

PRECAMBRIAN CRUSTAL EVOLUTION IN THE LIGHT OF PLATE TECTONICS AND THE UNDACTION THEORY

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ABSTRACT

Kröner, A. 1979 Precambrian crustal evolution in the light of plate tectonics and the undation theory. *In*: W. J. M. van der Linden (ed.): *Fixism, mobilism or relativism: Van Bemmelen's search for harmony* — *Geol. Mijnbouw* 58: 231-240.

The difference between Phanerozoic orogens and Precambrian mobile belts and granite/greenstone terrains suggests non-uniformitarian crustal evolution, probably related to changes in the asthenospheric convection system and lithospheric thickness as the earth cooled. Sea-floor spreading and modern-type plate tectonics did not operate during the Archaean and may only have begun in the upper Proterozoic as a result of increased rigidity of the crust following lithospheric thickening.

Archaean and Proterozoic belts developed over primitive spreading centres where the heated lower crust was rendered ductile and reacted by laminar flow, thus leading to upper crustal grabens and deep ensialic basins. Only in rare cases did crustal rupture lead to small ocean basins. Many high-grade mobile belts were not produced during distinct orogenic periods, but represent sections of the lower continental crust which were brought to the surface through internal rotation of rigid blocks in large continents and/or through large-scale over- and underthrusting along straightening zones.

Some features of the Precambrian evolution are in agreement with the undation theory, but the overall pattern seems to favour a systematic development characterized by increased rigidity and mobility of the earth's crust with time. Modern plate tectonics is the logical consequence of this evolution.

INTRODUCTION

The general debate whether Precambrian crustal evolution followed uniformitarian principles and is thus compatible with present-day plate tectonic processes or whether global tectonic mechanisms changed progressively since the Archaean, eventually leading to the New Global Tectonics, is still going on and is based on the observation that many Precambrian mobile belts display characteristics which are fundamentally different from typical Phanerozoic collision orogens (e.g. SUTTON & WATSON, 1974; WATSON, 1976-a, b; KRÖNER, 1977-a; BAER, 1977; BARR, 1976). A variety of explanations have been offered for the development of these apparently ensialic belts. These appeal to sublithospheric mantle convection resulting in the formation of asthenospheric 'blisters' followed by gravitational instability and crustal inversion, i.e. vertical tectonics in the sense of BELOUSSOV (1962), RAMBERG (1967) and VAN BEMMELEN (1977), or they invoke intracontinental movements between crustal blocks along linear zones of high strain (SUTTON, 1977; WAT-

SON, 1976-b; KRÖNER, in press) as a result of intraplate stresses which build up during horizontal movement of large plates carrying supercontinents (PIPER, 1976). The latter category also includes models which recognize plate motion in the Precambrian but question the worldwide operation of the Wilson cycle because of thermal constraints (BAER, 1977; LAMBERT, 1976; FYFE, 1978) and likely differences in lithospheric thickness as compared to modern figures. Thus, localized hot spots rather than long spreading ridges may have dominated processes along ancient plate margins (GOODWIN, 1977; FYFE, 1978), leading to incipient rifting, followed by opening and closing of narrow grabens or ocean basins (GOODWIN, 1977; BAER, 1977; KRÖNER, 1977-b, 1979). Field evidence suggests that a transition from predominantly intraplate tectonics to predominantly plate margin orogeny may have occurred between some 1200 Ma and 500 Ma ago and this can be demonstrated particularly well for the African continent (KRÖNER, 1977-b, 1979).

The apparent differences in crustal development during the Archaean, Proterozoic and Phanerozoic clearly indicate non-uniformitarian global evolution, probably related to changes in physical parameters (FYFE, 1978; BAER, 1977; LAMBERT, 1976), and it is attempted here to examine whether a

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modified form of plate tectonics can account for the phenomena or whether the Undation Theory as developed by VAN BEMMELEN (1954, 1972, 1977) may be more appropriate to explain these processes.

PRECAMBRIAN MOBILE BELTS AND THE UNDATION THEORY

The major difference between Phanerozoic orogens of Alpine or Appalachian type and many Precambrian mobile belts is the lack of characteristically thick continental margin deposits, mafic volcanism of ophiolite association, high-pressure metamorphic assemblages and molasse sediments in the latter. These features as well as the lack of identifiable plate margins and sutures suggest an ensialic evolution and, for some belts of the African continent, this is supported by palaeomagnetic and structural data indicating little crustal shortening and the apparent continuity of sialic basement from one foreland to the other (KRÖNER, 1977-b).

Of particular interest in this regard are the detailed craton-mobile belt relationships in Precambrian terrains, especially in those areas where linear zones of high-grade rocks apparently transect older crustal blocks and are thus juxtaposed to lower-grade assemblages in the neighbouring stable regimes. The Archaean Limpopo belt of southeastern Africa may serve as an example here since its tectono-metamorphic and geochronological history is now reasonably well established (for summaries see ERMANOVICS ET AL., 1977; COWARD ET AL., 1976; KRÖNER, in press).

The boundaries of the belt are difficult to define since both the northern and southern margins are diffuse and grade into the granite/greenstone terrains of the Rhodesia and Kaapvaal cratons respectively. New age data (BARTON & RYAN, 1977) demonstrate the existence of a very old basement floor in the belt which formed more than 3800 Ma ago and is thus equally old, if not older, than the pre-greenstone complexes in the neighbouring cratons. For each of the igneous-metamorphic episodes during the 1500 Ma long history of the belt there are equivalent and contemporaneous events in the two adjoining cratons and this close relationship argues for an intracontinental origin for the Limpopo belt.

The most significant difference between the belt and the cratons is one of metamorphic grade and thus of crustal level, and evaluation of structural data suggests that the Limpopo belt represents a 'window' of lower crust between two upper crustal Archaean blocks (KRÖNER, in press). This model implies that the granite-greenstone terrains of the cratons are underlain by Limpopo belt-type high-grade metamorphic assemblages, a view supported by gravity data (FAIRHEAD & SCOVELL, 1977) and heat-flow measurements (Oxburgh, pers. comm., 1978). A further consequence of this model is that the belt was no separate tectonic entity during the first 1000 Ma of its history. The real mobile-belt forming event took place about 2500-2600 Ma ago when large-scale transcurrent

faulting occurred as a result of rotation of the Rhodesian craton relative to the Kaapvaal craton (COWARD ET AL., 1976) and marginal straightening zones developed, thereby generating the pronounced linearity of the belt now observed. At the same time vertical movements along these straightening zones caused the high-grade gneissic assemblages of lower crustal regimes to become juxtaposed next to the lower-grade granite-greenstone terrains of the cratons.

A similar evolution is postulated for the high-grade Proterozoic Inari-Belomoride belt of northern Finland and Sowjet-Karelia (KRÖNER, in press) which may represent a giant transcurrent fault zone (fracture de fond of KRATZ ET AL., 1974; deep fault zone of BYLINSKI ET AL., 1976) or ancient lineament (WATSON, 1976-b) along which a 'slice' of Archaean lower crustal rocks was uplifted and tectonically realigned during the mobile belt forming event some 1900-2100 Ma ago. This was an entirely ensialic process and led to substantial crustal thickening in northern Finland, similar to that described by MYERS (1976) for the Archaean of West Greenland.

In summary the Limpopo and Inari-Belomoride belts, and probably many other Precambrian high-grade assemblages, have never gone through a geosynclinal stage and represent reworked segments of deep crust rather than accreted material. The linearity of these belts is a secondary effect due to uplift and limited internal rotation of crustal blocks. Where this later effect is lacking, like in the Archaean granulite-charnockite complex of southern India, there is no pronounced structural linearity giving these terrains 'mobile belt' character, and the transitional nature between these deep crustal rocks and the overlying and younger upper crustal assemblages (RAMIENGAR ET AL., 1978) is even more apparent than in the cases described above.

Another type of Precambrian mobile belt is more comparable to Phanerozoic orogens in that we can identify great thicknesses of metasedimentary and metavolcanic assemblages which must have been deposited in deep intracontinental basins. In Africa this type of belt becomes prominent in the mid-Proterozoic and includes such entities as the Ubendian-Ruzizian belt, the Ruwenzori belt, the Kibaran belt and the Irumide belt (for details see CAHEN & SNELLING, 1966; KRÖNER, 1977-b). Some of the late Precambrian-early Palaeozoic belts of the Pan African system also belong to this category (e.g. West Congo belt, Katangan belt). KRÖNER (1977-b) has discussed the characteristics of these belts and concluded that they were not produced by Wilson-cycle processes but developed from graben-controlled ensialic basins. One of the strongest arguments for this conclusion is seen in the fact that many belts end within continents and are underlain by continuous sialic basement (e.g. Irumide, Ruwenzori and West Congo belts).

It seems clear from this discussion that Precambrian mobile zones cannot be regarded as the direct result of modern-type plate tectonics and it is therefore necessary to search for alternative evolutionary models. VAN BEMMELEN (1976) ar-

gued that plate tectonics restricts itself to a uniformitarian extrapolation of the present situation and is therefore not compatible with Precambrian evolution. He suggested that his undation theory is more flexible and explains the changing global development by means of periodic asthenospheric convection circuits causing differential vertical movements on the one hand and continuous geochemical transformation of continental crust into oceanic crust on the other hand, thereby steadily decreasing the area of sialic crust. Let us shortly examine whether these speculations are in agreement with the Precambrian record.

Periodicity of tectono-metamorphic events in Precambrian terrains is documented by a significant grouping and cluster of radiometric ages at certain times. One of the most important worldwide events occurred about 2600-2800 Ma ago when large volumes of juvenile granitoid material were added to the ancient Archaean crust and the first identifiable proto-continents were established. There is still considerable controversy whether these rocks were produced in island-arc environments and were accreted to the old continental nuclei during collision processes (GLIKSON, 1972; ANHAEUSSER, 1973) or whether they represent products of vertical accretion, emplaced along continental fracture zones, rifts or in narrow zones of strong subsidence (sag-subduction of GOODWIN, 1977). Whatever the mechanism, the end-Archaean event substantially increased the amount of global sialic crust and it is most likely that this had an important consequence for later crustal development.

Periodicity as discussed here is reflected by rock and mineral ages resulting from closure of isotopic systems at particular temperatures. These ages tell us little about the duration of tectono-metamorphic events in mobile belts. For example the Limpopo belt material was uplifted after a complex polyphase history lasting more than 1000 Ma and conventional dating techniques only record the time of uplift, not the previous history. Detailed dating in other mobile zones (e.g. Namaqua belt of southwestern Africa, Grenville belt of North America, Lewisian of Scotland) shows equally long and complex crustal histories and it may well be that the presently recognized periodicity may disappear when more age data are available. A good example here is the Pan African belt system whose metamorphic history was first documented by mineral cooling ages and these data led to the definition of the apparently episodic and continent-wide "± 500 m.y. Pan African Thermo-Tectonic Episode" by KENNEDY (1964). More recent isotopic ages by various methods demonstrate strongly diachronous Pan African development, starting at about 1200 Ma in some areas (e.g. Arabian shield: GREENWOOD ET AL., 1976) and ending some 450 Ma ago in others (KRÖNER, in press).

RUNCORN (1965) and KANASEWICH ET AL. (1978) considered that the geochronologic age clusters and apparent worldwide orogenic events might reflect times of changes in the global mantle convection pattern since internal heat production is steadily decreasing. Thus mantle convection may have

developed from an early highly turbulent small cell pattern to a more uniform state of large and regular convection systems (FYFE, 1978). This relationship appears more plausible than the assumption of major periodic pulsations of mantle activity (VAN BEMMELEN, 1977) which are difficult to reconcile with continuously decreasing internal heat flow.

The undation theory relates the formation of 'geosynclines' and mobile belts to geo- or mega-undations of continental dimension (VAN BEMMELEN, 1976), but if the high-grade gneisses of many Precambrian belts are accepted as representing normal lower crust, and there is considerable seismic evidence for this assumption (SMITHON & BROWN, 1977; OLIVER, 1978), there is no need to infer the operation of undations and mantle diapirs for their generation. The belt linearity may be produced by rotational movements of crustal blocks or by thrusting as suggested by MYERS (1976).

Another problem concerns the lack of ophiolitic assemblages in most Precambrian belts discussed here. If, as the undation theory suggests, these rocks do not originate through ocean floor spreading but form in marginal trenches along mobile belts (VAN BEMMELEN, 1977) why do we not find them there? To me the first appearance of true ophiolites in certain Pan African belts with clearly defined continental margin characteristics signifies the operation of the Wilson cycle (KRÖNER, 1978) and it is difficult to imagine that such rocks with close petrological and geochemical affinities to modern oceanic crust can form in basins underlain by continental crust. Their lack in most Precambrian belts simply means that these zones evolved without ocean opening and closing.

The same applies to high-pressure assemblages such as blueschists. Their absence in the ancient belts may be expected from non-collisional tectonics or higher heat flow in the Precambrian but they should have formed in the zones of exceptionally high strain that are characteristic of many mobile belts if, as the undation theory suggests, they originate in synorogenic trenches.

An interesting speculation of the undation theory is the continuous decrease of sialic crust through 'corrosion', 'basification' and 'oceanization' and a concurrent growth of oceanic basins. It is not clear by what geochemical process this could be accomplished and there are no known remnants of possible ocean floor older than about 1000 Ma. REZANOV & FAYTELSON (1975) proposed a model of zonal fusion whereby the lower continental crust is progressively basified by upward expulsion of the acidic components so that the residue becomes close in composition to upper mantle material. This hypothetical process of oceanization is in complete disagreement with petrologic and Sr-isotopic data and there is no known mechanism that would explain the removal of vast quantities of silica and alkalis if the origin of our oceanic crust was indeed due to such phenomena. Furthermore, how could layered oceanic crust as we observe it today be produced by the zonal fusion model?

In terms of the oceanization or crustal destruction process of the undation theory the amount of mafic rocks of oceanic

affinity should have increased steadily from the Archaean to the Phanerozoic, but this is not reflected by the rock record. On the other hand, if the crust has grown from small continental nuclei, as uniformitarian plate tectonics implies, the opposite must be true and we should find a decreasing amount of ophiolites and continental-margin deposits amongst the many upper crustal Precambrian assemblages. This is not the case either and this suggests that alternative mechanisms must have operated.

Another way to lose continental crust is by weathering and subduction of oceanic and continental margin sediments in oceanic trenches. Such processes have recently been documented during Leg 57 of the DSDP in the Japan Trench (Geotimes, April 1978, p. 20) and FYFE (1978) has estimated that the sediment subduction rate based on present rates of sea-floor spreading is about 2-4 times higher than the net addition to the crust by andesitic volcanism. It is therefore possible that crust has been lost, at least since the beginning of Wilson-cycle tectonics, and this may explain why so few accreted plate margins are preserved and it may also be an explanation for the apparent 'growth' of ocean basins.

One fundamental difficulty of the undation theory is to explain the large-scale motion of crustal plates carrying supercontinents in the Precambrian (PIPER, 1976; MCELHINNY & MCWILLIAMS, 1977). If all the crust was initially sialic as the theory requires, plate motion was impossible in the early Precambrian since the wholesale subduction of continental lithosphere seems impossible (DEWEY & BIRD, 1970). However, apparent polar wander paths for North America, Africa and Australia reveal independent horizontal movements of substantial continental masses as far back as 2700 Ma ago (MCELHINNY & MCWILLIAMS, 1977) and it is difficult to understand this motion without some form of plate tectonics.

Despite these discrepancies there are other features of Precambrian evolution which may well be in accordance with the basic concept of the undation theory. Some of these are the great intracrustal basins which are typically developed in some ancient shield areas such as southern Africa and Australia and which can be related to large-scale epirogenetic crustal movements, faulting and tectonic downwarping (ANHAEUSSER, 1973; HUNTER, 1974; TRENDALL, 1968).

A further problem concerns the origin of Precambrian intracrustal andesites. These rocks are particularly voluminous in the 3000 Ma old Pongola and the 2500 Ma old Ventersdorp basins of the Kaapvaal craton in southern Africa (HUNTER, 1974) and in the Ventersdorp-equivalent Fortescue basin of Western Australia (TRENDALL, 1975) and are not related to orogenic processes. Recent data show that andesites may be the result of pervasive crust-mantle mixing (EICHELBERGER, 1978) and it is therefore possible that basin formation and crustal downwarp, accompanied by tensional faulting, leads to fusion along the crust-mantle boundary with subsequent andesite volcanism as suggested by the undation theory. Similar processes can perhaps be invoked for the development of andesite-rich Archaean greenstone belts

where mafic volcanism of oceanic affinity alternates with andesites of strong calc-alkaline and island-arc character (GOODWIN, 1977-b).

This unusual association may reflect unique conditions where crustal fissuring, graben-formation and the extrusion of komatiitic lava along mantle-tapping fractures is followed by subsidence of elongate sialic blocks which, in turn, induces crust-mantle mixing and the generation of andesites and co-genetic calc-alkaline granitoids.

PROPOSED PRECAMBRIAN CRUSTAL EVOLUTION

The formation of the earliest continental crust remains controversial for the time being although it is now clear that substantial segments of sialic material must have existed since at least 3600 Ma ago (e.g. West Greenland, Minnesota, southern Africa, India, Australia, Siberia). The recognition of granite/greenstone terrains ranging in age from more than 3800 Ma to about 2600 Ma signifies a unique period of crustal evolution generating large volumes of granitoid material (tonalites, trondjemites) which obliterated most of the earliest crustal history. The origin of the oldest greenstone belts (> 3500 Ma, e.g. Isua supracrustals, Barberton belt, Sebakwian belts) is still uncertain and some investigators prefer an ensimatic development (ANHAEUSSER, 1973) because there is no direct field evidence for the presence of still older continental basement. However, for the late Archaean belts (~2600 - 2800 Ma) pre-greenstone sialic basement is now known from virtually all shields (for summary see KRÖNER, 1977-a) and both field and laboratory data are compatible with greenstone development in rifting environments ranging from narrow grabens (e.g. ANHAEUSSER ET AL., 1969; HAWKESWORTH & O'NIONS, 1977) to small ocean basins of Red-Sea type (GOODWIN, 1977-a).

The sag-subduction model of GOODWIN (1977-a) accounts for most of the rock relationships and geochemical parameters observed in late Archaean greenstone belts and on the basis of this model I suggest the following evolutionary development.

Archaean heat flow was high and caused turbulent mantle convection resulting in small convection cells under a thin lithosphere with low torsional rigidity. This convection pattern prevented the formation of large oceanic ridge systems but led to the formation of closely spaced (100-200 km) thermal plumes or hot spots which were able to produce asthenospheric 'blisters' or wedges at the base of the ancient crust (Fig. 1). Crustal attenuation and fissuring follows and generates small elongate basins which collect shallow water sediments as well as mafic to ultramafic lavas (komatiites) produced by a high degree of melting in the subcrustal mantle. Further rifting causes crustal subsidence in the proto-greenstone basin and subsequent rise of the crust mantle boundary. This process is enhanced by the weight of the already extruded dense komatiitic and tholeiitic volcanics as

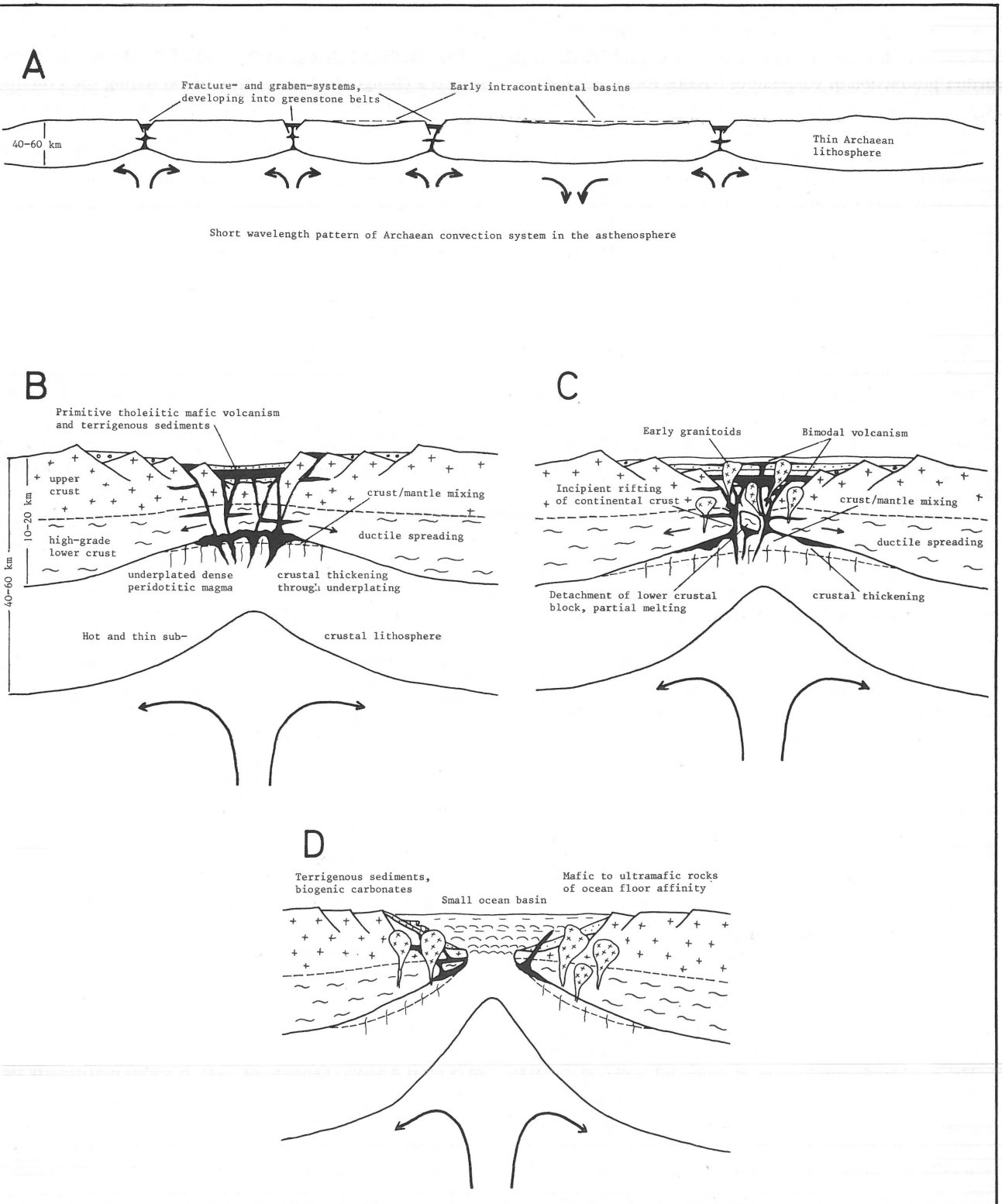


fig. 1
 Schematic cross-sections showing suggested evolution of thin Archaean lithosphere in response to small-scale convection pattern. For explanation: see text.

well as the downward drag by underplated perioditic magmas (FYFE, 1978) (Fig. 1B). Eventually the spreading and sagging process may lead to the decoupling of crustal blocks with further production of voluminous basaltic rocks. At that stage fusion and crust-mantle mixing becomes important and leads to the production of andesites and more highly differentiated volcanics higher in the greenstone pile as well as consanguineous calc-alkaline granitoid intrusives (Fig. 1C). This mechanism explains why rocks of ocean floor affinity (komatiitic and tholeiitic basalt) are now found in the same stratigraphic sequence as island-arc type assemblages (FYFE, 1978). The similarity of the latter with modern subduction-related rock types is not surprising since the process of vertical sag-subduction produces subcrustal settings which are chemically and petrologically comparable to those above oblique subduction zones.

If the crust becomes sufficiently thin during the stretching and sagging process it may eventually break apart with the formation of small ocean basins in which ensimatic greenstone belts can form (GOODWIN, 1977-a) (Fig. 1D). The mechanism of crustal fissuring and rupture proposed here may be analogous to the formation of modern rift systems, small ocean basins (Red Sea) or back-arc basins.

The Archaean high-grade terrains represent the pre-existing sialic crust together with new clastic deposits and granitoids produced during various stages of pre-greenstone fissuring as suggested above for the Limpopo belt. The rifted and in part lowered older crust underwent higher-grade metamorphism with the transformation of granitoids and supracrustals into migmatites, banded gneisses, granulites and grey tonalitic gneiss. It is suggested that this type of lower crust underlies most, if not all, granite/greenstone terrains (GOODWIN, 1977-a) in the ancient shields and was not produced during distinct 'orogenic' periods.

It seems clear from a review of modern isotopic data that large crustal segments of at least sub-continental proportions were in existence at the end of the Archaean (KRÖNER, 1977-a; RUTLAND, 1973; BARAGAR & MCGLYNN, 1976). One may speculate that the entire Archaean continental crust may have been assembled in one large supercontinent such as the later Pangaea, thus leaving a globe-encircling primeval ocean in which innumerable volcanic chains formed lines of hot spots -the forerunners of modern ridge systems- through which the earth outgassed and lost much of its early heat.

The worldwide production of granitoid rocks at ± 2800 - 2600 Ma ago may not only have increased the size and thickness of the early crust but must also have led to substantial cooling in the mantle thereby changing the convective pattern to larger, more regular convection cells (RUNCORN, 1965; FYFE, 1978) and probably also leading to thicker lithospheric segments. Palaeomagnetic data suggest that some form of continental drift must have operated by that time and this may indicate that the 'disorganized' Archaean hot-spot spreading gave way to a more regular pattern of linear volcanic activity along primitive ocean-ridge systems, deter-

mined by the orientation of the larger convective mantle currents.

This profound change at the end of the Archaean necessitated a change in crustal deformation during the Proterozoic. Although the geothermal gradients may still have prohibited the basalt-eclogite phase change so that no subduction of oceanic crust could have occurred (GREEN, 1975; BAER, 1977) this state need not have prohibited plate tectonics. Since oceanic crust is considered to be more rigid than continental crust (MCKENZIE, 1969; JORDAN, 1979) some relative motion between strong, rigid oceanic plates might have been possible with the intervening weaker continental plates taking up most of the necessary deformation through internal distortion or along large shearzones. This process led to the generation of remarkably linear belts (SUTTON, 1977) and segments of the lower crust were uplifted and overthrust on upper crustal blocks (Fig. 2A). Elsewhere the first large intercontinental basins developed as a result of epeirogenetic movements, possibly reflecting the larger dimensions of Proterozoic convection cells (geo-undations of VAN BEMMELLEN, 1977). The 2800-2300 Ma old Witwatersrand-Ventersdorp basin of South Africa (PRETORIUS, 1966) and the early Proterozoic Fortescue-Hammersley basin of western Australia (TRENDALL, 1975) are examples of this evolution.

In regions where lithospheric thickening was less pronounced, linear fracture zones could still develop above asthenospheric diapirs overlying convective rises and this led to the development of linear troughs or basins which subsided slowly and collected considerable amounts of terrigenous sediments (Fig. 2B). Volcanic rocks are much less prominent here than in the Archaean greenstone belts but may still reach considerable proportions. Their composition is often bimodal with acidic members greatly dominating over mafic volcanics. These features suggest that Proterozoic 'geosynclinal' basins developed along essentially similar lines as the greenstone belts but since the crust was considerably thicker then, though still not very rigid, convective drag and subcrustal heating was generally not sufficient to lead to complete break-up and formation of ocean basins. This may explain why modern-type ophiolites and continental collision tectonics have not been observed in Proterozoic mobile belts. Good African examples for this type of structure are the Ubendian-Ruzizian belt, the Ruwenzori belt, the Irumide and Kibaran-Burundian belts and the mid-Proterozoic belts of central Angola (KRÖNER, 1977-a). It seems particularly significant that the proportion of volcanic and granitoid rocks varies widely in these zones and these rock types may be completely absent in some belts (e.g. Irumide belt).

In summary the Proterozoic belts appear to be the result of incipient continental rifting in response to large-scale convective motion in the mantle and differences in basin development, and subsequent deformation from one belt to another may be due to varying degrees of crustal attenuation and following compression. The tectono-metamorphic development of these belts may be envisaged in terms of the

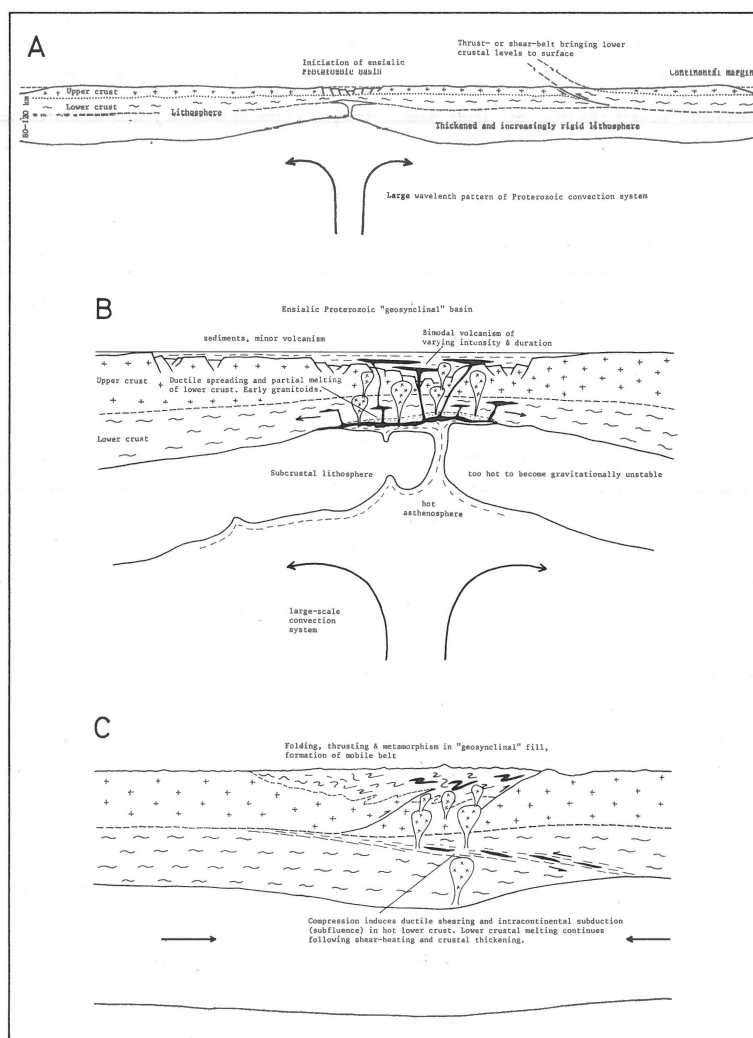


Fig. 2
Simplified and schematic sections showing suggested evolution for Proterozoic ensialic mobile belts. For explanation: see text.

millipede model of WYNNE-EDWARDS (1976) and limited intracrustal subduction (Fig. 2C).

With the exception of one example (Coronation belt of northeastern Canada: HOFFMAN, 1976) there is no early or middle Proterozoic mobile belt where field relationships, rock types and structural settings are compatible with Wilson-cycle tectonics and I believe that the development of these belts, though related to mantle convection and plate motion, is essentially ensialic.

Towards the end of the Precambrian another major change in global tectonics may have occurred, perhaps related to further convective cooling, changes in the convective system, lithospheric thickening and increased rigidity. The recognition of rock assemblages characterizing both passive and active continental margins as well as island-arc environments, together with the identification of true ophiolites and high-pressure mineral facies strongly suggests operation of modern-type Wilson-cycle processes (KRÖNER, 1979). The transition into the plate tectonic regime was facilitated by

conversion of gabbroic material at the base of the lower crust into eclogite (RINGWOOD, 1975), thereby creating a dense 'sinker' which can pull material of the lower lithosphere down into the asthenosphere (BAER, 1977).

TOKSÖZ & BIRD (1977) and BIRD (1978) have recently discussed a mechanism of continental convergence and intracontinental subduction which is modified here and may well be applicable to the formation of orogenic belts in the early stages of the plate tectonic regime: horizontal currents normal to the major vertical convection in the asthenosphere lead to lithospheric stretching and crustal fissuring (Fig. 3A). This weakening process may cause spontaneous gravitational instability and detachment of dense eclogitic lithosphere from the overlying lighter and more rigid crust (Fig. 3B). Hot asthenospheric material then fills the widening gap between the sinking lithospheric slab and the crust and causes significant heating of the overlying sialic segment, thereby facilitating further crustal attenuation and beginning of melting. This process may continue until a deep 'geosynclinal' basin

has formed (Fig. 3B) and, in the extreme case, it may lead to continental rupture and generation of small ocean basins.

Further downward pull of the delaminated asthenospheric slab will then cause continental convergence so that the greatly attenuated crust is thickened again by compression, folding of the geosynclinal fill and intrusion of syntectonic granites from the heated lower crustal regime. It is also possible that shallow ensialic subduction of one crustal segment under another as proposed for the Himalayan belt (BIRD, 1978) and the Hercynian belt of central Europe (BEHR, 1978; WEBER, 1978) adds to the crustal shortening and thickening effect and causes typical collision tectonics such as large thrusts and nappes (Fig. 3C). In cases where continental separation did not succeed no ophiolite assemblages have formed in the ensialic basins, and since continental convergence was not accompanied by consumption of oceanic lithosphere the typical island-arc volcanism could not develop. Typical examples of such environments are the Pan African Damara, Katanga, West Congo and Dahomeyan belts (KRÖNER, 1977-b, 1979).

The above model suggests that the end-Precambrian transitional tectonic regime has given rise to a whole range of different orogenic settings, ranging from intraplate to plate margin development and depending solely on the degree of crustal attenuation and continental separation (KRÖNER, 1978). I suggest that this transitional regime may have lasted well into the Palaeozoic and that a variety of early Phanerozoic belts such as the Hercynian (BEHR, 1978; WEBER, 1978), the Pyrenees (VON GÄRTNER, 1969) and the Hesperian massif of NW Spain (VAN CALSTEREN & DEN TEX, 1978) may be due to incipient continental rifting but not to Wilson-cycle evolution.

CONCLUSIONS

There is no doubt that global crustal evolution was non-uniformitarian. Major changes in the tectonic development of the crust at the end of the Archaean (± 2800 - 2600 Ma) and the end of the Precambrian (± 1000 - 600 Ma) are apparent and may be related to slow cooling in the mantle. This was accompanied by a change from small-scale turbulent convection to large-scale organized convection whereby the early hot-spot regime gradually developed to a stage where oceanic-ridge systems and thereby plate margins could form. At the same time lithospheric thicknesses increased and modern-type plate tectonic processes may have been triggered by gravitational drag and delamination of dense lithosphere from overlying crust.

It is speculated that organized motion of large crustal plates was impossible during the early Precambrian since the asthenospheric conveyor belt system was too small and too irregular to cause movement of extensive lithospheric slabs. The change from small-scale Archaean greenstone belts to large-scale Proterozoic mobile belts may be related to size

changes in the convective system and to an increasing rigidity of the thickening lithosphere.

It seems clear from this discussion that the causes for all major crustal activity are to be sought in the sub-lithospheric mantle, a fact which is acknowledged by the undation theory and the plate tectonic concept. Periodicity may be a reflection of changes in the mantle convection system; thus I believe that the convection process itself is steady whereas the changes are periodic and cause crustal phenomena which are reflected by increased magmatic, tectonic and thermal activity recorded by radiometric clocks. Periodicity in the Precambrian concerns significantly longer time intervals than in the Phanerozoic and this may partly be due to the fact that present global tectonics is explainable in terms of the interlocking nature of major plate boundaries rather than by periodic changes in mantle convection.

Certain aspects of the undation theory such as the concept of oceanization, crustal corrosion and the formation of ophiolites and blueschists appear to be erroneous and are not supported by the Precambrian and Phanerozoic rock record. However, with certain modifications the undation theory can be reconciled with plate tectonics if the latter is seen as the *present* response of the crust to mantle convection, and I feel that both hypotheses are flexible enough to incorporate the changing tectonic processes as reflected by the Precambrian evolution.

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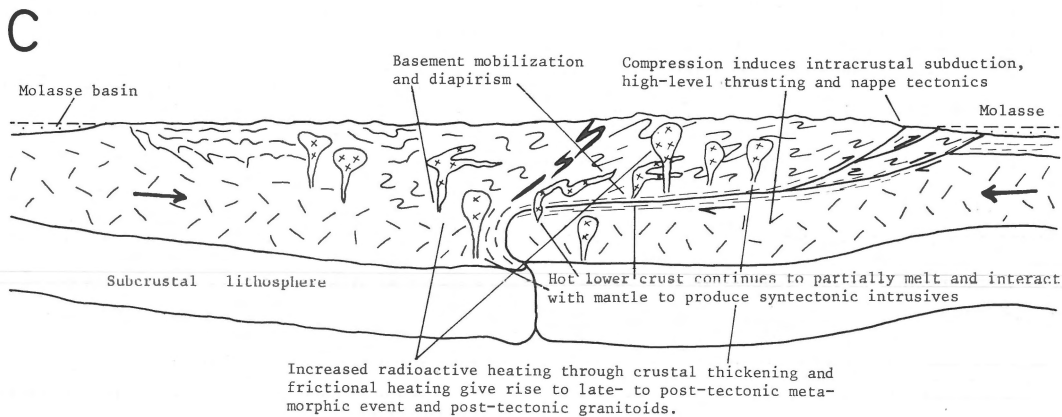
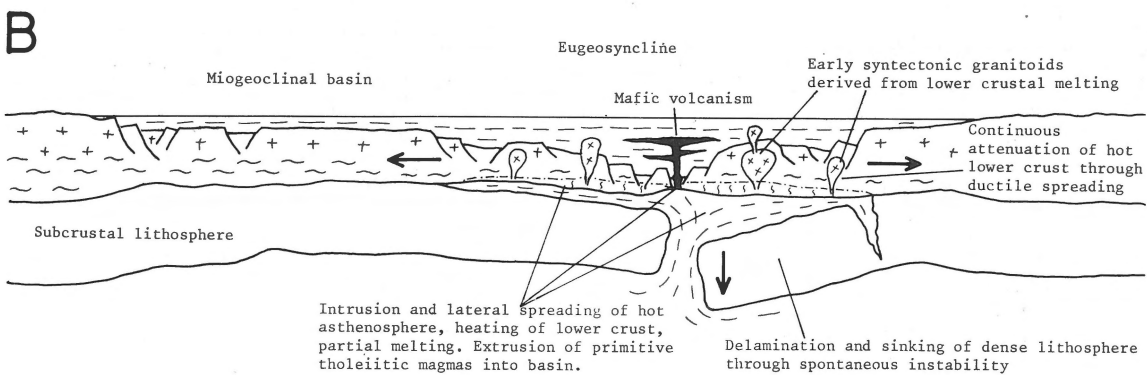
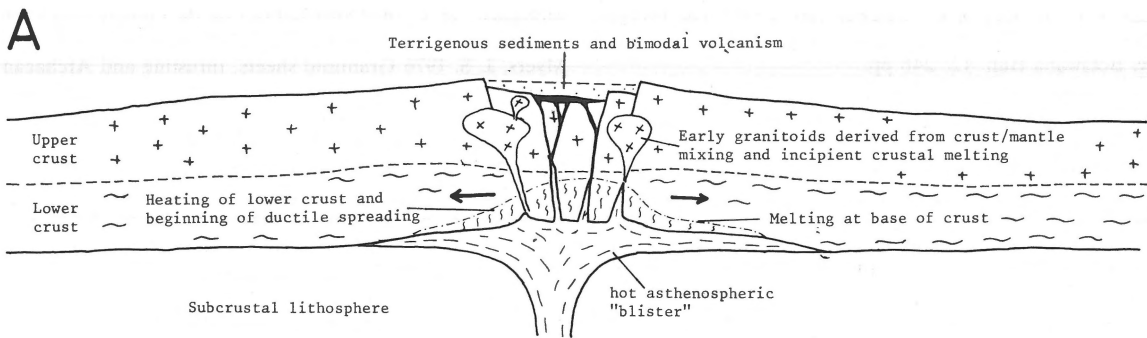


Fig. 3 Simplified and schematic sections showing suggested evolution of late Precambrian belts through crustal thinning, delamination and intra-crustal subduction. For explanation: see text.

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