested that the deeper portions of an Archaean plateau consisted of norite underlain by lherzolite, orthopyroxenite, gabbronorite and dunite. As yet, descriptions of possible deep sections of Archaean plateaus are rare. One example may be in the Superior Province where the basal part of the Vizien belt consists of serpentinite schists with gabbroic pods overlain by gabbros and pillow basalts (Skulski and Percival, 1996). Not surprisingly controversy has arisen about the interpretation of some Archaean sequences. For example, Kusky and Kidd (1992) interpreted a thrust-based 6.5 km thick succession of 2.7 Ga basaltic and peridotitic komatiites in the Belingwe greenstone belt in Zimbabwe as a fragment of an accreted and fragmented oceanic plateau. However, Bickle *et al* (1994) reaffirmed the existence of an unconformity between the lavas and underlying granites and gneisses, negating the plateau model. But what about the ridge subduction plume model of the Taitao Peninsula referred to above ?

The discovery of 3.2–3.3 Ga diamonds derived from over 150 km depth demonstrates that stable continental roots existed by that time. From their Re-Os isotope studies Pearson *et al.* (1995) found that shallow, spinel-facies and deep, diamond-facies Kaapvaal peridotites have similar ages of 3.3–3.5 Ga and concluded that 150 km of mantle lithosphere had accumulated quickly and that the stabilisation of cratonic lithosphere occurred by, at least, 3.5 Ga, when the lithosphere was over 200 km thick. Only hot mantle plumes would have been capable of generating rapidly such thick lithospheric keels by a process of harzburgite crystallisation from high-degree ($>50\%$) mantle melts. The presence of rare Ni-rich assemblages enriched in platinum group elements in high-temperature ultramafic rocks of the 3.5 Ga Jamestown ophiolites in South Africa led Tredoux *et al.* (1989) to conclude that ultramafic magmas rose though the mantle in a thermal plume which originated in the lowermost mantle (the D' layer). However, the Archaean plume model has come under fire from the results of Hart *et al.* (1997) who found that the Sc/Cr ratios in eclogite and peridotite inclusions in diamonds and the Au/Ir ratios in sulphide inclusions in diamonds are similar to those known in rocks of both the present-day oceanic lithosphere and the lavas in some Archaean greenstone belts. From these relationships they argued that the peridotites did not form as high pressure residues after extraction of komatiitic and basaltic lavas from the Archaean mantle as a result of mantle plume transport, but rather that the Archaean continental lithosphere, consisting of alternating peridotite and eclogite, evolved by tectonic stacking of oceanic crust and its underlying mantle respectively during oceanic collisions, subduction and obduction; tectonics controlled the petrology, not magmatism via plumes !

If plumes hit oceanic lithosphere, then somewhere they might have come up under continental lithosphere. The Dharwar craton may be such an example of reheating of continental crust by plume impact. The craton is characterised by dome-basin structures, granitic diapirs and intervening triple junctions of mafic material, which Chardon *et al.* (1996) and Choukroune *et al.* (1997) ascribed to the impact of a plume at 2.5 Ga, which resulted in diapirism. From field observations of high-grade gneissic terranes on several continents Choukroune *et al.* (1995) suggested that the dome-and-basin structures and flat-lying foliations caused by vertical flattening resulted from episodes of enhanced plume activity which thermally softened the continental crust, and thus gave rise to a structural style different from that of modern orogenic belts, which are generally marked by a uniform structural trend and vergence. Comparable, 2.5–2.4 Ga, vertically-flattened domal structures in granulites in North China were explained by DIRKS *et al.* (1997) as a result of the diapiric uprise of lower crustal material via solid-state advective flow independent of crustal thickening and tectonic denudation. However, it is interesting that very similar gneiss domes and metamorphic nodes in the 1.87–1.83 Ga Penokean orogen formed as a result of orogenic collapse superimposed on an earlier period of crustal shortening (SCHNEIDER *et al.*, 1996).

6. Oceanic Lithosphere

The best example of an Archaean, modern-type, ophiolite is the remarkable 2.7 Ga ophiolitic complex in the greenstone terrane of the Yilgarn craton of Western Australia; this complex has mafic lavas, excellent sheeted mafic dykes, and ophiolite-type peridotites and gabbros (FRIPP and JONES, 1997). Other interesting candidates of Archaean ophiolites are: the Barberton ultramafic-mafic complex in southern Africa (DE WIT *et al.*, 1987); the 2.70 to >2.72 Ga, mafic extrusive Kam Group in the Yellowknife greenstone belt in the Slave Province of Canada (HELMSTAEDT *et al.*, 1986) which has sheeted mafic dykes and pillowed basalts with MORB-type chemistry (ISACHSEN and BOWRING, 1997); a mafic-ultramafic assemblage in the Slave Province, which has an underlying high-temperature dynamothermal aureole (KUSKY, 1990); and a succession of pillow basalts, mafic dykes, gabbros and serpentinites on a terrane boundary in the Minnesota River Valley (SOUTHWICK and CHANDLER, 1996).

More recently, 3.1–3.3 Ga low-K tholeiites with MORB-type chemistry were described in Australia by OHTA *et al.* (1996), who proposed that the potential mantle temperature was about 120°C higher than today and that the oceanic crust would have been 2–3 times thicker than today; a crustal thickness of about 20–22 km thick was suggested by SLEEP and WINDLEY (1982), HOFFMAN and RANALLI (1988), and BICKLE *et al.* (1994). Delamination of volcanic units in a greenstone belt in the Superior Province led to preservation of only pillow basalts with modern type oceanic crust chemistry (TOMLINSON *et al.*, 1996).

Many oceanic-looking basalts from Archaean greenstone belts have geochemical affinities more like modern supra-subduction back-arc basalts, and thus an oceanic back-arc model has commonly been proposed; *e.g.* in the Superior Province (TOMLINSON *et al.*, 1996) and the Zimbabwe craton (JELSMA *et al.*, 1996). However, basalts dredged from the modern southern Chile Ridge close to the advancing continental margin have hybrid MORB-arc geochemical characteristics, comparable to those of some Archaean greenstone basaltic lavas, leading support to the idea that ridge subduction may have been an important mechanism in the Archaean (KARSTEN *et al.*, 1996).

7. Arcs and Subduction Zones

The creation of extensive oceanic lithosphere in the Archaean would necessitate a high degree of subduction to maintain a non-expansive Earth. Evidence for the existence in Archaean greenstone belts and granulite-gneiss belts of rocks with chemical affinities comparable to modern island arcs and continental arcs is abundant. For example, there is a huge quantity of high quality structural-geochemical-isotopic data that indicate that a vast segment of the Superior Province of Canada consists of arc-derived crust that formed in the period 3.1-2.65 Ga (CARD, 1990; WILLIAMS *et al.*, 1992; KIMURA *et al.*, 1993; SUTCLIFFE *et al.*, 1993; AYER and DAVIS, 1997). In particular, many lava piles are dominated by calc-alkaline andesites to basalts with trace element and LREE patterns, strong negative Nb anomalies and LILE enrichments comparable to those in high-K calc-alkaline lavas in modern island arcs. Significantly, TAIRA *et al.* (1992), the Japanese experts on Japanese island arcs, having studied Archaean arcs in the Pilbara craton of NW Australia, concluded that they could see little difference in their rock associations, petrology, structural relations and styles of accretion.

Several process-oriented aspects of Archaean arcs and associated structures are worth considering:

1) Many U-Pb age determinations indicate that the locus of subduction and arc accretion of the Superior Province migrated southwards (THURSTON *et al.*, 1991). The two principal tectonic models to account for this accretion are:

a. Arc-arc collision. This model, widely accepted by early workers (*e.g.* HOFFMAN, 1989; WILLIAMS, 1990; THURSTON and CHIVERS, 1990), involved the progressive northward accretion of new arcs, each on their own subduction zones, the arcs or collections of arcs being separated by sedimentary prisms.

b. Migrating or prograding arc-trench model (HOFFMAN, 1991; KIMURA *et al.*, 1993; JACKSON and CRUDEN, 1995). Many oceanic or continental fragments were swept northwards and accreted on one subduction zone to create an extensive accretionary package. This mechanism requires that new arcs were developed on each newly accreted accretionary prism, that the single subduction zone and trench backstepped or migrated oceanwards (SENGÖR *et al.*, 1993), this being caused by choking of the subduction zone, and that both the initiation and cessation of arc magmatism show an oceanward migration (KIMURA *et al.*, 1993).

2) The roots of volcanic arcs should be present in places. The Lac des Iles complex in the Superior Province consists of concentric bodies of peridotite, pyroxenite, hornblende gabbro and diorite, which resemble the Alaskan-type concentric intrusions in Phanerozoic magmatic arcs; they most likely represent the root zones of Archaean Andean-type continental margins (BRÜGMANN *et al.*, 1997).

3) In modern or ancient accretionary prisms we never find complete sections of either oceanic crust or plateaus, but most commonly only thin slices of basalt and pelagic sediment. The permeability contrast between low temperature-altered, more buoyant upper oceanic crust from the remainder of the downgoing slab causes delamination, the former being obducted and accreted, and the denser, mantle-dominated lower part of the plate being subducted (KIMURA and LUDDEN, 1995). To overcome the buoyancy problem, HOFFMAN and RANALLI (1988) suggested similar subduction-related delamination of Archaean oceanic crust. A comparable process may affect the upper and lower parts of accreting island arcs.

4) Once a substantial collage of Archaean accreted arcs, plateaus, continental fragments and accretionary prisms had been built up, they would act as an incipient microcontinent or proto-craton, the leading edge of which would effectively become an active continental margin, so giving rise to Andean-type magmas. PERCIVAL *et al.* (1994)

described such an incipient active 2.72 Ga continental margin magmatic arc in the Vizien greenstone belt in Canada, which has been imbricated with a sliver of 2.78 Ga plume-related oceanic plateau crust, and a 2.72 Ga volcanic sequence representing continental rift deposits (SKULSKI and PERCIVAL, 1996). Also in the Superior Province in the Beardmore-Geraldton greenstone belt rocks from oceanic, arc and back-arc crusts have been delaminated and juxtaposed (TOMLINSON *et al.*, 1996). The partial melting of the accretionary prism between the Abitibi and Pontiac terranes led to the formation of intrusive granitic rocks (DUCHARME *et al.*, 1997).

5) The paper by MARTIN (1986) has had profound influence on ideas of Archaean subduction tectonics. He proposed that the location of calc-alkaline magma genesis in subduction zone environments has changed with time from more slab melting without dehydration in the Archaean to more mantle wedge melting as a result of slab dehydration in post-Archaean time. This process would have facilitated the formation of abundant Andean-type tonalites, which indeed we see today in many Archaean granulite-gneiss belts such as West Greenland where melting of subducted mafic oceanic crust produced $\geq$3.70 Ga microcontinents consisting of tonalite-trondhjemite-granodiorite-dacite (TTG, TTD or adakite) suites (NUTMAN and COLLERSON, 1991; NUTMAN *et al.*, 1993). Similar high-Al adakite suites continue to form in modern arcs where hot oceanic crustal slabs less than 25 Ma old have been subducted and melted (DEFANT and DRUMMOND, 1990; DRUMMOND *et al.*, 1996) The 3.0 Ga TTG suite in the Lewisian of NW Scotland was also probably the product of partial melting of subducted mafic crust (ROLLINSON, 1996).

Another group of minor but important Archaean arc-type rocks are high-Mg, hornblende-bearing quartz monzodiorites, which are comparable to high-Mg andesites in modern subduction zone environments such as Japan, which are thought to be melts from a metasomatised mantle wedge (BÉDARD, 1996).

The oldest well-documented alkaline rocks are 2.7 Ga trachytes and leucite phonolites from the Kirkland Lake area of Canada, the trace element characteristics of which closely resemble those of shoshonitic lavas in modern island arcs (BLICHERT-TOFT *et al.*, 1996). However, the rarity of comparable Archaean alkaline rocks still requires explanation.

6) Geophysical data are beginning to provide important constraints on sub-surface Archaean structures. Seismic data from the LITHOPROBE profile across the boundary of the volcanic-dominated Abitibi granite-greenstone arc belt and the plutonic arc-related Opatica belt show dipping seismic reflections that extend through the crust and 30 km into the mantle. They are interpreted to represent a relict 2.69 Ga suture associated with subduction and collision of these terranes and provide "direct evidence that plate tectonics was active in the late Archaean times" (CALVERT *et al.*, 1995). In the same region magnetotelluric measurements reveal pronounced electrical anisotropy in the upper mantle, best explained by conducting graphite films associated with metasomatised mantle roots of major Archaean shear zones. They also demonstrate that the uppermost mantle beneath the Canadian Shield had remained fixed to the crust and isolated from significant tectonic reworking since the late Archaean (MARESCHAL *et al.*, 1995). Other LITHOPROBE seismic data across the Opatica and Wawa terranes reveal crustal-scale imbricate, 'in sequence' reflectors above a shallow dipping sole thrust at a mid-crustal level. They resemble the thrust stacks in many Phanerozoic orogenic belts, and are interpreted by LACROIX and SAWYER (1995) as a ductile-brittle fold-thrust belt.

In summary, Archaean greenstone belts are very similar in lithology, geological make-up, structural style, and tectonic evolution to younger accretionary orogens, such as the Palaeozoic Altaid collage of Central Asia, and to incipient accretionary orogens like those in Japan and Indonesia (TAIRA *et al.*, 1992; WINDLEY, 1995; SENGÖR and NATAL'IN, 1996). It is not surprising therefore that most greenstone belts have been explained in terms of modern-style plate tectonic processes as accretionary orogens containing volcanic arcs, back-arc basins, accretionary prisms and microcontinents, and their amalgamation gave rise to supercontinents (*e.g.* the YILGARN craton, MYERS, 1995). However, such accretion does require a back-stop against which the first terrane was able to accumulate. Such back-stops were provided by the continental granulite-gneiss blocks, several of which were already in existence by the time of peak of greenstone belt formation in the late Archaean.

By the end of the Archaean much mature continental crust with thick sub-continental lithosphere had developed to form cratons or continents (DE WIT *et al.*, 1992; MYERS, 1995). This heralded the beginning of the Proterozoic at 2.5 Ga by which time large continents or even supercontinents had formed.

8. Early Proterozoic Orogens

During the Early Proterozoic many accretionary and collisional orogens developed (WINDLEY, 1992).

Accretionary orogens include:
2.1 Ga. The Birimian of West Africa (ABOUCHAMI *et al.*, 1990; MILÉSI *et al.*, 1992; FEYBESSE and MILÉSI, 1994) and the contemporaneous Rio Itapicura in Brazil (DAVISON *et al.*, 1988).
1.9-1.7 Ga. The Yavapai-Mazatzal-Central Plains-Penokean of Central North America (PATCHETT and ARNDT, 1986).
1.9-1.8 Ga. The Svecofennian of the Baltic Shield (NIRONEN, 1997).

Collisional orogens include:
2.0-1.9 Ga. The Kola-Karelian of the northern Baltic Shield (MARKER, 1989).
2.02-1.91 Ga. The Thelon and the 1.97-1.84 Ga Wopmay of NW Canada (HOFFMAN, 1989).
1.9-1.83 Ga. The Trans-Hudson in North America (LEWRY *et al.*, 1994; LUCAS *et al.*, 1994).
And all in Australia, between 1880 and 1400 Ma the Strangways, Argilke and Chewings orogenies (MYERS *et al.*, 1996).

Seismic reflection profiles are providing valuable images which help to constrain tectonic processes. Profiles across Early Proterozoic orogens of the Svecofennian in the Baltic Shield, the Lewisian in the British and Irish Isles, and the Trans-Hudson in the Canadian Shield reveal well-defined crustal reflectors and laterally coherent mantle reflectors (SNYDER *et al.*, 1996). In all cases, juvenile 1.9-1.8 Ga lithosphere was delaminated and its crustal flakes overrode the adjacent Archaean margins during arc-continent collisions. Reflection data from the Makkovik, New Quebec, Torngat, and the Eastern Churchill (Rae) orogens in the Canadian Shield show that the Early Proterozoic crust in all cases has structural forms comparable with those of modern orogens, and accordingly its tectonic development was controlled by very similar collisional processes (HALL *et al.* 1995).

The following are examples in Early Proterozoic orogens of key units which have plate tectonic significance.

9. Passive Continental Margins

After the break-up of the supercontinent(s) at the Archaean-Proterozoic boundary extensive passive continental margins developed on which were deposited shelf sediments dominated by continent-derived clastics such as conglomerates, quartzites and sandstones; (bio)chemical carbonates and iron-formations; and immature potassium-rich arkoses derived by erosion of the commonly exposed Archaean granitic rocks. The increase in continental surface area at the Archaean-Proterozoic boundary increased the weathering rate and the rate of removal of the greenhouse gas CO_2 from the atmosphere. The formation of substantial shelves in the Early Proterozoic may be attributed to a substantial increase in ocean water mass through increased degassing of the mantle (BREUER and SPOHN, 1995).

2.69-2.47 Ga Hamersley Group, W. Australia. 400 m-thick carbonates pass into slope-basin sediments (SIMONSON *et al.*, 1993).

2.55 Ga Transvaal Group, South Africa. 1.5 km-thick dolomites (JAHN *et al.*, 1990).

2.45 Ga Huronian Group Canada. Syn-rift volcanics and sediments overlain by 2.3-2.2 Ga carbonate-bearing sediments (FRALICK and MIALL, 1989).

2.14 Ga New Quebec orogen Canada. Quartzites and carbonate reefs on passive margin of Superior craton (SKULSKI *et al.*, 1993).

2.05 Ga Jatulian Group, Finland. Basal quartzite and shelf carbonates overlie 2.3 Ga continental-rift conglomerates and tholeiitic lavas (WINDLEY, 1995).

1.9 Ga Wopmay orogen, NW Canada. Rift-fill clastics overlain by stromatolitic dolomites (HOFFMAN, 1989).

10. Ophiolites

In Phanerozoic orogens ophiolites occur in three tectonic environments; in thrust slices within accretionary orogens, in the suture zones of collisional orogens, where they may also occur as fragments in accretionary prisms, and on the craton-directed thrusted shelf or continental margin of collisional orogens. The last type stands topographically high, and is one of the first units to be eroded.

When searching for Precambrian ophiolites more reliance and general acceptance is given to those with sheeted mafic dykes. When ophiolites are subducted, remnant thrust shreds of ultramafic-mafic rocks may be the only relicts to be observed in deep crustal rocks. Examples of Early Proterozoic ophiolites with sheeted dykes include:

Portuniq and Watts Group, thrusted onto continental margin of Ungava orogen. Canada, 1.998±2 Ma (SCOTT *et al.*, 1992).

Jormua, Finland, thrusted onto continental margin of Svecofennian orogen, 1.95 Ga (PELTONON *et al.*, 1996; 1998).

Outokumpu assemblage, 1.97 Ga, within Svecofennian suture zone (LOUKKOLA-RUSKEENIEMI *et al*., 1991).

Payson, Arizona, USA, on top of island arc within accretionary collage of Yavapai-Mazatzal belt, 1.73 Ga (DANN and BOWRING, 1997).

Niagara suture zone of Penokean orogen, Canada-USA border, 1.85 Ga (SCHULZ, 1987).

In the Amisk collage of the 1.9 Ga Flin Flon belt within the Trans-Hudson orogen of N.W. Canada the thrusted Elbow-Athapap allochthon contains N-MORB-type and Mariana back-arc-type basalts suggesting derivation from a back-arc basin, and E-type basalts resembling plume MORB-types possibly derived from an oceanic plateau (STERN *et al*, 1995). These are associated with oceanic-type gabbros and ultramafic crustal cumulates, the whole collage being interpreted as a dismembered back-arc ophiolite, irrespective of the fact that sheeted dykes are absent (LUCAS *et al*, 1996).

11. Suture Zones

In collisional orogens the suture zone between collided continental blocks or between arcs and continental blocks may be well marked. In accretionary orogens there may be sutures between successively accreted arcs brought in by different subduction zones on different plates, or by just one subduction zone, as in the model of the SENGÖR *et al.* (1993). Sutures are more prominent between arcs and accreted blocks of high-grade gneissic rocks. Only some terrane boundaries may be sutures. Because sutures should separate blocks of different age and type, in Precambrian orogens it is necessary to obtain isotopic data to define the age parameters. In recent years geophysical anomalies of different types have been used to substantiate the existence of suture zones. Some Proterozoic orogens, that otherwise contain many plate tectonic signatures, have no exposed suture zone; *e.g.* the Wopmay orogen in NW Canada (HOFFMAN, 1989).
Examples of suture zones in Early Proterozoic orogens include:

The Luleå-Kuopio suture extends for at least 700 km along the northeastern margin of the 1.9 Ga Svecofennian orogen. Within it are many lenses of; serpentinite up to a 1 km wide, pillow lavas, turbidites deposited in debris flows on the continental margin, the Outokumpu ophiolitic rocks, and graphitic metal-enriched black schists that are comparable to hydrothermal vent deposits in present-day mid-oceanic ridges (LOUKOLA-RUSKEENIEMI *et al*., 1991). The suture zone is marked by a discontinuous geoelectrical conductor and a thick crust that comprises highly conductive graphitic and sulphide-bearing meta-sediments (KORJA *et al*., 1993). Electrical conductivity distribution marks at least three other fossil tectonic boundaries and sutures in the Fennoscandian Shield (KORJA, 1993).

The 1.85 Ga Niagara suture zone in the Penokean orogen of N. America contains an ophiolite with serpentinite, sheeted dykes, and tholeiitic basalts (SCHULZ, 1987).

The *ca.* 1.8 Ga Makkovikian-Ketildian orogen extends from Labrador to SW Greenland. Recent seismic reflection profiling of the ECSOOT Lithoprobe programme shows a major southerly-dipping reflector correlated by KERR *et al.* (1997) as the plate boundary between an Archaean block and the orogen on the south-east side. This confirms the suggestion by WINDLEY (1991) that this boundary at the surface in Greenland represents the southeast-dipping suture zone of the orogen. PATCHETT and BRIDGWATER (1984) demonstrated from Sm/Nd model data that the Ketilidian crust was juvenile and contrasted with the older Archaean crust to the north across this suture zone.

In Tanzania a 35-km long belt of eclogite-facies rocks yield a U-Pb age of 2.0 Ga on monazites and rutiles for the time of metamorphism, which was at a pressure of 18 kbar, and mafic eclogites have trace and rare earth element chemistry comparable to that of modern MORB basalts (Möller *et al.*, 1995). The evidence reasonably indicates that these high-pressure rocks formed during subduction of oceanic lithosphere, confirming the operation of plate tectonic processes at that time.

There are not many sutures which are exposed today at their mid-crustal level. One such example is the Tasiuyak gneiss which occupies the suture zone in the 1870–1840 Ma Torngat orogen in Canada (Rivers *et al.*, 1996).

12. Magmatic Arcs

If subduction zones were in operation in the Early Proterozoic, then calc-alkaline volcanic and/or plutonic arcs would be expected, preferably parallel to suture zones. The following are a few of many well-documented examples:

2.05 Ga. Ubendian-Usagaran orogen, Malawi. Ring *et al.* (1997).
2.0–1.9 Ga. Rae orogen, NW Canada. Hanmer *et al.* (1992).
1.90–1.88 Ga. Trans-Hudson, Flin Flon belt, Canada. David and Syme (1994).
1.89–1.83 Ga. Ungava orogen, Canada. St-Onge *et al.* (1997).
1.84–1.83 Ga. Trans-Hudson, Kisseynew belt, Canada. Ansdell *et al.* (1995).
1.83–1.81 Ga. SE Churchill, Western Labrador. James *et al.* (1996).
1.76 Ga. Gothian orogen, SW Sweden. Ahäll and Daly (1989).
1.75–1.71 Ga. Yavapai-Mazatzal. Arizona. Dann and Bowring (1997).

Many Early Proterozoic magmatic arcs are well-defined by their rare earth, trace element and isotopic signatures, which are comparable to those of modern equivalent arcs. They leave no doubt that subduction processes were active and responsible for them.

13. Conclusions

We return to the challenging remarks of Davies (1993), Goodwin (1996), Park (1997), and Hamilton (1998), namely that modern-style plate tectonic processes were either absent, or were a minor process in the Archaean relative to plume tectonics. Are they correct in their understanding or reading of the evidence? The conclusions referred to above in this paper refute their misunderstanding, in so far as the publications quoted provide a massive corpus of detailed evidence which collectively indicate that the present-day plate tectonic processes of oceanic plate accretion and subduction, generation of island arcs, oceanic plateaus, arc-arc and arc-continent collisions, arc-dominated collages, and the formation of suture zones were all in operation in the mid-late Archaean.

The Archaean was clearly a period of juvenile crustal growth, and the resultant island arcs, accretionary prisms, and incipient active continental margins had to form and coalesce before a supercontinent could form at the end of the Archaean. It is not surprising therefore the geology of the main Archaean greenstone belts is very similar to that of Proterozoic and Palaeozoic accretionary orogens, as indicated earlier. Significantly, the proponents of anti-plate tectonic models for the Archaean such as GOODWIN (1996) and HAMILTON (1998) do not make comparison with these younger accretionary collages. When HAMILTON (1998) states that "Granite-and-greenstone terrains typify Archean upper crust and have no structural and magmatic analogues younger than very early Proterozoic", he is wrong, because the accretionary collages of the Arabian-Nubian Shield (Pan-African) and of Central Asia (Palaeozoic) are indeed comparable, as emphasized by SENGÖR and NATAL'IN (1996).

Phanerozoic island arcs and magmatic arcs form at convergent plate margins. Wheras HAMILTON (1998) boldy stated that "no primary belts (of magmatic arcs) have been demonstrated to exist in Archean assemblages on the basis of either field relationships or geochronology", I suggest that the Japanese experts (in TAIRA *et al.*, 1992) on Phanerozoic island arcs have more credence in recognizing modern analogues in Archaean greenstone belts. However, it has to be said that there are still major problems in interpreting the TTG component of Archaean granulite-gneiss belts in terms of modern analogues, the main reason being the paucity of modern Andean-type orogens that have been eroded to a deep crustal level to provide the required comparative evidence.

HAMILTON (1998) stated that "Archaean ultramafic and mafic volcanic rocks neither resemble ophiolitic rocks in petrology nor occur in ophiolite-type successions". However, he has not taken account of the ophiolite successions in the Yilgarn block described by FRIPP and JONES (1997), which contain sheeted mafic dykes and a gabbro to peridotite succession comparable petrologically with that in modern ophiolites. BICKE *et al.* (1994) concluded from their analytical survey that no examples of oceanic crust exist in Archaean greenstone belts. We await their study of the Yilgarn occurrences.

Although many people are persuaded that plumes played an important role in Archaean crustal evolution, there have been surprisingly few discoveries of their products. This problem is exacerbated by the paucity of data on modern examples (often submarine) and of the lack of information on the geochemical characteristics to be expected of early equivalents. CONDIE (1997b) found that of 96 post-Archaean greenstones for which he had good quality data, only about 10% have oceanic plateau-MORB affinities, and that in greenstones of all ages lithological proportions show that arc-types greatly exceed oceanic plateau- and MORB-types in abundance. Moreover, the data and ideas of HART *et al.* (1997) throw doubt on the plume model for the Archaean. Much re-thinking and more corroborative data are required to substantiate the role of plumes in early crustal growth.

Evidence for the occurrence of one or more supercontinental blocks at about the Archaean-Proterozoic boundary is currently forthcoming. More obvious is the evidence (*e.g.* enormous basic dyke swarms) for the break-up of these blocks in the Early Proterozoic to give rise to extensive passive continental margins with the first major carbonate-quartzite shelf sequences. The formation of such shelves implies prior continental rifting and drifting, and the geological record provides us with a few (as would be expected) examples of obducted ophiolites, of evidence of many calc-alkaline magmatic arcs indicating the role of subduction tectonics, and finally of many Early Proterozoic suture zones within both accretionary and collisional orogens (WINDLEY, 1995).

However, we must also be aware that strict uniformitarian ideas can be taken too far. We know, for example, that the rate of break-down of radiogenic isotopes was several times higher in the Archaean than now, that the mantle was predictably hotter in the early Earth, and that komatiites are more common in the Archaean than in the modern rock record. In future, we need to better understand such factors as possible different styles of plate tectonic processes in the Archaean, the importance of delamination of the lower crust and lithosphere during extensional collapse of orogens, and the effects of crustal-scale tectonic stacking versus oceanic plateau generation in the hotter ambient thermal regime.

References

ABBOTT, D.H. (1996): Plumes and hotspots as sources of greenstone belts. Lithos, **37**, 113-127.

ABOUCHAMI, W., BOHER, M., MICHARD, A. and ALBAREDE, F. (1990); A major 2.1 Ga event of mafic magmatism in West Africa: an early stage of crustal accretion. J. Geophys. Res., **95**, 17605-17629.

AHÄLL, K.I. and DALY, J.S. (1989): Age, tectonic setting and provenance of Östfold-Marstrand Belt supracrustals: westward crustal growth of the Baltic Shield at 1760 Ma. Precamb. Res., **45**, 45-61.

ANDERSON, D.L. (1994): Komatiites and picrites: evidence that the 'plume' source is depleted. Earth Planet. Sci. Lett., **128**, 303-311.

ANSDELL, K.M., LUCAS, S.B., CONNORS, K. and STERN, R.A. (1995): Kisseynew metasedimentary gneiss belt, Trans-Hudson orogen (Canada): Back-arc origin and collisional inversion. Geology, **23**, 1039-1043.

ARNDT, N.T., KERR, A.C. and TARNEY, J. (1997): Dynamic melting in plume heads: the formation of Gorgona komatiites and basalts. Earth Planet. Sci. Lett., **146**, 289-301.

AYER, J.A. and DAVIS, D.W. (1997): Neoarchean evolution of differing convergent margin assemblages in the Wabigoon Subprovince: geochemical and geochronological evidence from the Lake of the Woods greenstone belt, Superior Province, northwestern Ontario. Precamb. Res., **81**, 155-178.

BÉDARD, L.P. (1996): Archean high-Mg quartz-monzodiorite suite: a re-evaluation of the parental magma and differentiation. J. Geol., **104**, 713-728.

BICKLE, M.J., NISBET, E.G. and MARTIN, A. (1994): Archaean greenstone belts are not oceanic crust ? J. Geol., **102**, 121-138.

BLICHERT-TOFT, J., ARNDT, N.T. and LUDDEN, J.N. (1996): Precambrian alkaline magmatism. Lithos, **37**, 97-111.

BOWRING, S.A.,WILLIAMS, I.S. and COMPSTON, W. (1989): 3.96 Ga gneisses from the Slave Province, Northwest Territories, Canada. Geology, **17**, 971-975.

BREUER, D. and SPOHN, T. (1995): Possible flush instability in mantle convection at the Archaean-Proterozoic transition. Nature, **378**, 608-610.

BRÜGMANN, G.E., REISCHMANN, T., NALDRETT, A.J. and SUTCLIFFE, R.H. (1997): Roots of an Archean volcanic arc complex: the Lac des Iles area in Ontario, Canada. Precamb. Res., **81**, 223-239.

CALVERT, A.J., SAWYER, E.W., DAVIS, W.J. and LUDDEN, J.N. (1995): Archaean subduction inferred from seismic images of a mantle suture in the Superior Province. Nature, **375**, 670-674.

CAMPBELL, I.H., GRIFFITHS, R.W. and HILL, R.I. (1989): Melting in an Archaean mantle plume: heads it's baskets, tails it's komatiites. Nature, **339**, 697-699.

CARD, K.D. (1990): A review of the Superior Province of the Canadian Shield; a product of Archaean accretion. Precamb. Res., **48**, 99-156.

CHARDON, D., CHOUKROUNE, P. and JAYANANDA, M. (1996): Strain patterns, décollement and incipient sagducted greenstone terrains in the Archaean Dharwar craton (South India). J. Struct. Geol., **18**, 991-1004.

CHASE, C.G. and PATCHETT, P.G. (1988): Stored mafic/ultramafic crust and early Archaean mantle depletion. Earth Planet. Sci. Lett., **91**, 66-72.

CHOUKROUNE, P., BOUHALLIER, H. and ARNDT, N.T. (1995): Soft lithosphere during periods of Archaean crustal growth or crustal reworking. Early Precambrian Processes, ed. by M.P. Coward and A.C. Ries. Oxford, Blackwell, 67-86 (Geol. Soc. London, Spec. Publ., **95**).

Choukroune, P., Ludden, J.N., Chardon, D., Calvet, A.J. and Bouhallier, H. (1997): Archaean crustal growth and tectonic processes: a comparison of the Superior Province, Canada and the Dharwar Craton, India. Orogeny through Time, ed. by J.-P. Burg and M. Ford. Oxford, Blackwell, 63-98 (Geol. Soc. London, Spec. Publ., **121**).

Collerson, K.D., Campbell, L.M., Weaver, B.L. and Palacz, Z.A. (1991): Evidence for extreme mantle fractionation in early Archaean ultramafic rocks from northern Labrador. Nature, **349**, 209-214.

Condie, K.C. (1997a): Plate Tectonics and Crustal Evolution. Oxford. Butterworth-Heinemann, 282 p.

Condie, K.C. (1997b): Contrasting sources for upper and lower continental crust: the greenstone connection. J. Geol., **105**, 729-736.

De Wit, M.J. and Ashwal, L.D., ed. (1997): Greenstone Belts. Oxford, Clarendon Press.

De Wit, M.J. and Hynes, A. (1995): On the onset of interaction between the hydrosphere and oceanic crust, and the origin of the first continental lithosphere. Oxford, Blackwell, 1-9 (Geol. Soc. London, Spec. Publ., **95**).

De Wit, M.J., Hart, R.A. and Hart, R.J. (1987): The Jamestown ophiolite complex, Barberton mountain belt: a section through 3.5 Ga oceanic crust. J. Afr. Earth Sci., **6**, 681-730.

De Wit, M.J. *et al.* (1992): Formation of an Archaean continent. Nature, **357**, 553-562.

Dann, J.C. and Bowring, S.A. (1997): The Paysan ophiolite and Yavapai-Mazatzal orogenic belt, central Arizona. Greenstone Belts, ed. by M.J. De Wit and L.D. Ashwal. Oxford, Clarendon Press, 781-790.

David, J. and Syme, E.C. (1994): U-Pb geochronology of late Neoarchean tonalites in the Flin Flon Belt, Trans-Hudson orogen: surprise at surface. Can. J. Earth Sci., **31**, 1785-1790.

Davies, G.F. (1993): Conjectures on the thermal and tectonic evolution of the Earth. Lithos, **30**, 281-289.

Davison, I., Teixeria, J.B.G., Silva, M., G., Neto, M.B.R. and Matos, F.M.V. (1988): The Rio Itapicura greenstone belt, Bahia, Brazil: structure and stratigraphic outline. Precamb. Res., **42**, 1-17.

Defant, M.J. and Drummond, M.S. (1990): Derivation of some modern arc magmas by melting of young subducted lithosphere. Nature, **347**, 662-665.

Desrochers, J-P., Hubert, C., Ludden, J.N. and Pilote, P. (1993): Accretion of Archean oceanic plateau fragments in the Abitibi greenstone belt, Canada. Geology, **21**, 451-454.

Dirks, P.H.G.M., Zhang, J.S. and Passchier, C.W. (1997): Exhumation of high-pressure granulites and the role of lower crustal advection in the North China Craton near Datong. J. Struct. Geol., **19**, 1343-1358.

Dostal, J. and Mueller, W.U. (1997): Komatiite flooding of a rifted Archean rhyolitic arc complex: geochemical signature and tectonic significance of the Stoughton-Roquemaure Group, Abitibi greenstone belt, Canada. J. Geol., **105**, 545-563.

Drummond, M.S., Defant, M.J. and Kepezhinskas, P.K. (1996): Petrogenesis of slab-derived trondhjemite-tonalite-dacite/adakite magmas. Trans. R. Soc. Edinburgh: Earth Sci., **87**, 205-215.

Ducharme, Y., Stevenson, R.K. and Machado, N. (1997): Sm-Nd geochemistry and U-Pb geochronology of the Preissac and Lamotte leucogranites, Abitibi subprovince. Can. J. Earth Sci., **34**, 1059-1071.

Eriksson, K.A. and Fedo, C.M. (1994): Archean synrift and stable-shelf sedimentary successions. Archaean Crustal Evolution, ed. by K.C. Condie. Amsterdam, Elsevier, 411-459.

Eriksson, K.A., Krapez, B. and Fralick, P.W. (1994): Sedimentology of Archean greenstone belts: signatures of tectonic evolution. Earth Sci. Rev., **37**, 1-88.

Fralick, W. and Miall, A.D. (1989): Sedimentology of the Lower Huronian Supergroup (Early Proterozoic), Elliot Lake area, Ontario, Canada. Sediment. Geol., **63**, 127-153.

Fripp, R.E.P. and Jones, M.G. (1997): Sheeted intrusions and peridotite-gabbro assemblages in the

Yilgarn craton, Western Australia: elements of Archaean ophiolites. Greenstone Belts, ed. by M.J. De Wit and L.D. Ashwal. Oxford, Clarendon Press, 422-437.

Goodwin, A.M. (1996): Principles of Precambrian Geology. London, Academic Press. 327 p.

Hall, J., Wardle, R.J., Gower, C.F., Kerr, A., Coflin, K., Keen, C.E. and Carroll, P. (1995): Proterozoic orogens of the northeastern Canadian Shield: new information from the Lithoprobe ESCOOT crustal reflection seismic survey. Can. J. Earth Sci., **32**, 1119-1131.

Hamilton, W.B. (1998): Archean tectonics and magmatism. Int. Geol. Rev., **40**, 1-39.

Hanmer, S., Bowring, S., Van Breemen, O. and Parrish, R. (1992): Great Slave Lake shear zone, NW Canada: mylonitic record of Early Proterozoic continental convergence, collision and indentation. J. Struct. Geol., **14**, 757-773.

Hart, R.J., Tredoux, M. and De Wit, M.J. (1997): Refractory trace elements in diamond inclusions: further clues to the origins of the ancient cratons. Geology, **25**, 1143-1146.

Helmstaedt, H., Padgham, W.A. and Brophy, J.A. (1986): Multiple dikes in Lower Kam Group, Yellowknife greenstone belt: evidence for Archean sea-floor spreading? Geology, **14**, 562-566.

Hill, R.E.T., Barnes, S.J., Gole, M.J. and Dowling, S.E. (1995): The volcanology of komatiites as deduced from field relationships in the Norseman-Wiluna greenstone belt, Western Australia. Lithos, **34**, 159-188.

Hill, R.I. (1993): Mantle plumes and continental tectonics. Lithos, **30**, 193-206.

Hoffman, P.F. (1989): Precambrian geology and tectonic history of North America. The Geology of North America: An Overview, ed. by A.W. Bally and R. Palmer. Boulder, Geol. Soc. Am., 447-512.

Hoffman, P.F. (1991): On accretion of granite-greenstone terranes. Greenstone, Gold and Crustal Evolution, ed. by F. Robert *et al.* Can., Geol. Assoc., 32-45.

Hoffman, P.F. and Ranalli, G. (1988): Archean oceanic flake tectonics. Geophys. Res. Lett., **15**, 1077-1080.

Isachsen, C.E. and Bowring, S.A. (1997): The Bell Lake group and Anton Complex: A basement-cover sequence beneath the Archean Yellowknife greenstone belt revealed and implicated in greenstone belt formation. Can. J. Earth Sci., **34**, 169-189.

Jackson, S.L. and Cruden, A.R. (1995): Formation of the Abitibi greenstone belt by arc-trench migration. Geology, **23**, 471-474.

Jahn, B-M., Bertrand-Sarfati, J., Morin, N. and Macé J. (1990): Direct dating of stromatolitic carbonates from the Schmidtsdrif Formation (Transvaal Dolomite), South Africa, with implications on the age of the Ventersdorp Supergroup. Geology, **18**, 1211-1214.

James, D.T., Connelly, J.N., Wasteneys, H.A. and Kilfoil, G.J. (1996): Paleoproterozoic lithotectonic divisions of the southeastern Churchill Province, western Labrador. Can. J. Earth Sci., **33**, 216-230.

Jelsma, H., Vinyu, M.L., Valbracht, P.J., Davies, G.R., Wijbrans, J.R. and Verdurmen, E.A.T. (1996): Constraints on Archaean crustal evolution of the Zimbabwe craton: a U-Pb, Sm-Nd, and Pb-Pb whole-rock isotope study. Contrib. Mineral. Petrol., **124**, 55-70.

Karsten, J.L., Klein, E.M. and Sherman, S.B. (1996): Subduction zone geochemical characteristics in ocean ridge basalts from the southern Chile Ridge: implications of modern ridge subduction systems for the Archean. Lithos, **37**, 143-161.

Kent, R.W., Hardarson, B.S., Saunders, A.D. and Storey, M. (1996): Plateaus ancient and modern: geochemical and sedimentological perspectives on Archaean oceanic magmatism. Lithos, **37**, 129-142.

Kerr, A., Hall., J., Wardle, R.J., Gower, C.F. and Ryan, B. (1997): New reflections on the structure and evolution of the Makkovikian-Ketilidian orogen in Labrador and southern Greenland. Tectonics, **16**, 942-965.

Kimura, G. and Ludden, J. (1995): Peeling oceanic crust in subduction zones. Geology, **23**, 217-220.

Kimura, G., Ludden, J.N., Desrochers, J-P. and Hori, R. (1993): A model of ocean-crust accretion for the Superior Province, Canada. Lithos, **30**, 337-355.

KORJA, A., KORJA, T., LUOSTO, U. and HEIKKINEN, P. (1993): Seismic and geoelectric evidence for collisional and extensional events in the Fennoscandian Shield-implications for Precambrian crustal evolution. Tectonophysics, **219**, 129-152.

KORJA, T. (1993): Electrical conductivity distribution of the lithosphere in the central Fennoscandian Shield. Precamb. Res., **64**, 85-108.

KROGH, T.E. (1993): High precision U-Pb ages for granulite metamorphism and deformation in the Kapuskasing structural zone, Ontario: implications for structure and development of the lower crust. Earth Planet. Sci. Lett., **1**(19), 141-144.

KRÖNER, A. (1991): Tectonic evolution in the Archaean and Proterozoic. Tectonophysics, **187**, 393-410.

KRÖNER, A., HEGNER, E., WENDT, J.I. and BYERLY, G.R. (1996): The oldest part of the Barberton granitoid-greenstone terrain, South Africa: evidence for crust formation between 3.5 and 3.7 Ga. Precamb. Res., **78**, 105-124.

KUSKY, T.M. (1990): Evidence for Archean ocean opening and closing in the southern Slave Province. Tectonics, **9**, 1533-1563.

KUSKY, T.M. and KIDD, W.S.F. (1992): Remnants of an Archean oceanic plateau, Belingwe greenstone belt, Zimbabwe. Geology, **20**, 43-46.

LACROIX, S. and SAWYER, E.W. (1995): An Archean fold-thrust belt in the northwestern Abitibi greenstone belt: structural and seismic evidence. Can. J. Earth. Sci., **32**, 97-112.

LEWRY, J.F., HAJNAL, Z., GREEN, A., LUCAS, S.B., WHITE, D., STAUFFER, M.R., ASHTON, K.E., WEBER, W. and CLOWES, R. (1994): Structure of a Paleoproterozoic continent-continent collision zone: a LITHOPROBE seismic reflection profile across the Trans-Hudson orogen, Canada. Tectonophysics, **232**, 143-160.

LOUKOLA-RUSKEENIEMI, K. (1991): Base metal-rich metamorphosed black shales associated with Proterozoic ophiolites in the Kainuu schist belt, Finland: a genetic link with the Outokumpu rock assemblage. Mineral. Deposita, **26**, 143-151.

LUCAS, S.B. and 12 others. (1994): Three-dimensional collisional structure of the Trans-Hudson orogen, Canada. Tectonophysics, **232**, 161-178.

LUCAS, S.B., STERN, R.A., SYME, E.C., REILLY, B.A. and THOMAS, D.J. (1996): Intraoceanic tectonics and the development of continental crust: 1.92-1.84 Ga evolution of the Flin Flon belt, Canada. Geol. Soc. Am. Bull., **108**, 602-629.

LUDDEN, J., HUBERT, C., BARNES, A., MILKEREIT, B. and SAWYER, E. (1993): A three dimensional perspective on the evolution of Archaean crust: LITHOPROBE seismic reflection images in the southwestern Superior Province. Lithos, **30**, 357-372.

MARESCHAL, M., KELLETT, R.L., KURTZ, R.D., LUDDEN, J.N., Ji, S. and BALLEY, R.C. (1995): Archaean cratonic roots, mantle shear zones and deep electrical anisotropy. Nature, **375**, 134-137.

MARKER, M. (1989): Tectonic interpretation and new crustal modelling along the POLAR profile, northern Baltic Shield. Sixth EGT Workshop, ed. by R. FREEMAN and S. MUELLER. Ensiedel, Eur. Sci. Found., 9-22.

MARTIN, H. (1986): Effect of steeper Archean geothermal gradient on geochemistry of subduction zone magmas. Geology, **14**, 753-756.

MILESI, J.P., LEDRU, P., FEYBESSE, J-L., DOMMANGET, A. and MARCOUX, E. (1992): Early Proterozoic ore deposits and tectonics of the Birimian orogenic belt, West Africa. Precamb. Res., **58**, 305-344.

MÖLLER, A., APPEL, P., MEZGER, K. and SCHENK, V. (1995): Evidence for a 2 Ga subduction zone: eclogites in the Usagaran belt of Tanzania. Geology, **23**, 1067-1070.

MURPHY, J.B. and NANCE, R.D. (1991): Supercontinent model for the contrasting character of Late Proterozoic orogenic belts. Geology, **19**, 469-472.

MYERS, J.S. (1995): The generation and assembly of an Archaean supercontinent: evidence from the Yilgarn craton, Western Australia. Early Precambrian Processes, ed. by M.P. COWARD and A.C. RIES. Oxford, Blackwell, 143-154 (Geol. Soc. London, Spec. Publ., **95**).

MYERS, J.S., SHAW, R.D. and TYLER, I.M. (1996): Tectonic evolution of Proterozoic Australia. Tectonics, **15**, 1431-1446.

NELSON, E.P. and FORSYTHE, R.D. (1989): Ridge collision at convergent margins: implications for Archean and post-Archean crustal growth. Tectonophysics, **161**, 307-315.

NIRONEN, M. (1997): The Svecofennian orogen: a tectonic model. Precamb. Res., **86**, 21-44.

NISBET, E.G., CHEADLE, M.J., ARNDT, N.T. and DICKLE, M.J. (1993): Constraining the potential temperature of the Archaean mantle: a review of the evidence from komatiites. Lithos, **30**, 291-307.

NIVIA, A. (1996): The Bolivar mafic-ultramafic complex, SW Columbia: the base of an obducted oceanic plateau. J. South Am. Earth Sci., **9**, 59-68.

NUTMAN, A.P. and COLLERSON, K.D. (1991): Very early Archaean crustal accretion complexes preserved in the North Atlantic craton. Geology, **19**, 791-794.

NUTMAN, A.P., FRIEND, C.R.L., KINNY, P.D. and MCGREGOR, V.R. (1993): Anatomy of an Early Archean gneiss complex: 3900 to 3600 Ma crustal evolution in southern West Greenland. Geology, **21**, 415-418.

OHTA, H., MARUYAMA, S., TAKAHASHI, E., WATANABE, Y. and KATO, Y. (1996): Field occurrence, geochemistry and petrogenesis of the Archean Mid-Oceanic Ridge Basalts (AMORBs) of the Cleaverville area, Pilbara craton, western Australia. Lithos, **37**, 199-221.

PARK, R.G. (1997): Early Precambrian plate tectonics. S. Afr. J. Geol., **100**, 23-35.

PARMAN, S.W., DANN, J.C., GROVE, T.L. and DE WIT, M.J. (1997): Emplacement conditions of komatiite magmas from the 3.49 Ga Komati Formation, Barberton greenstone belt, South Africa. Earth Planet. Sci. Lett., **150**, 303-323.

PATCHETT, P.J. and BRIDGWATER, D. (1984): Origin of continental crust of 1.9-1.7 Ga age defined by Nd isotopes in the Ketilidian terrain of South Greenland. Contrib. Mineral. Petrol., **87**, 311-318.

PATCHETT, P.J. and ARNDT, N.T. (1986): Nd isotopes and tectonics of 1.9-1.7 Ga crustal genesis. Earth Planet. Sci. Lett., **78**, 329-338.

PEARSON, D.G., CARLSON, R.W., SHIREY, S.B., BOYD, E.R. and NIXON, P.H. (1995): Stabilisation of Archaean lithospheric mantle: a Re-Os isotope study of peridotite xenoliths from the Kaapvaal craton. Earth Planet. Sci. Lett., **134**, 341-357.

PELTONEN, P., KONTINEN, A. and HUHMA, H. (1996): Petrology and geochemistry of metabasalts from the 1.95 Ga Jormua ophiolite, northeastern Finland. J. Petrol., **37**, 1359-1383.

PELTONEN, P., KONTINEN, A. and HUHMA, H. (1998): Petrogenesis of the mantle sequence of the Jormua ophiolite (Finland): Melt migration in the upper mantle during Palaeoproterozoic continental break-up. J. Petrol., **39**, 297-329.

PERCIVAL, J.A. and WEST, G.F. (1994): The Kapuskasing Uplift: a geological and geophysical synthesis. Can. J. Earth Sci., **31**, 1256-1286.

PERCIVAL, J.A., STERN, R.A., SKULSKI, T., CARD, K.D., MORTENSEN, J.K. and BÉGIN, N.J. (1994): Minto block, Superior Province: Missing link in deciphering assembly of the craton at 2.7 Ga. Geology, **22**, 839-842.

PERCIVAL, J.A., ROERING, C., VAN REENEN, D.D. and SMIT, C.A. (1997): Tectonic evolution of associated greenstone belts and high-grade terrains. Greenstone Belts, ed. by M.J. DE WIT, and L.D. ASHWAL. Oxford, Oxford University Press, 398-420.

RING, U., KRÖNER, A. and TOULKERIDIS, T. (1997): Palaeoproterozoic granulite-facies metamorphism and granitoid intrusions in the Ubendian-Usagaran orogen of northern Malawi, east-central Africa. Precamb. Res., **85**, 27-51.

RIVERS, T., MENGEL, F., SCOTT, D.J., CAMPBELL, L.M. and GOULET, T. (1996): Torngat orogen-a Palaeoproterozoic example of a narrow doubly vergent collisional orogen. Precambrian Crustal Evolution in the North Atlantic Regions, ed. by T.S. BREWER. Oxford, Blackwell, 117-136 (Geol. Soc. London, Spec. Publ., **112**).

ROGERS, J.J.W. (1996): A history of continents in the past three billion years. J. Geol., **104**, 91-107.

ROLLINSON, H.R. (1996): Tonalite-trondhjemite-granodiorite magmatism and the genesis of Lewisian crust during the Archaean. Precambrian Crustal Evolution in the North Atlantic Regions, ed. by T.S. BREWER. Oxford, Blackwell, 25-42 (Geol. Soc. London, Spec. Publ., **112**).

SCHNEIDER, D., HOLM, D. and LUX, D. (1996): On the origin of Early Proterozoic gneiss domes and metamorphic nodes, northern Michigan. Can. J. Earth Sci., **33**, 1053-1063.

SCHULZ, K.J. (1987): An Early Proterozoic ophiolite in the Penokean orogen. Geol. Assoc. Can., Progr. Abstr., **12**, 87.

SCOTT, D.J., HELMSTAEDT, H. and BICKLE, M.J. (1992): Portuniq ophiolite, Cape Smith belt, northern Quebec, Canada: a reconstructed section of Early Proterozoic oceanic crust. Geology, **20**, 173-176.

SENGÖR, A.M.C. and NATAL'IN, B.A. (1996): Turkic-type orogeny and its role in the making of the continental crust. Ann. Rev. Earth Planet. Sci., **24**, 263-337.

SENGÖR, A.M.C., NATAL'IN, B.A. and BURTMAN, V.S. (1993): Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. Nature, **364**, 299-307.

SIMONSON, B.W., SCHUBEL, K.A. and HASSLER, S.W. (1993): Carbonate sedimentology of the early Precambrian Hamersley Group of Western Australia. Precamb. Res., **60**, 287-335.

SKULSKI, T. and PERCIVAL, J.A. (1996); Allochthonous 2.78 Ga oceanic plateau slivers in a 2.72 Ga continental arc sequence: Vizien greenstone belt, northeastern Superior Province, Canada. Lithos, **37**, 163-179.

SKULSKI, T., WARES, R.P. and SMITH, A.D. (1993): Early Proterozoic (1.88-1.87 Ga) tholeiitic magmatism in the New Quéc orogen. Can. J. Earth Sci., **30**, 1505-1520.

SLEEP, N.H. and WINDLEY, B.F. (1982): Archaean plate tectonics: constraints and inferences. J. Geol., **90**, 363-379.

SNYDER, D.D., LUCAS, S.B. and MCBRIDE, J.H. (1996): Crustal and mantle reflectors from Paleoproterozoic orogens and their relation to arc-continent collisions. Precambrian Crustal Evolution in the North Atlantic Regions, ed. by T.S. BREWER. Oxford, Blackwell, 1-23 (Geol. Soc. London, Spec. Publ., **112**).

SOUTHWICK, D.L. and CHANDLER, V.W. (1996): Block and shear-zone architecture of the Minnesota River Valley subprovince: implications for late Archean accretionary tectonics. Can. J. Earth Sci., **33**, 831-847.

ST-ONGE, M.R., LUCAS, S.B. and SCOTT, D.J. (1997): The Ungava orogen and the Cape Smith thrust belt. Greenstone Belts, ed. by. M.J. DE WIT and L.D. ASHWAL. Oxford, Clarendon Press, 772-780.

STEIN, M. and HOFFMANN, A.W. (1994): Mantle plumes and episodic crustal growth. Nature, **372**, 63-68.

STERN, R.A., SYME, E.C. and LUCAS, S.B. (1995): Geochemistry of 1.9 Ga MORB- and OIB-like basalts from the Amisk collage, Flin Flon belt, Canada: evidence for an intra-oceanic origin. Geochim. Cosmochim. Acta, **59**, 3131-3154.

STOREY, M., MAHONEY, J.J., KROENKE, L.W. and SAUNDERS, A.A. (1991): Are oceanic plateaus sites of komatiite formation ? Geology, **19**, 376-379.

SUTCLIFFE, R.H., BARRIE, C.T., BURROWS, D.R. and BEAKHOUSE, G.P. (1993): Plutonism in the southern Abitibi subprovince: a tectonic and petrogenetic framework. Econ. Geol., **88**, 1359-1375.

TAIRA, A., PICKERING, K.T., WINDLEY, B.F. and SOH, W. (1992): Accretion of Japanese island arcs and implications for the origin of Archean greenstone belts. Tectonics, **11**, 1224-1244.

TARDUNO, J.A. *et al.* (9 authors). (1991): Rapid formation of the Ontong Java Plateau by Aptian mantle plume volcanism. Science, **254**, 399-403.

THURSTON, P.C. and CHIVERS, K.M. (1990): Secular variation in greenstone sequence development emphasizing Superior Province. Precamb. Res., **46**, 21-58.

THURSTON, P.C., OSMANI, I.A. and STONE, D. (1991): Northwestern Superior Province: review and terrane analysis. Geology of Ontario, ed. by P.C. THURSTON *et al.* Ontario Geol. Surv., Spec. Vol. 4, pt. 1, 81-142.

TOMLINSON, K.Y., HALL., R.P., HUGHES, D.J. and THURSTON, P.C. (1996): Geochemistry and assemblage accretion of metavolcanic rocks in the Beardmore-Geraldton greenstone belt, Superior Province. Can. J. Earth Sci., **33**, 1520-1533.

TREDOUX, M., DE WIT, M.J., HART, R.J., ARMSTRONG, R.A., LINDSAY, N.M. and SELLSCHOP, J.P.F. (1989): Platinum group elements in a 3.5 Ga nickel-iron occurrence: possible evidence of a deep mantle origin. J. Geophys. Res., **94**, 795-813.

Williams, H.R. (1990): Subprovince accretion tectonics in the south-central Superior Province. Can. J. Earth. Sci., **26**, 570-581.

Williams, H.R. *et al.* (7 authors). (1992): Tectonic evolution of Ontario: summary and synthesis. Geology of Ontario, ed. by P.C. Thurston *et al.* Ontario Geol. Surv., Spec. Vol. 4, pt. 2, 1255-1332.

Windley, B.F. (1991): Early Proterozoic collision tectonics, and rapakivi granites as intrusions in an extensional thrust-thickened crust: the Ketilidian orogen, South Greenland. Tectonophysics, **195**, 1-10.

Windley, B.F. (1993): Proterozoic collisional and accretionary orogens. Proterozoic Crustal Evolution, ed. by K.C. Condie. Amsterdam, Elsevier, 419-446.

Windley, B.F. (1995): The Evolving Continents, 3rd ed. Chichester, Wiley, 526 p.

(Received March 2, 1998; Accepted April 6, 1998)