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ARCHAEAN TO EARLY PROTEROZOIC TECTONICS AND CRUSTAL EVOLUTION: A REVIEW

ALFRED KRÖNER*

ABSTRACT Hypothesis on the formation and evolution of the Earth's continental crust in the Early Precambrian have to account for the independent and directionally consistent motion of crustal segments of considerable dimensions since at least 3.5 Ga ago, and at minimum velocities comparable to those of today. It seems established, therefore, that plate tectonics has governed lithospheric evolution since the generation of rigid crustal segments, and it is speculated that a change in style of plate interaction, rather than a change in fundamental mechanisms, has determined non-uniformitarian crustal evolution towards the present Wilson cycle.

Uncertainties in the reliable reconstruction of Archaean tectonic settings are caused by low--temperature rock alteration that may obliterate primary magmatic trends, by the variable possible sources and melting processes for the generation of bimodal and calc-alkaline associations, and by disagreement on the interpretation of rocks with "primitive" isotopic characteristics. It is suggested that magmatic underplating played a major role in lithospheric growth and that reworking of continental crust during large-scale crustal differentiation was more important in the Archaean than recognized by most currently popular models.

The generation and survival of first continental crust is seen in analogy with the evolution of Iceland, and later greenstone belt development was probably largely intracontinental, following a rift-and-sag model in response to crustal rearrangements. Most high-grade terrains are considered to be older than neighbouring or overlying greenstone associations and were brought to the surface through low-angle thrusting.

Archaean lithospheric growth built stable cratons that experienced little internal deformation in early Proterozoic times. Less stabilized crust reacts to large-scale distortions predominantly by stretching, elongate basin-formation and "ensialic" orogeny through mechanisms ranging from crust restacking to transform shearing, finally generating mobile belts. Locally, modern-type convergent plate margins become recognizable at about 2.2 Ga ago while the full Wilson cycle is finally established in the late Proterozoic.

INTRODUCTION Some 20 years of plate tectonics, combined with new insights into the fine structure of the lithosphere as derived from seismic data, the application of multi-element geochemical and isotopic studies, and paleomagnetism have profoundly influenced present thinking on the origin and evolution of the Earth's continental crust.

Although there is now general agreement on how the Earth worked for the last 200 Ma because of observable evidence in the oceans and continents (*e.g.* Bird, 1980; Condie, 1982*a*), it has proved difficult to extend this history into more ancient times in view of the lost oceanic record and the ambiguity and complexity of the pre-Mesozoic rock relationships in the continents (Dewey, 1982). However, preserved characteristic rock assemblages uniquely identifying modern Wilson cycle processes have now been abundantly recognized in continental terrains as old as *ca.* 800-900 Ma and provide strong evidence for the conclusion that the present global tectonic regime has governed the evolution of the lithosphere at least since the Late Precambrian (Baer, 1977; Kröner, 1977).

Profound disagreement on the older crustal history, however, prevails to the present day, but it seems clear that the earlier period of dogmatism that followed the introduction of the plate tectonic concept is now giving way to a more balanced approach in attempts to decipher the Precambrian evolution of the continents. Thus, the early enthusiasm of postulating vanished oceans and defining crustal sutures merely by tiny occurrences of mafic-ultramafic rocks, nappe tectonics and the presence of calc-alkaline rock assemblages (*e.g.* Burke *et al.*, 1977) and by inferring tectonic processes almost exclusively from geochemical data (*e.g.* Taylor, 1967; Glikson, 1972; Tarney, 1976) and thus postulating uniformitarian crustal evolution back to the Early Archaean (Burke *et al.*, 1976; Burke, 1981), is now succeeded by more realistic models that recognize fundamental changes in the Earth's internal processes following global cooling and concomitant changes in lithospheric behaviour through time (Baer, 1981; Goodwin, 1981*a*; Kröner, 1981*a*). It is also satisfying to see that modern workers place increasing importance on field relationships rather than on conceptual interpretations, particularly as regards such controversial problems as the evolution of Archaean greenstone-granitoid-gneiss terrains and Proterozoic mobile belts.

The plate tectonic concept is now flexible enough to accomodate such previously rejected models as "ensialic" orogeny (Bally, 1981; Dewey, 1982; Kröner, in press), while adversaries of Precambrian plate motion have to accept the dominance of horizontal tectonics in continental crust formation since the earliest Archaean (Myers, 1976) and the growing evidence for independent motion of rigid lithospheric plates of considerable dimensions since at least 3.5 Ga ago (Kröner and McWilliams, in press). The conclusion is inescapable, therefore, that oceanic crust has been recycled back into the mantle since plates move around, although

* Institut für Geowissenschaften, Johannes-Gutenberg-Universität, Saarstr. 21, 6 500 Mainz, West Germany

the detailed process of ancient subduction as well as the mechanism that triggered it remain speculative (Hargraves, 1981; Kröner, 1981*a*; Lambert, 1981).

Uniformitarianists acknowledge significant differences between Archaean and younger terrains (*e.g.* Sleep and Windley, 1982), yet they appeal largely to crustal-evolution models that are based on processes occurring along modern plate boundaries in explaining crustal growth through time (*e.g.* Windley, 1979; Moorbath, 1978), in line with the dogma: comparable rocks imply comparable origins (Dickinson, 1981).

The crucial questions not answered by these models are why crustal growth took place episodically rather than continuously (DePaolo, 1981) and why 70%-85% of the present continental crust apparently formed in Archaean times despite the lack of evidence for significantly faster plate motion in the early Precambrian as compared to later periods. The present Wilson cycle and associated subduction-related continental margin and island-arc magmatism, therefore, appear to be less efficient continent-building mechanisms than required by the Archaean rate of crustal growth. This paper reviews the situation and speculates on alternative processes that seem compatible with the geological, geochemical and palaeomagnetic data as well as the general concept of plate tectonics.

PRECAMBRIAN PLATE MOTION It has been a widely held opinion that higher heat flow in the Precambrian resulted in faster plate motion and that this explains the decreasing rate of crust-formation through time (*e.g.* Bickle, 1978; Dewey and Windley, 1981; Park, 1981; Smith, 1981). The argument goes like this: Archaean terrestrial heat flow was two-three times present rates (Lambert, 1981) and required upper mantle temperatures to have been up to 150°C higher than now (Davies, 1979; Cook and Turcotte, 1981; Smith, 1981). Direct evidence of these higher temperatures is seen in the widespread occurrence of MgO-rich komatiitic volcanic rocks in Archaean terrains that are commonly ascribed to high degrees of partial melting in the mantle (Green, 1975, 1981). Since there is no evidence that significant heat was lost by conduction through the Archaean continental crust (Tarney and Windley, 1977), the greater heat flux must have been removed via the oceanic crust, either by an increased rate of plate production or by an increased total length of oceanic ridges (Bickle, 1978). About six times the current global oceanic crust formation rate of 3 km^2/a would thus be required by 2.8 Ga ago or an average age of ocean crust at the time of subduction of only *ca.* 20 Ma (Sleep and Windley, 1982).

It is also argued that plate motion would have been faster due to a lower viscosity in the mantle. Hager and O'Connell (1980), for example, calculated that a temperature increase of 100°C in the mantle results in a viscosity decrease by a factor of 10, leading to a 3-fold increase in plate velocities. The high calc-alkaline magma generation rate of the Archaean (Moorbath, 1978) is seen as a consequence of this postulated greater plate motion (Dewey and Windley, 1981).

However, presently available palaeomagnetic data for Achaean rocks do not support this concept in that they fail to reveal significantly higher minimum continental velocities with respect to the poles in the early Precambrian. These data come from the Superior Province in Canada (Dunlop, 1981), the Pilbara Block of western Australia (McElhinny and Senanayake, 1980) and the Kaapvaal craton of southern Africa (Kröner and McWilliams, in press) (Fig. 1). The reader should be aware of the limitations of palaeomagnetic data in that they only record longitudinal motion with respect to the poles and that motion is also difficult to detect in cases where palaeomagnetic and rotation poles are in close proximity (McWilliams, 1981).

The Canadian results imply a minimum average velocity of about 2cm/a for the period 2.8 to 2.5 Ga ago (Ullrich and Van Der Voo, 1981), comparable to the Western Aus-

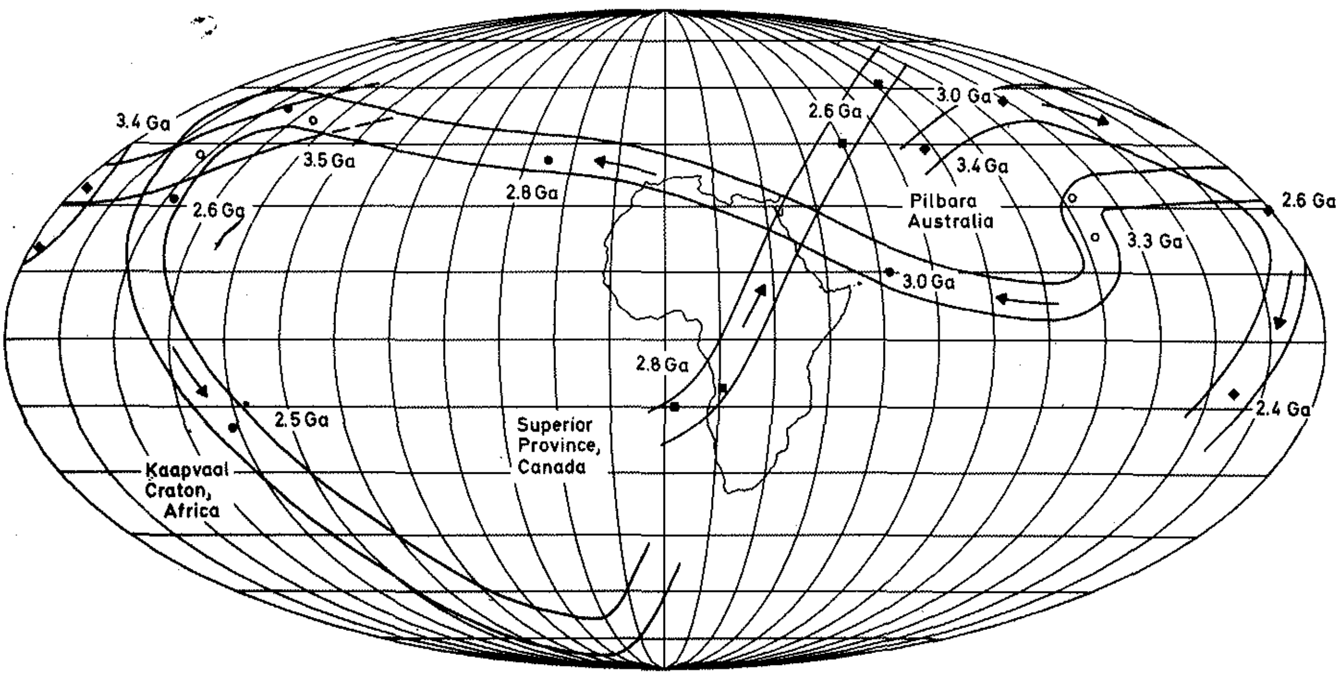

Figure 1 – Preliminary apparent polar wander paths for the Kaapvaal craton, southern Africa, the Pilbara Block, Australia, and the Superior Province, Canada, for various periods of early Precambrian time. Note the divergent but consistent motion of the three cratons. Data from Dunlop (1981), McElhinny and Senanayake (1980) and Kröner and McWilliams (unpubl.). Circles = Kaapvaal craton; squares = Superior Province; diamonds = Pilbara Block

tralian data that suggest a drift rate of *ca.* 1.5 cm/a for the period 3.5-2.4 Ga ago. The Kaapvaal craton experienced an appreciably higher minimum velocity of about 4 cm/a during the same period, but still comparable to present rates. The limited data do not yet permit to recognize strongly fluctuating drift rates in the Archaean as has been postulated for later times (Ullrich and Van Der Voo, 1981), but an important conclusion to emerge is that although each Archaean craton has its own velocity signature, the overall mean minimum velocity of 2.8 cm/a for the continents in post-Archaean times (Ullrich and Van Der Voo, 1981) does not appear to have been *significantly* higher in earlier periods as is suggested as one possibility by the above models.

This is also borne out by the geological data. Dewey (1982) has argued that increased rates of plate motion are signified by marine transgressions, a higher incidence of ophiolite obduction and the generation of blueschists and granitoid rocks. Except for the granitoids, whose origin and role in Archaean crustal evolution will be discussed below, none of these processes are characteristic of the early earth. In fact, no ancient ophiolites or blueschists have been reported despite excellent preservation of Archaean upper crustal segments, and it remains one of the enigmatic problems for most uniformitarian models to explain this phenomenon if early Precambrian plates moved indeed much faster and subduction-complexes would thus have risen correspondingly fast to preserve primary high-pressure metamorphic assemblages. Also, if Archaean oceanic crust was non-subductible as is sometimes claimed (Green, 1975; Baer, 1977, 1981), because its turnover was fast and thus did not allow for substantial cooling (Bickle, 1978), why did this crust not preferentially obduct, particularly if there was less elevation contrast between surfaces of continents and the mean depth of the ocean floor (Dickinson, 1981; Dewey and Windley, 1981)? N.T. Arndt (pers. comm., 1982) suggests that Archaean ocean crust was komatiite-dominated and was therefore dense enough some 20 Ma after generation to be subducted. Survival of such crust is therefore unlikely.

A second, equally important, consequence of the palaeomagnetic data is that ancient continental nuclei must have belonged to plates that drifted independently of each other at different velocities and in different directions (Fig. 1) since the early Archaean, thus seriously questioning models that infer one-plate scenarios for the early Earth (*e.g.* Fyfe, 1974; Shaw, 1976) or the aggregation of early sialic nuclei into a supercontinent (Goodwin, 1974; Condie; 1980).

The apparent "smoothness" of Archaean polar wander path for the 3 cratons cited above (Fig. 1) also seems to contradict the scenario of "jostling platelets on a turbulent asthenosphere (Kröner, 1981*a*; Goodwin, 1981*b*), at least for post-3.5 Ga times, unless such motion was at scales not detectable by palaeomagnetism. To the contrary, the directional consistency in continental motion over several hundreds million years as shown by the apparent polar wander paths (APWP) of Fig. 1 implies the existence of relatively large plates and the operation of mantle convection cells comparable to those of the present Earth.

It is, however, seen as significant that both the Australian and Kaapvaal Archaean APWPs display distinct bends at those intervals of time that are considered as major crust-forming episodes due to the emplacement of voluminous granitoid complexes. In analogy with loops in younger APWPs these changes in plate motion may signify major rearrangements in Archaean lithospheric geometry that may have had their cause in changing mantle dynamics.

In summary, present data favour the existence, since the Early Archaean, of comparatively large plates that drifted independently at minimum velocities comparable to those of today. Since there is no evidence to suggest large-scale andesite-dominated crust formation in the Archaean (*see below*), crustal growth rates greater than about 6 km^3/a, or approximately ten times present rates, as deduced from geochemical modelling (McLennan and Taylor, 1982) remain unexplained by uniformitarian models.

TECTONIC SETTINGS AND ALTERATION OF VOLCANIC ROCKS The application of geochemical discrimination diagrams to infer tectonic settings (*e.g.* Pearce, 1976, 1982; Pearce and Cann, 1973; Pearce *et al.*, 1977; Floyd and Winchester, 1975; Winchester and Floyd, 1977) has resulted in a flood of papers over the last ten years in which major and trace element data of volcanic rocks regardless of age and state of preservation were used to construct evolutionary models in line with the particular setting predicted by the diagrams applied.

Although the authors of these discrimination methods explicitly state that their diagrams are derived from data of modern, carefully selected, fresh volcanic rocks and do not necessarily apply to Precambrian environments, this warning is frequently ignored since relative immobility of the critical elements during post-depositional alteration and recrystallization is claimed, and there is widespread belief that geochemical patterns resulting from present magmatic processes can confidently portray tectonic settings as far back as the Archaean (Glikson, 1971; Naqvi, 1976; Dickinson, 1981; Hamilton, 1981; Weaver and Tarney, 1982). Thus, Archaean and Proterozoic metabasalts of tholeiitic affinity are frequently interpreted as remnants of ancient oceanic crust, and rocks classified as calc-alkaline andesites invariably denote ancient arcs related to subduction (*e.g.* Glikson, 1972).

Although it is not denied that, in many cases, the geochemical discrimination method is supported by Precambrian rock associations and geological field relationships (*e.g.* Roobol *et al.*, 1982; Condie, 1981*a*) there is growing evidence that many so-called "distinctive rock types" may occur in more than one environment. For example, Archaean komatiites and basalts have been interpreted as primitive ocean crust (Glikson, 1976; Naqvi, 1976; Anhaeusser, 1981), yet such rocks are often found in sequences that demonstrably rest on granitoid basement (Nisbet *et al.*, 1977; Kröner, 1981*c*), are interfingering with calc-alkaline volcanics in shallow-water environments (Barley, 1981) and/or are interbedded with continental-type sediments (Archibald *et al.*, 1981; Schau, 1977). Likewise, Archaean and early Proterozoic andesites that classify as calc-alkaline lavas and thus would demand a plate-margin setting have been shown to belong to intracratonic rift-related sequences (*e.g.* Hallberg *et al.* 1976; Hegner *et al.*, 1981; Schweitzer, 1982).

Even if great care is taken in the selection of samples and alteration is at a minimum, discrimination diagrams often do not give conclusive results in that analysis plot in all possible fields, as demonstrated for the early Archaean Pilbara greenstones of Western Australia (Glikson and Hickman, 1981).

More serious for the tectonic interpretation of geochemical data, however, is the effect of low-temperature alteration in volcanic and volcaniclastic rocks and the effect of crustal contamination. Superheated aqueous solutions have profoundly altered modern oceanic crust to depth of more than 5 km in places (East Pacific Rise Study Group, 1981), and it is easily visualized that hydrothermal convection in marine volcanic sequences was even more important in Archaean times when mantle and ocean temperatures were significantly higher than today (Fyfe, 1978).

Dimroth and Lichtblau (1979) demonstrated alteration-induced element variations greatly exceeding the apparent magmatic trends from Archaean greenstone volcanics at Noranda, Canada, thus confirming earlier studies (summarized in Condie, 1982*a*) that many elements, including some of those commonly regarded as immobile, are affected to varying degrees by chloritization, epidotization and carbonization. Such alteration as well as post-depositional silicification (Fig. 2) tend to impose an apparent calc-alkaline element distribution pattern on originally tholeiitic volcanic rocks and can therefore lead to completely erroneous interpretations.

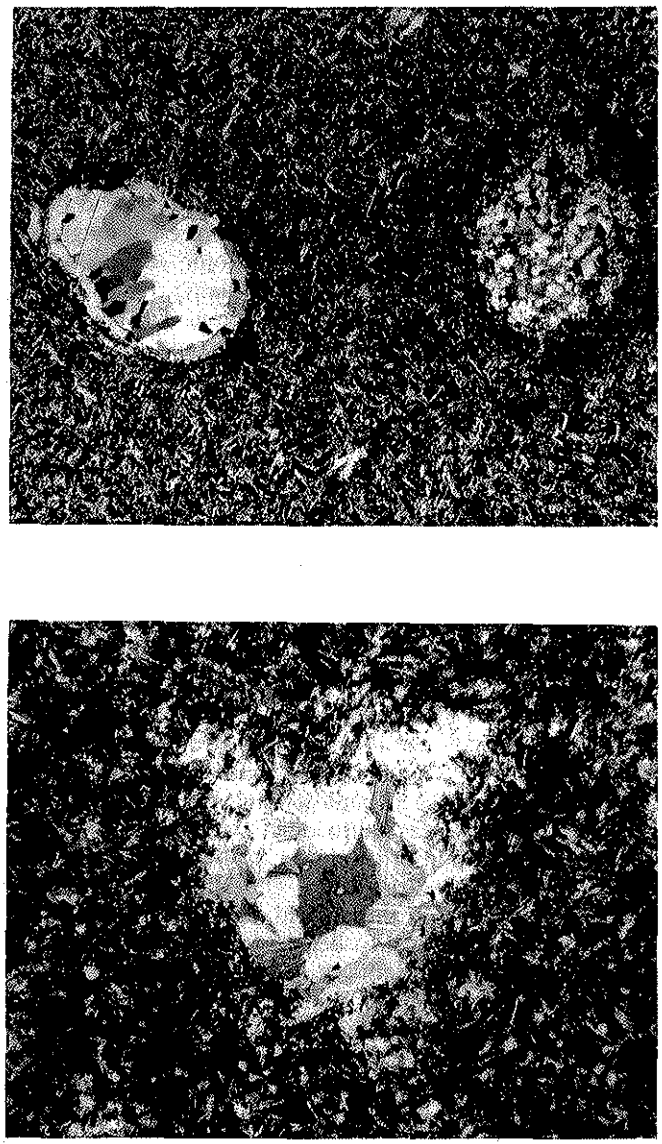

Figure 2 – Low-temperature alteration in basaltic andesite of the lower Proterozoic Ventersdorp Supergroup, South Africa, as revealed by (a) silicification and (b) carbonatization. Crossed Nicols, 20 × magnification

MacGeehan and McLean (1980), for example, have shown that many "andesites" of Canadian greenstone belts are, in fact, altered tholeiitic basalts, and Kröner and Schweitzer (unpubl. data) also demonstrate that superficially fresh but profoundly altered Early Proterozoic volcanics that plot in the shoshonite and calc-alkaline fields in some discrimination diagrams are in reality within-plate tholeiites (Fig. 3).

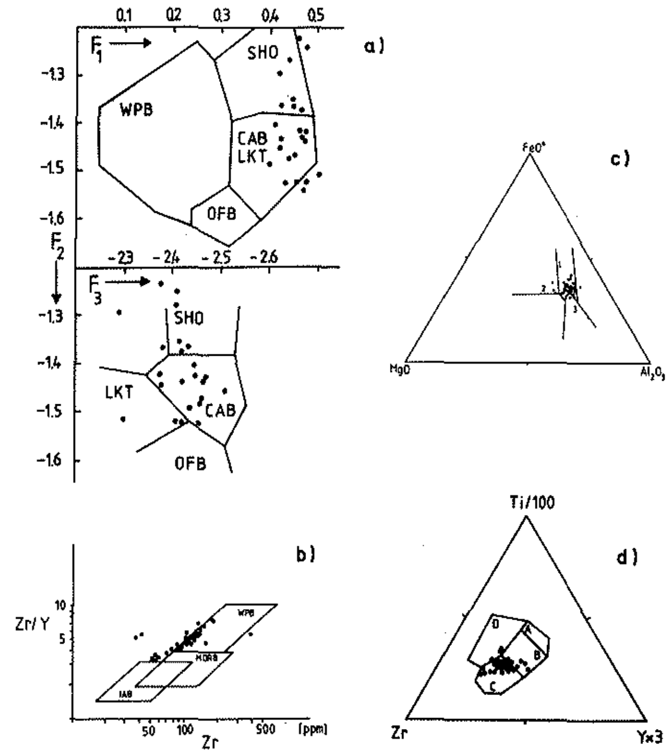

Figure 3 – Discrimination diagrams to determine tectonic settings of mafic volcanic rocks of the lower Proterozoic Ventersdorp Supergroup, South Africa (Schweitzer, 1982). Diagrams a *and* d *suggest plate margin calc-alkaline associations with shoshonites, while diagrams* b *and* c *clearly support the correct within-plate origin of these rocks*

Although present dogma holds that calc-alkaline magmas are predominantly produced in the mantle-wedge overlying subduction zones (Gill, 1980; Thorpe, 1982), there are examples of anorogenic basalt-tholeiitic andesite-dacite-rhyolite associations from the Tertiary (Wilkinson and Binns, 1977) to the Archaean (Hegner *et al.*, 1981), and these assemblages apparently occur in extensional environments where crustal melting is required to account for the observed chemical variations.

Several recent investigations have shown that andesitic to rhyolitic rock types in such settings may be produced by varying degrees of mixing of lower crust and mantle material (*for summaries see* EOS, 61, 67-68, 1980) and that underplating of dense picritic to gabbroic magmas at the base of the crust played an important role in this process (Betton and Cox, 1979; Ewart *et al.*, 1980).

In accounting for the origin of the clearly ensialic metavolcanics of the Archaean Yellowknife Supergroup in the Canadian Slave Province, Baragar (1966) concluded that mafic magmas generated at the base of the crust were contaminated by crustal melts before they could be extruded, resulting in strong calc-alkaline trends superimposed on originally basaltic magmas. Significantly, the setting as revealed by excellent exposures and detailed fieldwork, was one of stretching and rifting in the > 3 Ga old pre-Yellowknife granitic crust (Padgham, 1981).

Taylor and Hallberg (1977) also invoke a rift-setting for the generation of calc-alkaline andesite-bearing volcanics in the Archaean Marda Complex of Western Australia and conclude that crustal anatexis played an important role. Giles (1981), in addition, showed that calc-alkaline rocks in greenstones of the Yilgarn Block do not occur in arcs but in rather discrete, isolated centres. He advocates subduction-unrelated wet melting in the upper mantle and subsequent fractional crystallization from a mafic source at the base of the crust, perhaps related to a hot spot. The conditions of magma generation created in the upper mantle would essentially duplicate those produced in the mantle wedge above a descending oceanic crustal slab in a modern subduction zone (Giles, 1981).

To summarize, many claims for modern-type tectonic settings as deduced from the geochemistry of ancient volcanic rocks are suspect and are not supported by geological field evidence. Low-temperature alteration and contamination of basaltic rocks can produce secondary calc-alkaline trends that are easily misinterpreted, particularly in complexly deformed terrains, and that may suggest wrong tectonic environments. The great majority of Archaean volcanic sequences belongs to bimodal basalt-dacite/rhyolite suites while true andesites are rare except for the Canadian shield (Condie, 1981*a*; Goodwin, 1981*b*). This bimodal distribution pattern is also reflected in the composition of most Archaean grey gneiss complexes (Barker and Arth, 1976) – a situation that is in conflict with crustal evolution models advocating Archaean continental growth predominantly through processes at destructive plate margins.

The assessment of geochemical data for most Early Proterozoic metavolcanic successions is more difficult due to few published reliable high-quality analysis (Condie, 1982*b*). However, the same limitations as detailed above apply, and the generally high degree of metamorphism in the mobile zones renders deduction of the tectonic setting from the geochemistry of such recrystallized volcanic rocks even more speculative than in the low-grade Archaean terrains.

Magma mixing and crustal underplating may be processes that enable the generation of calc-alkaline rock assemblages in extensional environments, and this concept is further explored below.

SOURCE OF ARCHAEAN BIMODAL SUITES

All presently known Archaean terrains consist of varying proportions of greenstone belts, upper crustal granitoid intrusives and a variety of banded medium- to high-grade "grey gneisses" that frequently contain metasedimentary remnants and that are either older or formed broadly contemporaneously with the greenstone belt rocks (*for summaries see* Windley, 1977; Glover and Groves, 1981). Taken together, an Archaean crustal column composed of these units would have broadly andesitic composition (Taylor, 1967) while the individual rock units themselves are remarkably andesite-free and almost universally reveal a pronounced "Daly gap" (Barker and Arth, 1976).

The origin of the potassic granitoid complexes that appear late in the evolutionary history of most Archaean terrains (Anhaeusser and Robb, 1981) is least controversial since many of these batholithic bodies have geochemical and isotopic characteristics indicating derivation from older sialic crust of tonalitic or more mafic composition (*e.g.* Hunter *et al.*, 1978; Collerson *et al.*, 1982; Hanson, 1981; Muhling, 1981; Condie, 1981*b*). On the other hand, the postulated mantle-source for a considerable number of such complexes as deduced from low $^{87}Sr/^{86}Sr$ initial ratios has led to the proposal of major crustal accretion events, particularly at the end of the Archaean 2.8-2.5 Ga ago (Moorbath, 1978). However, such speculations lose some of their significance in the light of recent demonstrations that simple one-stage Sr-evolution diagrams may be inappropriate in portraying the crustal history of granitoid rocks whose Rb/Sr ratio is significantly higher than that of their source (*e.g.* Hart *et al.*, 1981; Davies and Allsopp, 1976; Cooper *et al.*, 1982). The implications of this conclusion for crustal evolution models are further discussed below.

Condie (1981*b*) argued from geochemical model studies that tonalite-trondhjemite and high-grade gneiss compositions define acceptable source rocks for Archaean granites and that most of the ancient lower crust must have been involved in the production of these rocks, leaving a depleted residue. This model, however, is in sharp contrast to the conclusion of Weaver and Tarney (1982) who suggested that most granulites represent liquid compositions rather than refractory residues, while the crustal layering and chemical differentiation revealed by seismic (Drummond *et al.*, 1981) and isotopic data (Hart *et al.*, 1981) as well as petrological considerations (O'Hara, 1977) seem to support the partial melting model.

The volumetrically most important granitoid rocks of most Archaean terrains are tonalites and cogenetic trondhjemites as well as their tectonized gneissic equivalents. Much controversy exists as to the origin of these rocks that typically form large composite "gregarious batholiths" (MacGregor, 1951) and that often contain xenoliths of greenstone belt material as well as banded gneisses and/or migmatites that may either represent older sialic basement or products of interaction between greenstones and granitoid melt.

Anhaeusser (1973), Anhaeusser and Robb (1981) and Glikson (1979) have suggested that the tonalite-trondhjemite complexes are derived from anatexis of a primitive mafic-ultramafic crust as found in lower greenstone successions and that the evolving magmas ascend to higher crustal levels where they intrude the higher greenstone units and form multilobate diapirs. This results in extensive assimilation of greenstone material and in the formation of marginal migmatite zones that develop into banded gneisses in high strain zones.

Petrogenetic considerations do not favour this model (Condie and Hunter, 1976; Hanson, 1981), and it is particularly difficult to explain the derivation of the widespread interbanded bimodal basalt-trondhjemite gneisses from such a process. Bettenay *et al.* (1981) have summarized the field evidence against greenstone anatexis, and most of their arguments are confirmed by my own observations in the Barberton region and Swaziland, southern Africa.

An alternative origin is proposed by most uniformitarian models that see similarities between Archaean tonalites and modern calc-alkaline batholiths and their gneissic roots that characterize Andean and Cordilleran belts (Windley, 1979; Hamilton, 1981; Weaver and Tarney, 1982). Tonalites and trondhjemites are generated from upper mantle-derived melts that originate above subduction zones and either intrude into the evolving arc or continental margin or accrete at or near the base of the crust (Weaver and Tarney, 1982) where they solidify and develop into granulite-gneiss belts (Windley, 1979). These processes require no or only short crustal residence times for the granitoid precursors – a feature supported by many isotope data (*e.g.* Moorbath, 1978).

The great volumes of tonalite-trondhjemite produced in the Archaean are conveniently ascribed to rapid ocean crust recycling, and the frequent collision of fast-moving, numerous small plates (Dewey and Windley, 1981), but this scenario neither accounts for the spatial and temporal distribution of these rocks nor for their generation during world-wide well-defined crustal accretion events (Moorbath, 1978). The conflict of this hypothesis with the available palaeomagnetic data has already been discussed.

The equation of ancient high-grade bimodal gneisses and their associated metasediments with modern accretionary thrust stacks that were transferred to deep crustal levels during the accretion event (Dewey and Windley, 1981) completely ignores the fact that the Archaean granulites frequently contain metasedimentary assemblages derived from shallow-water sandstone-shale-limestone sequences (Katz, 1977). The extensive granulite terrains of southern India, Enderby Land and Southern Africa are also contrary to the narrow, short, linear belts that would be expected from subduction-accretion along small continental plates. An alternative origin for the Archaean high-grade gneisses has been suggested by Myers (1976) and Kröner (1981*d*), and this is more fully explored below.

A third origin for the tonalite-trondhjemite suite is proposed by Barker and Arth (1976), Barker *et al.* (1981), Condie and Hunter (1976), Condie (1981*a*), and Hanson (1981) on the basis of petrogenetic and geochemical modelling. These models show that K-poor granitoid magmas may be derived from mafic-ultramafic sources, either as products of partial melting of amphibolite or eclogite, or through fractional crystallization of basaltic liquid. The scarcity of intermediate magmas and melting experiments that yielded trondhjemite from an amphibolite source (Helz, 1976) favour the partial melting mechanism.

Partial melting of 10%-20% amphibolite of basaltic to komatiitic composition at or near the amphibolite-granulite transition, *i.e.* near the base of the crust, produced tonalite-trondhjemite melts (Barker *et al.*, 1981). In the lower crust these magmas intrude as sheets and, together with their host rocks, they are involved in plastic flow by lateral extension and form high-grade gneisses with generally flat foliations (Gastil, 1979). The 3.8 Ga old Sand River Gneisses of the Limpopo belt (Fripp, 1981) may be an example of this model. At higher levels the melts may still intrude as sheets and form complex structural relationships with the tectonized roots of greenstone belts, including marginal zones of migmatites (own observations in Southern Africa, see also Bettenay *et al.*, 1981; McGregor, 1979). But the majority of the magma rises diapirically to form large composite batholiths that often engulf the previously deformed greenstones and obliterate their relationships with older basement. Structural work (*e.g.* Archibald *et al.*, 1981; Platt, 1980; Williams and Furnell, 1979; De Wit, 1982) demonstrates that the batholitic granitoids are not responsible for the first deformation in most greenstone belts but rather modify existing structures by steepening originally flat foliations and thrusts.

Hanson (1981) pointed out that mantle-derived mafic melts high in MgO and FeO such as komatiites have densities higher than most crustal rocks and that many of such melts would therefore not reach upper crustal levels. Trapped at the base of the crust, they would form a possible source for tonalite, diorite and granodiorite. Mafic underplating, as advocated here, has previously been discussed as a likely phenomenon in extensional environments and may also play a major role in greenstone volcanism as discussed below.

The tonalite-trondhjemite suites with "primitive" isotope characteristics satisfy the above model but do not preclude the possibility that their source terrains had very low Rb/Sr so that considerable crustal residence times up to several hundred million years are possible for the granitoid precursors (*e.g.* Barton, 1981).

Barker *et al.* (1981) distinguish between relatively homogeneous tonalites that are often compositionally similar to dacitic volcanics in neighbouring greenstone belts and that may originate through the process as described above, from well foliated, commonly migmatitic and heterogeneous varieties that often form part of extensive gneiss terranes and may include metasedimentary remnants. These latter rocks are ascribed to remobilization of older tonalite or "grey gneiss", and examples of this type include the Vikan gneisses of North Norway (Moorbath and Taylor, 1981), the Kiyuktok gneisses of Labrador (Collerson *et al.*, 1982), as well as several granitoid complexes in southern Africa (Davies and Allsopp, 1976) and in the Yilgarn Block of Western Australia (Archibald *et al.*, 1981).

In summary, Archaean tonalite-trondhjemite suites and compositionally similar grey gneiss terrains are unlikely to represent the products of greenstone anatexis. From the many dissimilarities of these rocks to Cordilleran batholiths and their root zones, their spatial distribution and their structural evolution it is considered unlikely that they formed along modern-type convergent zones. Models that consider underplating of dense mafic magmas in extensional environments, generation of tonalite-diorite-trondhjemite plutons from these sources and from remelting of older sialic gneissic crust are considered more realistic and satisfy constraints from field relationships, petrology and geochemistry.

Recent seismic and isotopic studies lend support to large-scale crustal differentiation due to metamorphic segregation in the Archaean crust, a process that almost certainly accompanied the evolution of granite-greenstone terrains and probably caused early cratonization of some shield areas. The Yilgarn Block of western Australia has a 3-layer ca. 40-50 km thick crust with the lowest part consisting of high-velocity (7.0-7.4 km. s^{-1}) material considered to be residual mafic granulite (Drummond *et al.*, 1981; Archibald *et al.*, 1981). The deep crustal profile through the Vredefort Dome, South Africa, exhibits a similarly layered crust that formed at least 2.8 Ga ago (Hart *et al.*, 1981), and the deposition of cratonic sedimentary rocks on parts of the Kaapvaal craton as early as 3 Ga ago (Kröner, 1981*a*) suggests completion of crustal differentiation before that time. The speculation that little differentiation, uplift and erosion occurred in the Archaean and should therefore explain the lack of ancient subduction-accretion prisms (Dewey and Windley, 1981) is in conflict with the above data and with the evidence for crustal thicknesses, at least locally, comparable to those of today since 3.8 Ga ago.

RELATIONSHIPS IN GREENSTONE BELT STRATIGRAPHIES AND ORIGIN OF VOLCANIC ROCKS

Much early speculation on greenstone belt development has been based on "model" stratigraphies that were erected in the belief that there is a cyclical evolution in all belts from mafic-ultramafic rocks at the base through andesites to highly differentiated volcanics and overlying, predominantly sedimentary successions (*e.g.* Anhaeusser, 1971). The basal units were regarded as primeval mafic crust while the stratigraphically higher and more evolved sequences, together with the neighbouring granitoids, were ascribed to ensimatic island-arc evolution (Anhaeusser, 1973; Glikson, 1976). Apparent geochemical similarities of the mafic-ultramafic volcanics and the more differentiated rocks with modern MORB and intraoceanic arc complexes (Condie, 1981*a*) led to ensimatic subduction-related models that were the main reason for speculations that the present Wilson-cycle operated since the earliest Archaean (Burke *et al.*, 1976; Burke, 1981).

Much fieldwork and more refined geochemical and geophysical data have resulted in a drastic revision of the above simplistic models (*for summaries see* Kröner, 1981*b*; Condie, 1981*a*; Glover and Groves, 1981) since it was recognized that each greenstone belt has its own distinctive stratigraphy, with the proportion of individual rock types varying widely between belts, that there is evidence for older granitoid crust in most cases or that sialic material was at least nearby, and that original greenstone basins had dimensions often greatly exceeding their present outcrop size (Schwerdtner, 1980; Kröner, 1981*c*).

Of considerable importance are the discoveries that felsic volcanic associations may appear low in the greenstone stratigraphy and may be overlain by, or intercalated with, komatiitic lavas (Schulz, 1980; Barley, 1981; Hickman, 1981), that there is abundant evidence for shallow-water conditions during initial greenstone deposition (Dunlop, 1978; Lowe and Knauth, 1977; Eriksson, 1981) and that terrigenous sediments appear throughout greenstone sequences (Archibald *et al.*, 1981). Barley (1981) found that calc-alkaline volcanics and volcaniclastic sediments are interlayered with tholeiitic basalts in the early Archaean Warrawoona Group of the Pilbara Block, and that there is neither a genetic relationship between the tholeiitic and calc-alkaline rocks nor a consistent trend toward more acidic composition in the evolution of the entire sequence. Such results cast serious doubt on island-arc and marginal basin greenstone models (Tarney and Windley, 1981), particularly if seen in conjunction with the occurrence of calc-alkaline rocks in discrete, isolated centres rather than in arcs (see p. 19) and the generally broad rather than linear form of many early greenstone basins (*e.g.* Hickman, 1981; Gee *et al.*, 1981; Nisbet *et al.*, 1981).

The stratigraphic continuity of even thin units such as cherts over distances up to 430 km (Hickman 1981), the occurrence of evaporites and stromatolitic carbonates (Dunlop, 1978), platform (alluvial) sediments (Eriksson, 1981) and subaerial acid volcanics (Thurston, 1980; D.I. Groves, pers. comm., 1982) as well as the considerable size of some greenstone basins all argue for intracontinental evolution of most greenstone belts on older sialic crust of remarkable stability and of dimensions exceeding several hundred kilometres (Kröner, 1981*c*). This is also in accord with the palaeomagnetic data and casts doubt on the arc-microcontinent collision model for the Archaean.

Another matter of continued considerable dispute is the basement-cover relationship in Archaean granite-greenstone terrains. Field evidence is often equivocal due to faulted contacts, insufficient exposure or obliteration of critical relationships by later intrusive rocks.

Discovery of several well preserved original contacts of greenstone or metasedimentary sequences as old as 3 Ga with clearly underlying older sialic basement has led to rejection of ensimatic models for most late Archaean greenstone belts in favour of rift or marginal basin evolution (*for summaries see* Windley, 1977; Platt, 1980; Kröner, 1981*a*), but "hard-core" defenders of intraoceanic crustal evolution still envisage the Early Archaean *ca.* 3.5 Ga greenstone generation to have formed on primeval oceanic crust despite the observational fact that such crust has never been identified and that even the oldest preserved greenstone assemblages contain evidence for shallow-water deposition and the presence of sialic components (*e.g.* Hickman, 1981; Archibald *et al.*, 1981). J.F. Wilson (pers. comm.) has now also documented first direct evidence for sialic basement under the >3.4 Ga old Selukwe greenstone belt in Zimbabwe.

In some cases sialic gneisses show structural complexities not recorded in neighbouring greenstones, and, for this reason, have been interpreted as basement. Rb-Sr isotopic data, however, revealed very low $^{87}Sr/^{86}Sr$ initial ratios for such rocks and ages that are virtually indistinguishable from those of the presumed overlying greenstones (*e.g.* Barberton greenstones 3.51 ± 0.06 Ga, Ancient Gneiss Complex 3.56 ± 0.11 Ga; Barton, 1981; Pilbara lower greenstones 3.56–3.45 Ga, Shaw batholith 3.42 ± 0.03 Ga; McCulloch, quoted in Hickman, 1981). In view of the long-standing dogma that rocks with "primitive" Sr isotopic ratios must be regarded as juvenile additions to the crust and thus cannot have appreciably older crustal parents (Moorbath 1975, 1978) these granitoid ages were interpreted as primary, thus overruling the above structural evidence.

As is demonstrated below the isotopic criteria are open to reinterpretation in the light of recent work, and many so-called "juvenile gneisses" may have been in existence prior to greenstone generation.

Modern geochemical data also contradict the earlier view of ensimatic greenstone evolution since neither the tholeiitic nor the calc-alkaline suites are strictly identical to modern ocean floor and island arc volcanics (*e.g.* Hawkesworth and O'Nions, 1977; Grachev and Fedorowsky, 1981; Glikson, 1979; Condie, 1981*a*). The pronounced bimodality of greenstone successions strongly favours a rift-related setting for the initial stage of greenstone belt formation.

Oceanic rifts such as mid-ocean ridge systems are not a plausible setting since they do not explain the appreciable sialic detritus found in some greenstone belt sediments. Also, modern ocean crust experiences amphibolite-grade metamorphism at crustal depths of about 5 km (East Pacific Rise Study Group, 1981) while greenstone belt successions with apparent thicknesses of more than 10 km display only greenschist grade, thereby suggesting some thermal "shielding" mechanism below their bases, believed to be continental crust.

Early models assumed that greenstone belts follow a pattern from ultramafic-to-mafic-to-siliceous volcanics, succeeded by a suite of granitoids evolving from Na-rich to K-rich types, and that this process should reflect "maturing" of intraoceanic arcs to microcontinents (*e.g.* Glikson, 1976). However, the cyclicity concept has already been shown to be of only local significance, and careful modern dating has demonstrated that both extrusive and intrusive rocks are broadly contemporaneous (*e.g.* Barton, 1981; DeLaeter *et al.*, 1981), thereby again implying that the latter are unlikely to represent melting products of the former. Large-scale melting of lower greenstone units to form granitoids and in order to explain the missing primeval oceanic crust is an implausible mechanism and Bettenay *et al.* (1981) succintly demonstrate that greenstone belts are probably shallow structures restricted to upper crustal layers and that the average crustal composition underneath granitoid-greenstone terrains probably corresponds to siliceous (banded) gneisses with intercalated components derived from older supracrustal sequences including minor greenstones and, characteristically, shallow-water metasediments as well as early granitoid intrusives. Hart *et al.* (1981) have given a superb demonstration of precisely this association from the centre of the Vredefort Dome in South Africa, believed to be a uniquely preserved "window" of the Early Archaean lower continental crust.

Given the scenario of fracturing of continental crust during continental breakup or for the formation of pull-apart basins, and assuming that mafic underplating is an important process in this setting, the origin of Archaean bimodal volcanic suites may now be broadly compared with the evolution of magmas in modern rift environments where both juvenile mantle-derived melts and anatectic melts derived from partial melting of previously solidified mafic crust play a crucial role in the petrogenesis of observed bimodal associations (*e.g.* Oskarsson *et al.*, 1979).

Hanson (1981) argued that large volumes of dense, iron-rich melts representing low degrees of mantle melting could have existed near the Archaean crust-mantle boundary, since there is evidence for such more recent mantle melting from the study of mantle xenoliths. Such melts, too dense to rise to the surface, would tend to form immiscible liquids, separate gravitationally, and then ascend into the crust to form either basalt and/or mafic tonalite, or to solidify as dacite/rhyolite and/or granite. The models of Cox (1980) and Ewart *et al.* (1980) likewise see the primary source for bimodal rift-generated volcanics in underplated mafic magmas, and there is also a strong likelihood of melting and mixing with components of mafic lower continental crust during this process. A conceptual model has been suggested by Kröner (1981*a*) and is further developed below.

In summary, basement-cover relationships and internal greenstone belt stratigraphies favour evolution of greenstone basins in rift environments on thick, relatively stable continental crust.

CRUSTAL REWORKING AND JUVENILE CRUSTAL GROWTH The demonstration that low Sr-initial ratios for a rock body do *not* automatically imply a juvenile mantle-related origin but may also be found in suites derived from parents with *extended crustal prehistory* must be regarded as one of the major recent achievements in isotope geochemistry (*e.g.* Collerson *et al.*; 1982; Hart *et al.*, 1981) and may significantly change our understanding of crustal evolution processes.

First, it is now demonstrated without reasonable doubt that the mantle was inhomogeneous with respect to most isotopic systems since at least 3.6 Ga ago and that simple model age calculations based on so-called "mantle growth lines" may be erroneous or at least imprecise. For the Rb-Sr system such calculations may give ages too low or too high, while for the Sm-Nd system the model ages are always too low (DePaolo, 1981).

Second, most evolutionary diagrams tacitly assume that the isotopic ratios measured on a few samples of a given dated rock unit reflect the average ratio for the parent and, therefore, isotopic growth lines with corresponding slopes are drawn in calculating maximum model ages. Hart *et al.* (1981) have recently demonstrated that this assumption may be invalid, and that *significant* amounts of Rb and U move upwards in the crust during high-grade dehydration events, thus profoundly changing the isotopic systematics. Recent studies show that CO_2 may be a major vapour phase during high-grade metamorphism (Newton *et al.*, 1980) and may be able to cause significant depletion of heavy REE in the dehydrated lower crust with complementary enrichment of light REE in higher levels (Collerson and Fryer, 1978). Such REE mobility may therefore also affect model age calculations using the Sm-Nd system.

Hart *et al.* (1981) demonstrated by combining several dating techniques, that upper crustal granitic gneisses in the Vredefort Structure of the Archaean Kaapvaal Craton, South Africa, derived their present Rb/Sr and U/Pb ratios from a major lower crustal high-grade "reworking" event about 3 Ga ago. In spite of the "primitive" $^{87}Sr/^{86}Sr$ ratio of 0.7019 ± 2 and an average Rb/Sr ratio of 0.35 established in these rocks at that time (and therefore implying a juvenile origin in terms of conventional interpretation) they can in fact be shown to originate from *ca.* 3.5 Ga old sialic crust with primary Rb/Sr of *ca.* 0.1. It is contended that such cases are the rule and not the exception in Archaean terrains and that reliable crustal evolution models must therefore be based on combined studies of several isotopic systems (*e.g.* Moorbath and Taylor, 1981). Many greenstone-granitoid-gneiss relationships and models will have to be re-evaluated if the concept of world wide massive juvenile growth throughout the Archaean requires substantial revision.

ORIGIN OF HIGH-GRADE TERRAINS Archaean high-grade metamorphic assemblages support the concept of average gradients and average thickness of continental crust between 30 km and 40 km as early as 3 Ga ago although there seems to be a tendency for average metamorphic pressures to have increased through time (Grambling, 1981).

Generation of isobaric or prograde pressure regimes together with prograde temperatures have probably been the cause for the generation of most granulite complexes in the lower crust and have been ascribed either to magmatic crustal accretion mechanisms (Wells, 1980; 1981) or to tectonic thickening through crustal interstacking (Bridgwater *et al.*, 1974) or continental collision (Dewey and Burke, 1973).

The first model is based on the concept of massive crustal accretion through juvenile mantle-derived magmas (*e.g.* Moorbath, 1978) at Cordilleran-type continental margins and is discussed in detail by Tarney and Windley (1977) and Wells (1981). The composition and age of Archaean high-grade terrains with their ubiquitous metasedimentary assemblages as well as their size and dimension, however, render this model unlikely for the early Earth since it implies a predominance of *juvenile* sialic rocks in granulite complexes, a feature not seen in presently exposed Archaean terrains (Katz, 1977; Hart *et al.*, 1981).

Continental collision is an elegant and plausible mechanism for the generation of high-grade sialic rocks and presently converts much of the old Indian upper crust that has disappeared underneath Asia over the last 30 Ma to high-grade assemblages that may reappear at the surface after substantial erosion following crustal thickening. The process, in the present Wilson-cycle regime, is restricted to regions commonly classified as "orogenic" and is the final product of mountain-building. Since Archaean greenstone belts are no longer considered to be ancient analogues of modern orogens (Anhaeusser *et al.*, 1969) it is unlikely that ocean closure and continental collision in the present sense were responsible for the large areas of high-grade gneisses in ancient cratons.

Models proposing plane-strain thrust restacking of thinned or mechanically weakened continental crust as presently observed in the Alps (Hsü, 1979; Dewey, 1982) do not require the previously discussed conditions and, in my opinion, account for the rock assemblages and structural features observed in ancient granulite complexes. The Limpopo belt of Southern Africa, with several granulite-forming events, the oldest dated at 3.8 Ga, has been cited as an example of this type (Coward, 1976; Barton, 1981) and much of the Archaean development of the North Atlantic craton is ascribed to this process (Park, 1981).

Crustal thinning through faulting and development of shallow continental basins is shown by many Archaean supracrustal sequences found in high-grade gneisses and may have preceded thrust- or wrench-faulting that took place along detachment surfaces sometimes reaching to the base of the crust. It is speculated that such motion is perhaps reflecting major rearrangements of crustal segments within relatively large continental plates. The thrusting mechanism, coupled with intense deformation and granitoid intrusions, transferred the once shallow-level assemblages to deep crustal regions where they recrystallized and eventually returned to the surface after isostatic equilibration of the thickened block.

Katz (1976) ascribes the generation of Archaean granulite terrains essentially to large-scale intracratonic transform motion along zones of weakness demarkated by sediment-filled aulacogens, but other scenarios are equally compatible with the available data as suggested above.

Common to all these suggestions is that horizontal tectonics probably played a decisive role in the generation of Archaean granulites but that Cordilleran or continental collision settings were not required.

ARCHAEAN LITHOSPHERIC THICKNESS AND CRATONIZATION The preservation of Archaean lower crustal assemblages with mineral parageneses suggesting normal average geothermal gradients despite an appreciably higher global heat flow at that time has led to the suggestion that the ancient oceanic lithosphere was thin (20-30 km) whereas continental lithosphere under the cratons must have been fairly thick, thus insulating the continental crust against heat flux from the convecting mantle (Davies, 1979). By analogy, Wells (1981) has suggested that the survival of 30-40 km thick Archaean crust implies the presence of a stable subcrustal root zone to continents, not less than 200 km thick, that probably grew during crustal formation and thickening. These concepts are supported by heat flow data from Archaean cratons (Oxburgh, 1981), by seismic ScS wave travel-time variations (Jordan, 1979, 1981) and by geotherms deduced from kimberlite pyroxenes that require a plate thickness of at least 200 km (Davies and Strebeck, 1982). That such thick lithosphere was already present in the Archaean is substantiated by the occurrence of kimberlite-derived diamonds in the *ca.* 2.6 Ga old Witwatersrand conglomerates of South Africa (Hallbauer *et al.*, 1980).

Jordan has argued repeatedly (1979, 1981) that subcrustal lithospheric growth results from basalt extraction in fertile, undepleted mantle, leaving a peridotitic residue that is less dense than the starting material. This depleted, light residue would therefore tend to float on undepleted mantle and would tend to be incorporated in the overlying lithospheric plate. Repeated continental basaltic volcanism would constitute primary episodes of basalt extraction from the mantle and would thus thicken the continental lithosphere from below, resulting in a relatively buoyant, thick subcontinental root that is not likely to be the site of further large-scale melting. An important implication of this persuasive model is that it explains cratonization of continental crust as a direct consequence of early formation of a thick lithosphere (Jordan, 1981).

The above vertical lithospheric growth model does not necessarily depend on the operation of continental margin subduction processes in the Archaean but accounts for crustal stabilization through widespread and extensive basalt extraction from the mantle. Such extraction may be seen in the form of massive crustal underplating as discussed in previous sections and the generation of greenstone belt volcanics as well as granitoid intrusives from this underplated reservoir and from the mantle below. The areally extensive worldwide crustal accretion event at the end of the Archaean has almost certainly resulted in substantial cratonization as revealed by thick, late Archaean to early Proterozoic intracontinental volcano-sedimentary successions some of which may constitute "failed" greenstone belts (Hegner *et al.*, 1981). Continental lithosphere that was not sufficiently thickened in the Archaean through mantle-derived magmatism remained tectonically mobile and was therefore substantially modified, in some cases beyond recognition, during Proterozoic and later deformation.

The "subcontinental lithospheric root" concept may also be able to explain the observation that, in some cases, isotopic heterogeneities have persisted in local closed systems in the upper mantle under old cratons since Archaean times (Kramers, 1979) since this material has obviously not participated in later re-equilibration with undepleted mantle through convection or significant melting. If this interpretation is correct, model age calculations for rocks derived from old, depleted and heterogeneous subcontinental mantle should be treated with caution.

There are several ways is which Archaean lithospheric growth by underplating can be envisaged. The Jordan (1979, 1981) model requires a heat source in the mantle to cause melting and basalt extraction. Under continental (and modern oceanic) areas such sources are generally seen in hot-spots or mantle-plumes (Hofmann and White, 1982) and, in some cases, these thermal anomalies must have been of considerable dimensions and duration as judged by the voluminous continental basalt suites such as the Early Proterozoic Ventersdorp and Fortescue Supergroups of South Africa and Western Australia or by the Mesozoic Karoo volcanism of Gondwanaland.

Since mantle plumes are major agents for transferring heat from the deeper mantle, they may have been more common in the Archaean than today, perhaps forming planar arrays (Hanson, 1981). They may ultimately have been responsible for greenstone belt formation and granitoid magmatism in the crust while the subcrustal lithosphere gradually (or episodically) thickened and thus contributed to continental stabilization.

An alternative mechanism to cause lithospheric underplating may be seen in the proposal by Ringwood (in press) whereby subducted oceanic lithosphere sinks into the mantle to depth of about 600 km where the depleted basaltic component is denser than the surrounding mantle and thus keeps sinking while the former harzburgite part of the slab becomes buoyant and rises diapirically. This material, being less dense than undepleted mantle just as in the Jordan model, underplates the lithosphere and causes thickening. In this model old cratons have thick lithosphere simply because they have been subjected to this type of underplating for long times.

Ringwood (op. cit.) further suggests that the process from subduction to thermal equilibration with the mantle and subsequent diapirism and underplating takes place on a timescale of 1-2 Ga. For the Archaean this may mean that the extensive global magmatism and continental stabilization at 2.7-2.5 Ga ago may be due to massive underplating as a result of substantial ocean crust recycling 1-2 Ga earlier, *i.e.* at a time when most models predict that continental crust formation began.

In summary, thick continental roots under old shields may have been responsible for the preservation of ancient lower crust and may be the prime reason for cratonization. Current models in support of this concept see the cause of thick subcontinental lithosphere in underplating and the operation of mantle-plumes.

A MODEL FOR CONTINENT-FORMATION Following rapid cooling of the originally melted surface of the Earth after core formation (Ringwood, 1979), a very thin crust composed chiefly of ultramafic rocks (Condie, 1980; Nisbet and Walker, 1982) forms small but coherent rigid segments like the crust on lava lakes of present active volcanoes. These segments frequently break up again and are recycled back into the underlying melted mantle because of their high density and viscous drag at their bases resulting from convection below. The breakup and recycling is further enhanced through heavy meteorite bombardment.

As cooling progresses the early crustal segments thicken and komatiitic to basaltic volcanism becomes widespread as outlined by Condie (1980) and Nisbet and Walker (1982). An Early Archaean heat flow of 200-250 mW/m^2 implies volcanic activity over virtually the entire surface of the early Earth (Smith, 1981). It is unlikely that this volcanism took place along linear zones comparable to present oceanic ridge systems. Rather, the closely spaced convection cells in a vigorously convecting mantle would suggest a system of thermal plumes (Kröner, 1981*a*; Lambert, 1981; Smith, 1981).

The early ultramafic crust with overlying komatiitic volcanics was still too dense to survive and was completely recycled back into the hot mantle at comparatively short time rates. At about 4 Ga ago mantle temperatures and heat flow had decreased sufficiently to permit komatiite-domimated crust that now had a longer survival rate. Continued volcanism then had the chance to build volcanic centres that grew rapidly in height. Growth of the volcanic pile through partial melting of the subcrustal mantle immediately below results in basalt depletion and cooling of the depleted region so as to form a minitectosphere (Jordan, 1979) that further stabilizes the overlying crust and contributes to its continued survival.

Regions of the early crust that do not experience extensive and continued volcanism are likely to maintain relatively thin lithospheres and are easily dragged down back into the mantle, while continental segments over plumes grow rapidly and tend to survive longer.

The evolution of Iceland may be an appropriate scenario for the next stage of continental differentiation (Kröner, 1981*d*) since the present heat flow there is about 200 mW/m^2 (Smith, 1981). Continued melting in the mantle produces further tholeiitic magmas but a large portion does no longer reach the surface of the growing crust but accumulates at its base and forms the reservoir for bimodal volcanic suites and the first rising tonalite-trondhjemite diapirs (Fig. 4). As the volcanic pile thickens its lower parts and the underlying ultramafic protocrust melt and form a vast reservoir for further differentiated magmas. It is speculated that the dense residue remaining from these processes may become decoupled from the crust through viscous drag to allow recycling into the convecting mantle. Continued growth of this kind gradually reduces the overall density of the evolving crust which is now less than about 3 cm^3/g and, through partial melting at its base, establishes a two-layered structure with the lower part transformed into high-grade assemblages and the upper part consisting of both primitive and differentiated volcanics and granitoid intrusives.

Eventually a situation may be reached where a mixture of granitoid intrusives and differentiated volcanics constitutes the surface of this now predominantly sialic early upper crust. If it emerges above sealevel, erosion ensues and early sediments with strong calc-alkaline affinities that reflect the composition of their parents are deposited. The *ca.* 3.8 Ga old Sand River tonalites of the Limpopo belt could be examples of this type, and I visualize that the crust had evolved to this stage by about 4 Ga ago. However, no extensive sedimentary basins formed at that time since only small parts of the microcontinents emerged significantly above sea level because vertical continental accretion was compensated by fusion at depth and, perhaps, sideways flow by ductile spreading of the lower crust (cf. Hess, 1962).

The scenario postulated above guarantees survival of these early continental nuclei which are now too light to be recycled and whose subcrustal roots gradually thicken and thus "shield" the overlying crust against extensive disruption. Neighbouring lithospheric segments, where mantle melting and volcanism were insufficient to form sialic nuclei, remained comparatively thin and dense, *i.e.* oceanic in character, and were sites of drag-induced "sag-subduction" (Goodwin, 1981*b*; Kröner, 1981*a*). Such subduction may have been caused by meteorite impacts or drag above downgoing mantle currents (Fig. 4). Whatever the mechanism, none of this early "oceanic" crust has survived while the contemporaneous sialic differentiates are considered to form the oldest preserved crustal remnants.

GREENSTONE BELT EVOLUTION Accepting the above highly speculative model for early crustal differentiation, and given the constraints of field relationships as detailed in previous sections, the following development is envisaged for greenstone-granite-gneiss terrains (Kröner, 1981*a*, 1981*c*):

By about 3.6 Ga ago continental crustal segments of dimensions exceeding several hundred km in size and of sufficient thickness and rigidity to support large basins were

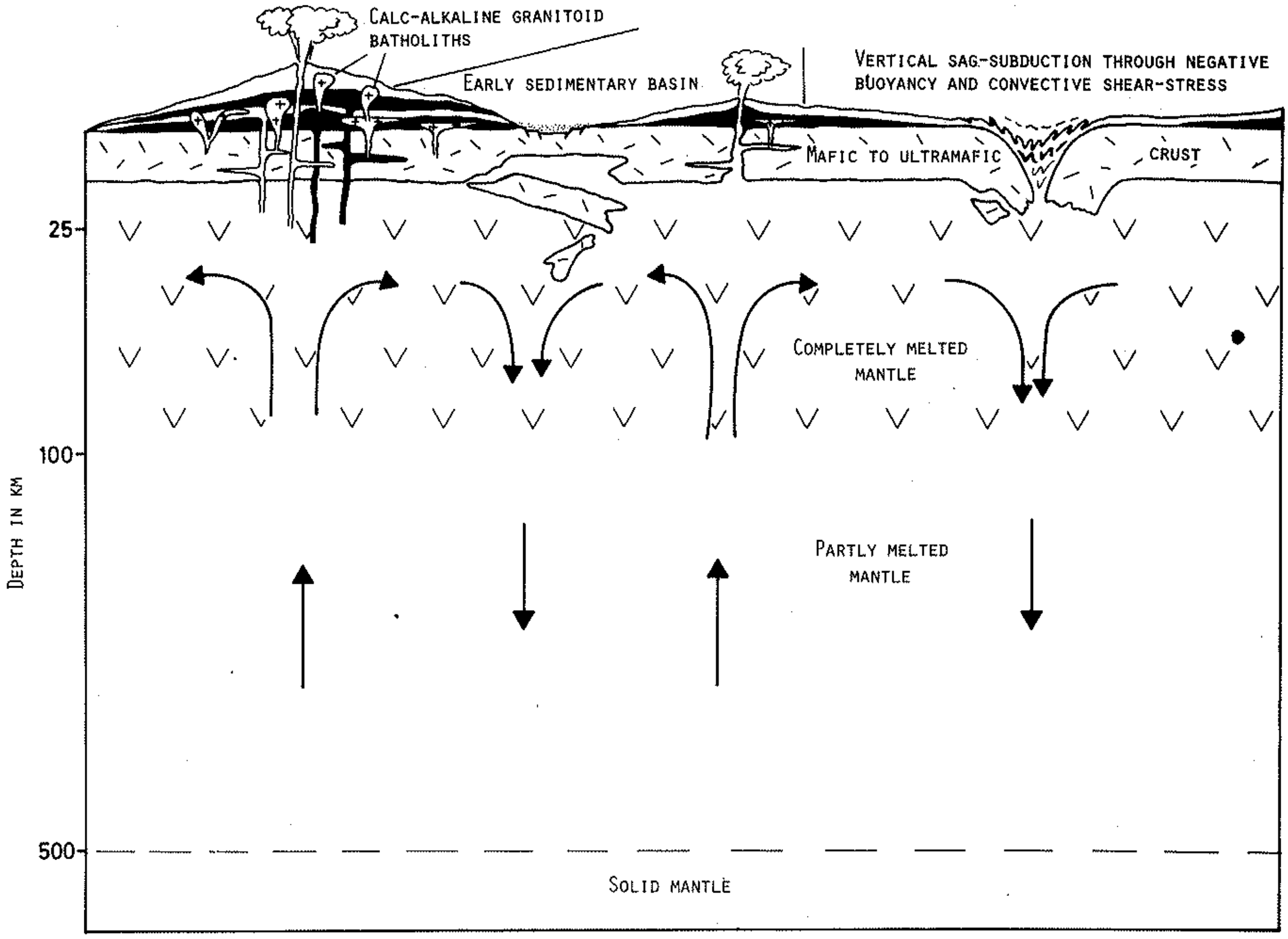

Figure 4 – Simplified, schematic and highly speculative model for the origin and growth of the earliest continental crust (modified after Condie, 1980). For explanation see text

in existence as demonstrated by the evolution of the Pilbara Block in western Australia (Hickman, 1981). For the late Archaean greenstone basins similar or even larger dimensions can be inferred. These crustal segments are subjected to crustal attenuation or fissuring above mantle plumes or "hot lines" (Hanson, 1981), thereby generating oval or elongate basins or sharply bounded, fault-controlled graben systems (Fig. 5*A*). These basins collect shallow-water sediments as well as mafic to ultramafic lavas produced by a high degree of melting in the subcrustal mantle (Fig. 5*B*). Only a small proportion of these melts can rise to the surface, however, and extrude as Mg-rich lava while a much larger volume remains near the base of the crust to become the source for bimodal volcanic assemblages and early tonalitic-trondhjemitic intrusives. Further stretching in the lower crust causes continued block rotation along listric faults during basin widening, perhaps anologous to the Basin-and--Range Province of the western USA. In this way exceptionally thick sequences of volcanic rocks may be accumulated, accompanied by subsidence in the proto-greenstone basis and subsequent rise of the crust-mantle boundary. Eventually the spreading and sagging process may lead to the decoupling of lower crustal blocks together with dense residues of earlier underplated material, with further production of large volumes of basaltic rocks. At this stage crustal fussion and crust-mantle mixing become important and lead to the production of calc-alkaline suites as well as crustal-derived granitoids (Fig. 5*C*).

If the crust becomes sufficiently thin during stretching and sagging it may eventually break apart with the formation of small ocean basins where the continental input is minimal (Fig. 5*D*). The mechanism of rupture proposed here may be analogous to the formation of modern rift systems and is described in detail by Keen (1980). It is also possible that strike-slip induced pull-apart basins as a result of transcurrent movements following crustal distortion may develop into greenstone depositories. Platt (1980) suggests large--scale ductile wrench-faulting as a possible mechanism.

"Oceanic" greenstones as in Fig. 5*D* would have to be founded on ancient layered oceanic crust. Such crust has not been convincingly demonstrated from any Archaean greenstone belt, but there are many belts whose bases are not exposed or whose basal contacts are concealed by later tectonism or granitoid intrusives.

Closure of the greenstone basin by horizontal shortening causes early recumbent folding and shallow thrusts (Fig. 5*E*) that may lead to stratigraphic repetition and obliteration of original depositional relationships (DeWit, 1982; Stowe, 1974; Platt, 1980). Many of these early flat structures were later modified and frequently steepened during the emplacement of granitoid batholiths that caused further horizontal shortening in the greenstone pile.

The marginal basin model for the evolution of Archaean greenstones as proposed by Tarney *et al.* (1976) fails to account for many of the observed greenstone belt relationships (*e.g.* Groves *et al.*, 1978; Platt, 1980; Hickman, 1981; Gee *et al.*, 1981; Archibald *et al.*, 1981), in particular the apparently large greenstone basins and the remarkably continuous stratigraphy in some regions. Furthermore, available age data suggest that most greenstone belts and associated granitoids had evolutionary histories extending over *ca.* 200 Ma or more while, on the average. Recent marginal basins have relatively short lifetimes of 40 Ma or less (Talwani and Langseth, 1981).

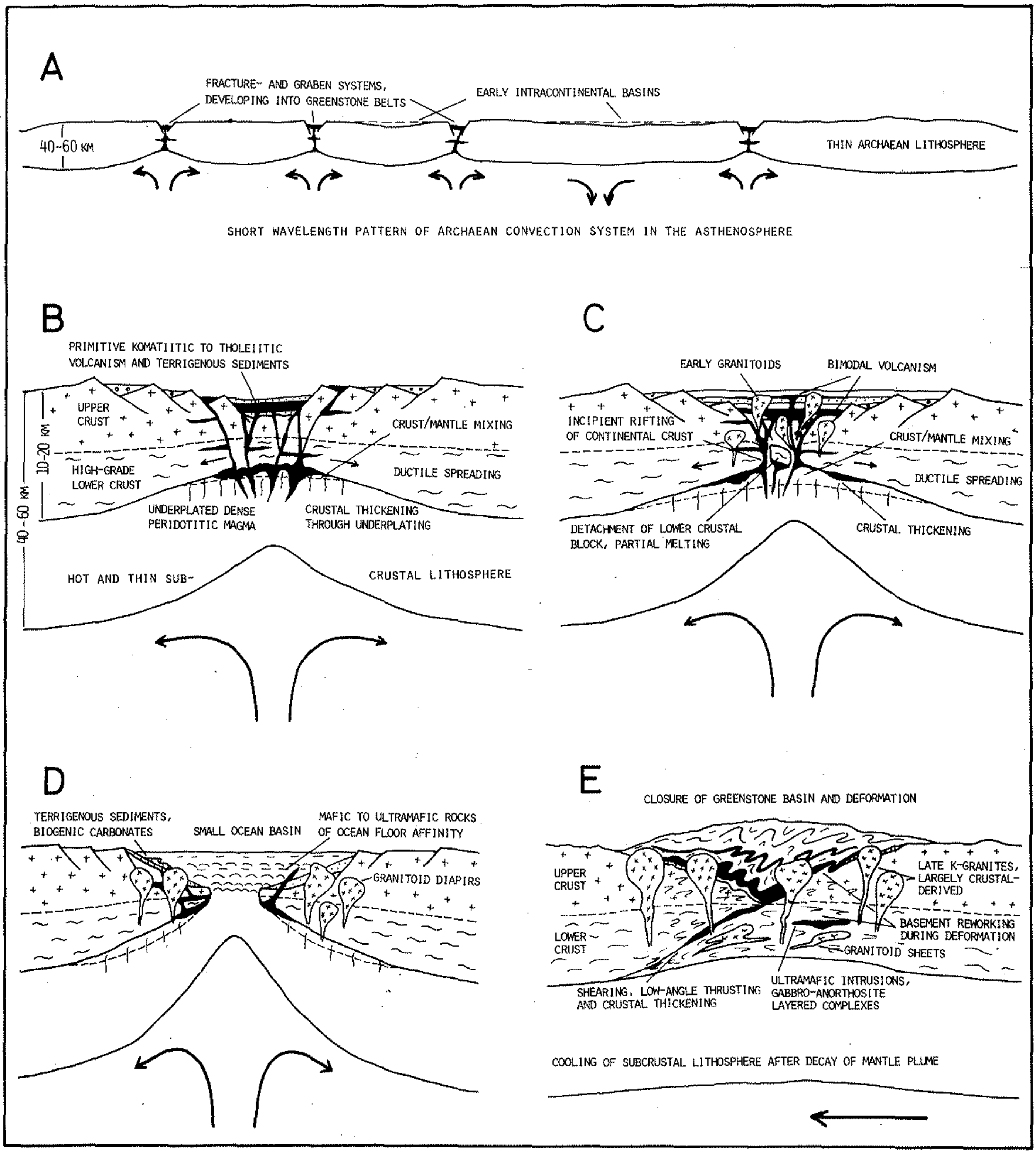

Figure 5 – Schematic cross-sections showing suggested evolution of early Archaean lithosphere in response to small-scale convection pattern in the mantle (A) *and various stages in the development of a greenstone belt* (B-D). *For explanations see text. Modified after Kröner (1981*a)

The Archaean high-grade terrains represent largely pre--greenstone sialic crust, together with predominantly shallow-water sedimentary deposits and granitoids, produced during various stages of incomplete crustal fissuring and subsidence. Crustal interstacking moved much of this material into lower crustal levels with transformation of granitoids and supracrustal rocks into high-grade metamorphic assemblages.

Periodic subcrustal mantle decoupling of dense, heavy residues may provide the mechanism for ductile flow and horizontal tectonics in Archaean lower crust. Combined with "thinned-crust collision" this may explain tectonic mixing through interstacking (Park, 1981). It is suggested that this type of lower crust underlies most, if not all, granite-greenstone terrains in the ancient shields as suggested by the crustal profile in the Vredefort Dome, South Africa (Hart *et al.*, 1981).

By the end of the Archaean large crustal segments of at least subcontinental proportions were in existence (Kröner, 1981*c*) that moved around independently and with different average minimum velocities comparable to those of today.

The remaining questions of why no Archaean ocean crust and no typical continental slope deposits are preserved remain enigmatic. As for the former it is speculated that near-vertical subduction in the ancient oceans and the comparatively high density of largely komatiitic ocean crust (N. Arndt, pers. comm., 1982) prohibited obduction. If "sag-subduction" caused complete recycling of the Archaean oceanic lithosphere the viscous drag forces in the ancient upper mantle must indeed have been considerable (Hargraves, 1981). Vertical subduction involving no mantle wedge would also explain the scarcity of andesites in the Archaean (Barker *et al.*, 1981) and would largely rule out the marginal basin model for greenstone evolution.

The missing widespread turbidites that should be expected from the margins of Archaean continents may either be due to a considerably lower elevation contrast between continental surfaces and ancient ocean basins as expected from the relatively young average age of ocean crust at that time and/or such rocks were lost through processes of "subduction erosion" (Dewey and Windley, 1981) where the downgoing slab drags down most of the oceanic and trench sediments as well as the underside of the forearc crust and thus inhibits the development of subduction-accretion complexes like at the Japan, Mariana and Middle America trenches (Talwani and Langseth, 1981).

EARLY PROTEROZOIC TECTONICS A period of comparative crustal stability following Late Archaean cratonization through voluminous granitoid magmatism characterizes most old shields in the Early Proterozoic. In southern Africa considerable crustal stability was already achieved some 3 Ga ago as documented by still little-deformed volcanics and sediments that were deposited in intracratonic basins (Kröner, 1981*a,c*) while elsewhere this stability is documented at about 2.6-2.4 Ga ago by such sequences as the Fortescue in Western Australia and the Dharwar in Peninsular India. All these units developed in continental rift environments on thick, older granitoid crust and their subsequent deformation, if any reflects the degree of stability of the underlying craton. In some cases the basin evolution closely follows the greenstone belt pattern of the Archaean but ultramafic volcanics and granitoids are less frequent and deformation is markedly less intense. The 3 Ga old Pongola sequence of Southern Africa and the 2.4-2.5 Ga old Dharwar suites are examples of this kind and have been termed "failed greenstone belts" by Hegner *et al.* (1981) since they may reflect abortive attempts of the stabilized crust to break apart.

Elsewhere such sequences were deposited on less stable crust and formed successions that are somewhat intermediate between greenstones and deposits in Phanerozoic "geosynclines" in that the proportion of more differentiated volcanics including andesites as well as immature sediments is appreciably higher than in most Archaean suites (*e.g.* Condie, 1982*b*). The Birrimian of West Africa, the Jacobina and Minas Groups of Brazil and the Huronian of the Canadian shield may be examples of this type.

Although clearly associated with older continental crust the evolution of these sequences is still a matter of considerable debate since they were deposited in elongate, well--defined basins and experienced a tectonic history that resembles modern collision belts of Alpine- or Himalaya--type or active continental margin evolution of Cordilleran--style. The whole discussion is now receiving an added complexity in that it is likely that exotic terranes that played a decisive role in the accretionary history of Phanerozoic Cordilleran belts (Coney *et al.*, 1980) have also existed in Proterozoic times as already suspected from palaeomagnetic data of the Canadian shield (Irving and McGlynn, 1981) and of the late Precambrian accretion complex of Arabia (Kröner, unpubl. data).

Condie (1982*b*) has reviewed the composition of Early and Middle Proterozoic successions and concludes that the period before *ca.* 1.7 Ga was dominated by stable continental margin or intracratonic basins while later assemblages suggest more mobile environments with frequent continental rifting and the local onset of buoyancy-driven subduction. Suggestions for Middle Proterozoic convergent plate boundary tectonics come from the Wopmay orogen and the Circum Superior belt of the Canadian shield, the Svecofennides of the Baltic shield and the Mid-continent region of North America (*for reviews see* Medaris, in press), while contrary, but less convincing, data suggest the existence of a stable supercontinent throughout the Proterozoic (*e.g.* Piper, 1982).

The similarity of some early Proterozoic associations with modern "geosynclinal" assemblages has resulted in strongly divergent interpretations where one opinion holds that the full modern Wilson-cycle was in operation while the other opinion favours "ensialic" tectonics with relatively little relative motion of crustal segments now bordering these mobile belts (*see* Medaris, in press, for full discussion). These contrasting points of view have now largely been reconciled by the general acceptance of considerable sialic underplating (A-subduction) during orogeny as presently documented in the Himalayas, and by the recognition of plate tectonicians that several Phanerozoic orogenic belts such as the Alps and Pyrenees appear to have resulted from largely intracontinental deformation whereby severely attenuated continental lithosphere was shortened and thickened by a variety of mechanisms ranging from thrust restacking to transform shearing (Dewey, 1982).

Dewey (1982) has discussed basin formation, lithospheric stretching and crust restacking while Kröner (1977, 1980, 1981*b*, 1982) applied identical concepts in models for the evolution of African Proterozoic belts. It is clear, therefore, that plate tectonics does not require complete plate separation prior to orogeny, and a whole variety of different settings can now be imagined that do not follow the Wilson cycle pattern.

Following the speculation of Bird (1978) that subcrustal mantle lithosphere may delaminate during orogeny, Kröner (in press) has developed a model for the ensialic evolution of Proterozoic mobile belts that includes the concepts discussed above and that infers subcrustal mantle rather than ocean crust subduction during horizontal shortening of previously attenuated continental crust. This model is presented in Fig. 6 in a simplified form. It invokes rifting, heating and stretching of the crust as a result of lithospheric thinning over a mantle plume. This mechanism eventually leads to a "geosynclinal" basin entirely floored by continental crust. The rise of asthenosphere enhances gravitational instabilities in the old and dense subcrustal lithosphere and, on fracturing following crustal stretching, results in spontaneous delamination. Hot asthenospheric material rises to take the place of the detached and sinking lithospheric slab, thereby inducing A-subduction and interstacking of continental crust. The much thickened crust is partially melted at depth, intruded by syn- and post-orogenic granites and finally uplifted and eroded to its present level of exposure. Episodic thermal anomalies during orogeny are caused by the rise of asthenospheric magmas to the base of the crust and by radioactive self-heating after crustal interstacking.

The model is entirely compatible with the concept of horizontally moving plates but differs from the Wilson cycle in that no wet oceanic crust is generated during basin formation and none is consumed during orogeny. Instead, dry subcrustal lithosphere sinks down but does not cause calc-alkaline magmatism.

It is suggested that the majority of Early Proterozoic mobile belts, particularly those originating between 2.1 and 1.8 Ga ago, evolved along lines as suggested above, *i.e.* without significant relative motion of cratonic blocks, and this is in line with the palaeomagnetic record (*for reviews see* Kröner, 1981*b*). Towards the end of the Precambrian modern Wilson cycle evolution begins to dominate global tectonics as documented by the frequent occurrence of ophiolites and other collision and accretion signatures (Kröner, in press).

CONCLUDING REMARKS Crustal evolution and the style of global tectonics were dominated by horizontal motion since the formation of the first continental segments about 4 Ga ago. Since average minimum velocities of the continents do not seem to have changed significantly over the last 3.5 Ga, it may have been the changing style of

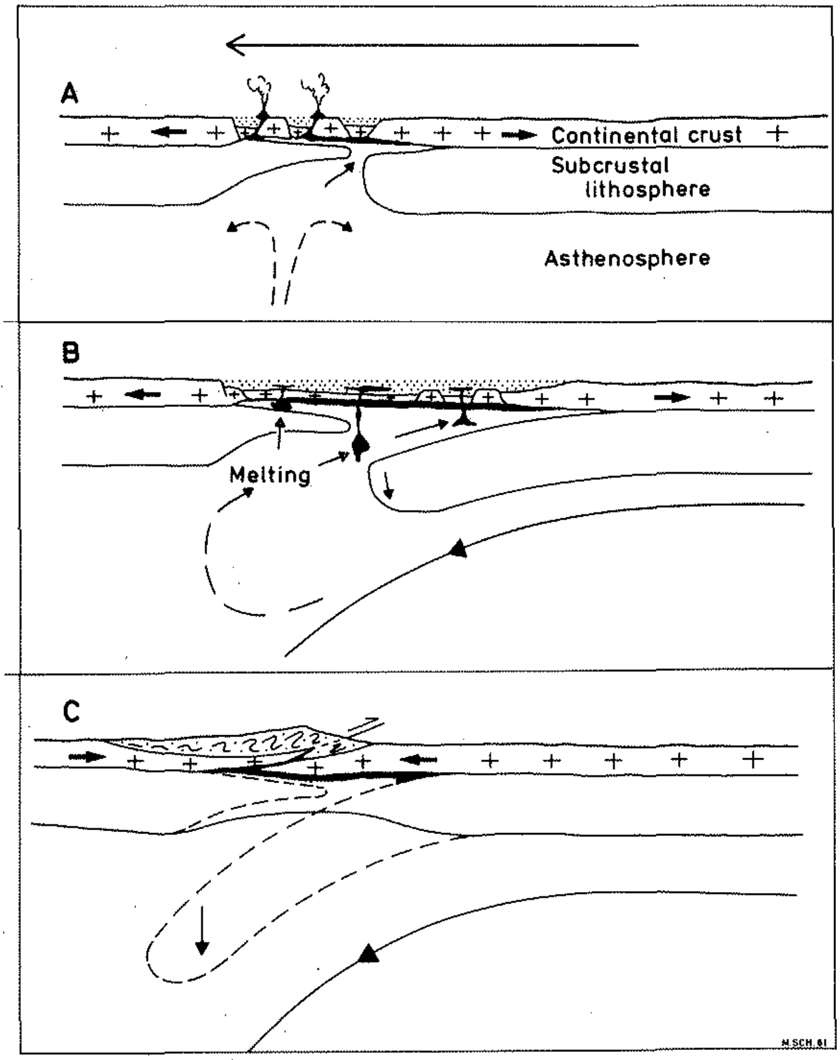

Figure 6 – Cartoon depicting three stages in the evolution of an "ensialic" foldbelt through rifting, lithospheric stretching, delamination of mantle lithosphere and crustal interstacking or A-subduction causing horizontal shortening and orogeny. (From Kröner, in press)

crustal interaction that determined non-uniformitarian development towards modern plate tectonics. At present, many plate tectonicians still see models of intracrustal Archaean evolution as advocated in this paper as idiosyncratic, non-uniformitarian mechanisms (Windley, 1981), but I feel confident that the final acceptance of ensialic orogeny as just one form of the complex interplay of rigid plates (Dewey, 1982) demonstrates the flexibility of the plate tectonic concept whose expression in the rock record has left evidence for a unidirectional development that we are still unable to decipher in detail.

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