A Plate Tectonic Model for the Archaean Crust [and Discussion]

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CONTENTS

The characteristics of Archaean greenstone belt terrains are briefly summarized together with some of the models which have been used to account for their genesis.

Crystalline sialic crust is interpreted as having increased with time by separation from the mantle. Many of the problems posed by Archaean greenstone belt terrains may be eased if the first sialic crust is assumed to have consisted of small masses concentrated by plate tectonic processes similar to those still in operation.

Even if Archaean plates were of similar size, and were formed and lost at rates similar to those since the Mesozoic, there would be differences in the manner in which the sialic crust was concentrated because so little had separated from the mantle during Archaean times. The original formation of the rocks now forming the earliest tonalite gneisses and migmatites is attributed to very early Archaean times when no large sialic concentrations are likely to have existed on subducted lithospheric plates and the only form of orogeny was of the Island Arc type. Even after sialic concentrations did become incorporated in subducted plates they may for a long time have been too small for significant areas to survive extensive remobilization and addition of magmas from below whenever they were associated with plate boundary zones. Sets of greenstone belts are interpreted as vestiges of former oceans.

By the end of Archaean times the sialic crustal concentrations, despite possible fragmentation and periods of independent development, became sufficiently extensive for large areas to survive ocean closure without significant remobilization.

This model implies that there is no need for orogeny to have been any more extensive in Archaean times than now; it could merely have been more extensive compared to the area of the sialic crust in existence at the time.

Plate tectonic models of Archaean tectonics are distinguished from the alternatives by their implication that large relative motions occurred between the oldest parts of the granitoid masses now on either side of the greenstone belts. Palaeomagnetism may be able to distinguish the relative usefulness of the models if any such relative motions can be recognized through the effects of remobilization of most, if not all, the sialic crust in Archaean times. Other tests are possible but the most useful might be the necessity for any model of the formation of the greenstone belts being adaptable enough to account for the relationships emerging from studies of the Archaean crustal remnants characterized by granulite facies metamorphism and anorthosites.

INTRODUCTION

This paper discusses the development of the crust over the interval of time which elapsed before the oldest recognizable craton was formed. The age of the oldest surviving craton will be taken here as defining the end of Archaean time. In the light of present knowledge this limit appears to be about 2500 Ma, although future work will no doubt recognize still older blocks which suffered little or no penetrative strain while contemporaneous orogeny was occurring elsewhere.

Remnants of crust which have survived more or less undisturbed from Archaean times are of two broad types: there are those composed of high-grade gneisses, often in the pyroxene granulite facies, which are characteristically accompanied by large bodies of anorthosite. A second association is composed of comparatively small volumes of sediments and volcanics of low metamorphic grades (largely green-schist facies) which are partially incorporated in and surrounded by large volumes of granitic rocks. The possible relations between these two associations are discussed elsewhere in this volume (Windley, Watson and Fyfe, this volume) and this contribution examines a number of alternative hypotheses which might account for the development of the greenstone and granite associations.

THE CHARACTERISTICS OF ARCHAEAN CRUST CONTAINING GREENSTONE BELTS

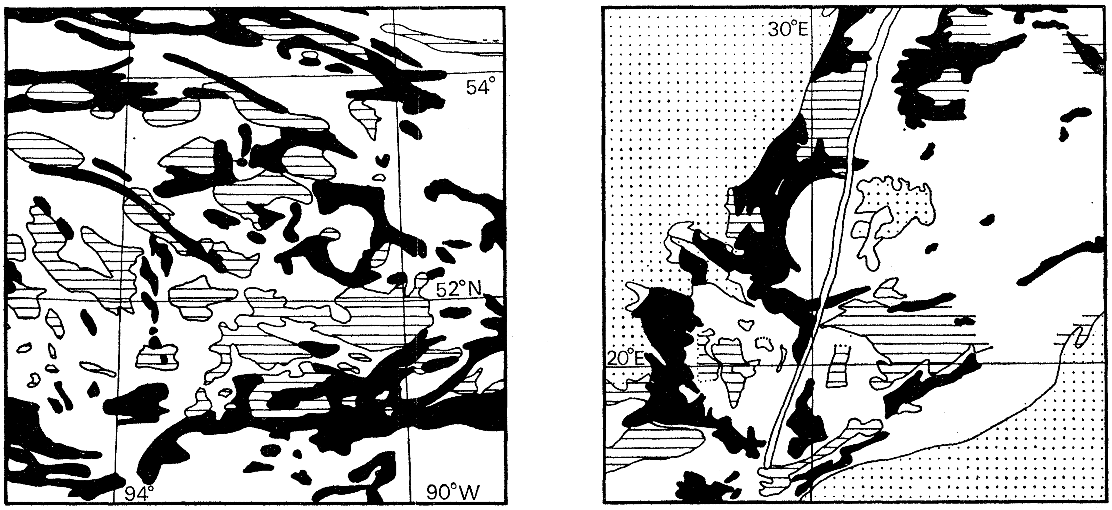
Remnants of Archaean crust in Canada, India, Western Australia and eastern, western and southern Africa, are very similar in aspect.

Figure 1 shows simplified geological maps of parts of the Archaean rocks on these four continents, all reduced to the same scale. Even for the Superior Province, for which the best maps on a scale suitable for figure 1 are available, it is immediately obvious that the ratios of granitoid rocks, metabasic volcanics and metasediments exposed at the surface are distinctive when compared with younger terrains.

Few of the rock types involved in the low-grade Archaean crustal remnants are unique, it is their relative proportions in outcrop and their metamorphic and structural unit of character which are remarkable.

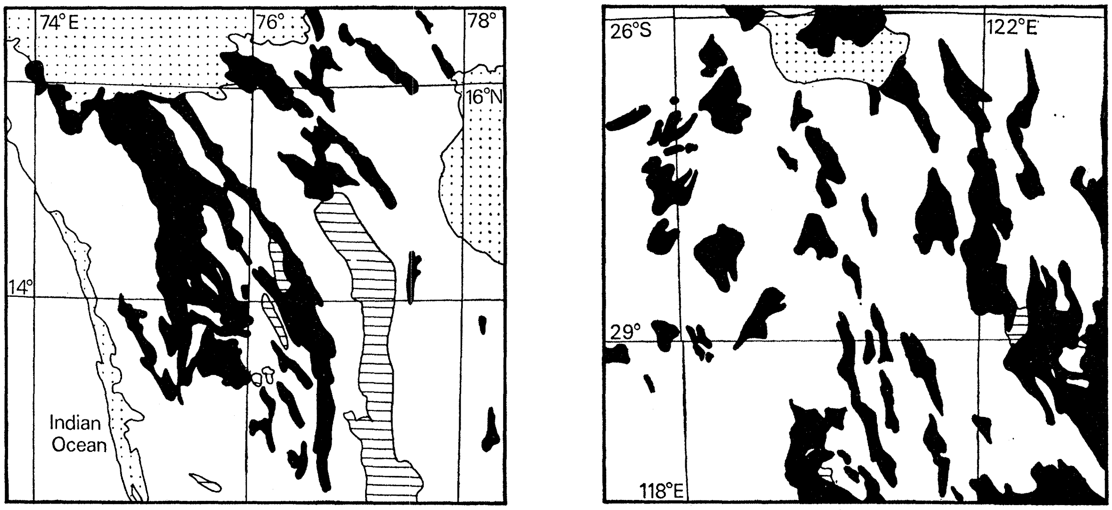
What are commonly referred to as greenstone belts in Canada, and schist belts or gold belts in Australia and Africa, consist largely of basic volcanics and immature clastic sediments in the green schist metamorphic facies. The stratigraphy of almost every greenstone belt which has been studied is to some extent unique and has its own local formation names, but recent summaries of greenstone terrains have emphasized the worldwide similarities of them all (see, for example, Sutton 1967; Goodwin 1968*b*; Anhaeusser, Mason, Viljoen & Viljoen 1969; Glickson 1970).

The rocks in a characteristic greenstone belt are largely metavolcanics at the base and pass gradually to sediments at the top. The metavolcanic lavas, pillow lavas and pyroclastics are almost invariably calc-alkaline in overall chemistry and tend to be ultramafic at the base of the full characteristic sequence and pass upwards through tholeiite basaltic to andesitic, and less voluminous dacitic and rhyolitic rock types. Minor cycles of basic to acid eruptives are often present within this general succession. The geochemical characterisitics of the metavolcanic rocks tend to be similar wherever they are found and the intermediate and acid members are



Superior Province of Canada

Rhodesia



Mysore State of India

Yilgarn block of Western Australia

FIGURE 1. Four different areas of Archaean rocks, all 483 km (300 miles) square. Greenstone belts, shown in black, are surrounded by a 'sea of granite' (left clear) in which younger granitic rocks (ruled) have been differentiated in places. Rocks younger than the Archaean are dotted.

frequently believed to be differentiation products of tholeiitic parent magmas. The whole igneous suite has often been compared to the igneous rocks of present island arcs and ocean floors (see, for example, Jacobs, Russell & Wilson 1959; Engel 1966; Goodwin 1968*b*; Glickson 1970).

The sediments, which increase in volume and importance towards the top of the characteristic greenstone belt succession, are largely undifferentiated immature clastic sediments with pyroclastic additions important near the base. Subsidiary developments of chemical precipitates are thought to be locally represented by banded ironstone, cherts and jaspilites.

The clastic sequences which have been studied in detail (see, for example, Pettijohn 1943) appear to have been derived from local granitic terrains. A very significant absence of greenstone debris has recently been reported in one area (Walker & Pettijohn 1971), and the application of modern sedimentological thought to Archaean sediments has great potential.

The very abrupt changes in thickness and facies suggest that the sediments of the greenstone belts were deposited in tectonically unstable marine conditions. It is common for individual greenstone belt successions to reach great thicknesses in comparatively small areas – e.g. 18 to 30 km in Western Australia (McCall 1968; Glickson 1970), 15 km in Barberton Mountain Land in South Africa, and 7 to 12 km in Canada (Sutton 1967, p. 514). The clastic sediment successions are usually eugeosynclinal in nature, although molasse-type sequences have been reported at the top of individual greenstone belts (Anhaeusser *et al.* 1969; Glickson 1970). Well sorted miogeosynclinal type deposits appear to be uncommon.

The greenstone belts have been studied comparatively intensively because of their economic potential; large proportions of the world's gold, silver, chrome and nickel have been mined from them. The surrounding granites are less well known and for long were left as 'a sea of granite' surrounding and engulfing wisps of greenstone belts. Where they have been studied in detail (e.g. parts of Canada and Rhodesia) they display a wide range of rock types of different ages.

The oldest granitic rocks tend to be sodium-rich tonalitic and granodioritic gneisses and migmatites with recognizable paragneisses in places (see for example, Hunter 1970; Bliss 1969). It is a matter for conjecture whether the paragneiss remnants are migmatized equivalents of the greenstone belts – but this seems unlikely in view of the strong metamorphic contrast on either side of any mutual contacts. These old migmatites and foliated tonalites yield radiogenic ages ranging from well over 3300 Ma to about 2800 Ma where they have been distinguished.

There are many opinions on the age relationships between the greenstone belts and the oldest migmatites and gneisses. The two rock sequences with their strongly contrasted metamorphic grades commonly appear to have been deformed together and have conformable foliations, but elsewhere their outcrops are separated by narrow zones of homogeneous and younger potassium rich granites (Hunter 1970). No simple undeformed unconformities have been reported, although basal conglomerates containing pebbles of granites have been reported. The oldest gneisses seem the most likely candidates for the basement on or beside which the greenstone belts were deposited and from which the siliceous clastic sediments were derived.

Other bodies, often as extensive as those of the tonalitic gneisses and migmatites, are more homogeneous, contain more potassium and appear to have large-scale diapiric relationships with the greenstone belts, having gradational, conformable and markedly transgressive contacts in different places. There are difficulties in separating the two categories of granites mentioned and Bliss has suggested their differences may be due to different levels of erosion in similar masses (Bliss 1969, p. 972).

The youngest granitic rocks are comparatively easy to separate from the others being homogeneous, often porphyritic, adamellites or true granites. They may intrude any of the other rock types with sharp transgressive contacts but often occur as narrow strips separating the greenstone belts from the underlying tonalitic gneisses and as small high-level stocks injected along the synformal axes of the greenstone belts. Metamorphic aureoles may be absent around the bodies of tonalitic gneisses, but obvious aureoles around the young potassium rich granites may be a thousand metres or so in thickness. The youngest granites in greenstone belt terrains are often as late as 1500 Ma. Although these ages imply that the youngest granites are not Archaean as the term is defined here, they are still relevant to this discussion, for, as Bliss (1969) has emphasized, the great range of apparent ages derived from the granitic rocks commonly taken as Archaean precludes their genesis being due to a single tectonic event.

The picture discerned through the complications due to the intrusions of the younger granites allows some generalizations concerning the major structures in Archaean crustal remnants. The greenstone belts tend to be synclinal about very steep axial surfaces. Steep mineral orientation and shape lineations lie in the very well-developed steep cleavages in the synclinoria – which are commonly cut by important strike faults. Anticlines are rare and faults are often present between the synforms in the greenstone belts, although the intervening major granitic gneisses generally appear to represent the antiformal bodies. The down-folded greenstone belts and their intervening granitic masses are usually linear in trend for as far along their strike as they are visible (e.g. 19000 km in Canada) but in places (e.g. Rhodesia) the granitic masses are large domes with ellipsoidal plans and the greenstone belts are preserved in three cornered synclines or synclinoria between them.

Models to account for Archaean tectonics

It appears to be a general assumption that Archaean terrains characterized by greenstone and granite associations are not merely the exposed lower levels of orogens comparable to those which have formed since Archaean times (see, for example, Macgregor 1951). This is for three main reasons: the metamorphic grade in the greenstone belts is generally too low, the scale of the structural pattern is generally too large, and the tectonic and plutonic activity appears to have lasted too long.

Two models to account for the tectonic pattern of remnants of Archaean crust will be described before a plate tectonic model is introduced which assumes that Archaean terrains do in fact consist of several orogens formed by processes still active.

Model 1 (Macgregor 1951)

The first model which has general applicability to greenstone belt terrains is based on an explanation by Eskola in 1948 of some granitic gneiss domes in Finland. He showed how these gneisses could first serve as a basement on which a sedimentary sequence could be deposited (and from which at least some of the sediments could be derived) – and yet how that same gneissose basement could subsequently intrude the overlying sedimentary sequence as 'mantled gneiss domes'. In 1951 Macgregor compared what he called the 'gregarious ovoid batholiths' of Rhodesia (see figure 1) to mantled gneiss domes.

The Archaean crustal pattern is attributed in an adaptation of Macgregor's model to the eruption of the volcanic rocks of the future greenstone belts through and onto an essentially continuous migmatitic and tonalitic gneiss basement (see top row of diagrams in figure 2). The heavy volcanics are assumed to have subsequently sunk as linear or circular furrows into the underlying lighter and more mobile acid gneisses, driving them towards the surface as large domes or ridges. These plastic bodies of remobilized basement would have been conformable with their cover rocks at low crustal levels but might have diapirically transgressed their cover at shallow levels. As the greenstone belts flowed off them, the rising domes would have been unroofed and erosion could have poured immature clastic sediments into the subsiding troughs floored by volcanic rocks. The movements could have continued and the unconformable sediments themselves may have subsequently been folded into large synclines.

Ramberg (1967) has simulated the mechanical aspects of gravity-driven movements in unstable rock sequences in a remarkable series of carefully scaled models. Such movements

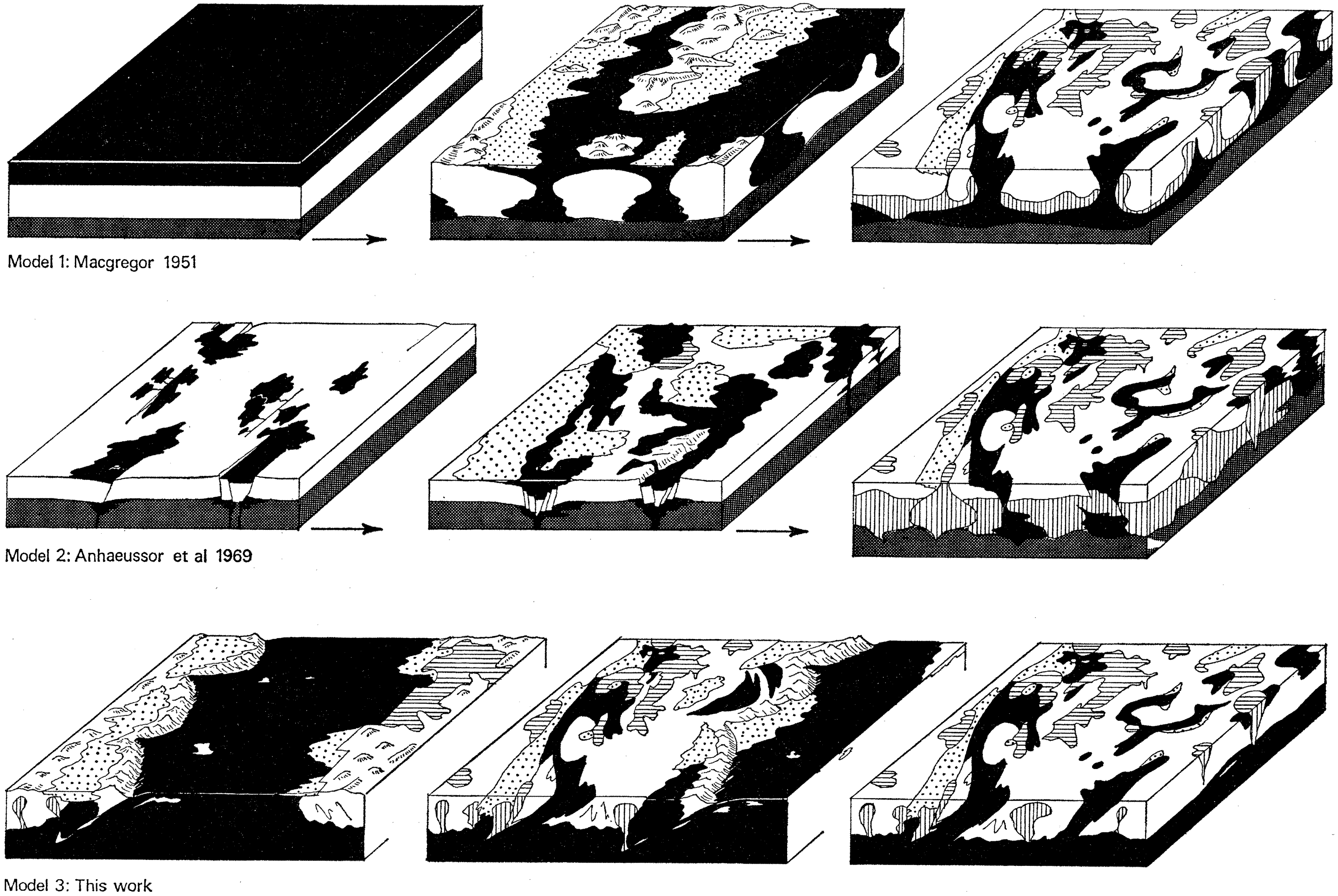


FIGURE 2. Three very different ways of accounting for an area of typical Archaean rocks.

Model 1 (top row of diagrams) interprets the volcanic greenstone belts (black) as the remnants at the surface of a heavy rock layer which fell through a previously underlying and more mobile granitoid layer (clear) which gave rise to siliceous clastic sediments (lightly stippled) when they were unroofed. The mantle is shown in dense stipple.

Model 2 (central row of diagrams) interprets the granitoid masses as fault blocks in an originally thin and continuous sialic crust thickened and distorted by the addition of granites from the mantle.

Model 3 (bottom row of diagrams) shows how the same end product at the surface may have involved the closure of oceans and the loss from the surface of huge areas of simatic topped plate.

seem possible in geologically acceptable times given thermal gradients sufficient to allow the crust to creep or deform under the influence of gravity as layers of rheids or viscous fluids. This process has almost certainly occurred on a smaller scale in many post-Archaean orogenic belts and may be incorporated to a greater or lesser extent in the other models to be described. A variation of model 1 (Talbot 1968) added the effect of a secondary, thermally induced, density inversion and suggested that the granitoid layer may have been circulating as a whole by thermal convection as the greenstone belts sank into and through it at the margins of crude rectangular or hexagonal cells. The confinement of such general crustal tectonics to Archaean times was ascribed to subtleties in the development of the thermal gradient of the granitic crust. The effective viscosities of granitoid rocks are nonlinear with temperature. In Archaean times the thermal gradient in the sialic crust could have been over a range of temperatures, either higher or lower than subsequent anorogenic gradients, which allowed the granitoid crust to act as a single layer (and all other parameters being the same, thermal convection is more likely the thicker the fluid layer). Post-Archaean tectonics may have been different because the granitoid crust may have been effectively divided into different layers by barriers of comparatively abrupt viscosity changes since about 2000 Ma. Such layers could have been too thin to allow thermally induced mechanical instability except in orogenic thermal gradients. The disruption of the generally simple tectonic pattern assumed to have developed in early Archaean times is attributed in the last diagram of the top row on figure 2 to diapirs rising from just such a thin mobile layer beneath a steep viscosity gradient introduced into the crust during its thermal evolution.

Model 1 and its variant are similar in attributing Archaean tectonics to gravitationally driven movements in a crust with much the same thickness as at present and at temperatures well below their melting ranges. Both localize the greenstone belts comparatively late in the development of the distinctive tectonic patterns and can easily accommodate the linear granitoid strips and the more blob like granite gneiss bodies of Rhodesia by invoking movements to achieve gravitational stability in either rectangular or hexagonal cells.

Model 2. (Anhauesser *et al.* 1969)

The starting-points of model 1 and its variant beg the question of how such a mechanically unstable crust developed. Model 2 (illustrated on figure 2), due to Anhaeusser *et al.* (1969), deals with both the localization of the eventual greenstone belts and the arrival of large volumes of volcanic rocks onto a crystalline granitic crust in one move. Low temperatures are involved in this model, not by invoking slow inelastic strains, but by localizing the eventual greenstone belts with the introduction of magmas along fault zones and associated downwarps in a very thin sialic crust. The large strains in the greenstone belts and their granite gneiss basement are relegated to the later addition of granites which would have thickened and distorted the crust from below (see figure 2, middle row of diagrams).

Model 3. *A plate tectonic model for Archaean times*

This model arises from the combination of two basic ideas: (1) that sialic crust has been separating more or less continuously from the mantle (see, for example, Wilson 1949; Hurley *et al.* 1962; Engel 1963; Goodwin 1968*b*; Dickinson & Luth 1971; Ward 1971); and (2) that it has been concentrated behind plate subduction zones since early in Archaean time (see, for example, Dewey & Horsfield 1970; Oxburgh & Turcotte 1970).

The distinctiveness of Archaean tectonics is attributed to those orogenic processes seen in action now which would be relevant to an Earth in which all the concentrations of sialic crust were too small for cratons to survive. In very simple terms, the granitic masses of the Archaean crustal remnants are interpreted as having been independently accreted microcontinents, and sets of greenstone belts are interpreted as vestiges of former oceans.

The formation of sialic crust

It has been estimated that Iceland, which includes one of the most accessible plate accretion zones, consists of about 9 % by volume of acid rocks, and a further 5 % of intermediate rocks, which have differentiated from mantle-derived magmas (Walker 1966). It will be assumed that the separation of primary sial from the mantle along the calc-alkaline trend has been common at many, if not all, suitably hydrous plate accreting zones throughout geological time.

It seems to be commonly accepted that once formed, sialic crust is too light, and melts at temperatures too low, for it ever to return very far back into the mantle for very long. It is not inconceivable that the more refractory components of temporarily subduced sialic crust do not return towards the surface, none the less, it will be assumed here that more sialic crust is formed than is lost. This is not a new view and it is common to interpret the areas of sialic crust yielding different radiogenic ages and ^{87}Sr/^{86}Sr ratios as indicating some form of crustal accretion (Wilson 1949; Hurley *et al.* 1962; Engel 1963; Goodwin 1968*b*). Dickinson & Luth (1971) have gone further and interpreted isotopic evidence as indicating the evolution of the sialic crust and the mesosphere from a formerly considerably thicker rheosphere.

One of the problems common to ideas concerning both Archaean tectonics and crustal accretion is how efficient tectonic reworking might be at disguising the existence of older crust. Because the surviving remnants of Archean crust are of deformed rocks which were obviously more extensive in the past it has been assumed that both the Archaean crust and Archaean tectonic processes were considerably more extensive (Sutton 1967) or even world wide (Dearnley 1966). It will be assumed for this model that there was never very much more Archaean crust than is still obvious. The effects of reworking are not neglected however, because the distinctiveness of Archaean tectonics is attributed to their pervasiveness – not because active orogenic processes were necessarily any more extensive than now, but because the crustal units they affected were so small.

The concentration of sialic crust

If small proportions of the top of oceanic lithospheric plates consist of bodies of primary sial then the sial is likely to be concentrated as igneous and orogenically deformed metamorphic rocks by various separation processes behind or above the sites at which those plates are subduced.

Orogeny will be taken here to be largely a skimming process by which fragments of ocean floor volcanics and the majority of any sediments on the ocean floor (secondary sial) are scraped off a subduced plate onto the leading edge of the subducing plate. These metamorphic rocks are subsequently reinforced by magmas rising from where differential melting has separated any primary and potential sial from the subduced plate (Dietz 1963; Oxburgh & Turcotte 1970). Any old sialic accumulations closely involved with subduction zones are likely to be strained and heated and perhaps even partially melted. Such remobilization is obviously an important aspect of orogeny and would be particularly important in Archaean times if none of the concentrations of sial were large enough for significant portions to escape such reworking whenever they were associated with subduction zones.

Dewey & Horsfield (1970) have divided what will be considered here as the basic process of skimming orogeny into four categories. What are probably the two most important categories they called the island arc type (if the leading edge of the subducing plate was originally oceanic in character) and the Cordilleran type (if a continent exists on the leading edge of the subducing plate). As Dewey & Horsfield pointed out, Cordilleran type orogeny would have been less common in the past if the sialic crust has been increasing in area. Unless the first set of plate boundaries were established on an Earth in which large concentrations of sialic crust already existed, Cordilleran type orogeny must have been non-existent early in Archaean times.

Although skimming orogeny may be a complicated and spasmodic phenomenon on a short-time scale, it is interpreted here as essentially a continuous process on a broad time scale. It will be assumed to have occurred whenever and wherever oceanic plate containing existing or potential sial is subduced. If uninterrupted, and fed a sufficient supply of sialic material, island arc orogens could presumably evolve to Cordilleran orogens by a form of progressive cratonization behind the active site of sialic accretion.

Various interruptions to individual skimming orogens are inevitable because of the migration of plate boundaries (McKenzie & Morgan 1969). If a skimming orogen were ever to subduce a complete oceanic plate and reach parts of the plate-accreting margin to its rear, it would suffer transform faulting (McKenzie & Morgan 1969, fig. 5). Having run the gauntlet of the transform faults, it is possible that the skimmed orogen and any craton behind it may actually subduce the whole plate accreting zone and run the risk of fragmentation and separation. Following the reassertion of the subduced plate accretion zone and any consequent fragmentation, some portions of the skimmed sialic accumulation might be driven back the way they had come, towards a new subduction zone developed in the formerly expanding plate. Other fragments of the sialic accumulation may be incorporated in entirely different plates from those with which they had earlier been associated. For some, and possibly all, such fragments orogeny would cease until they again were involved with subduction zones. If complete oceanic plates are ever subduced then sialic accumulations may be transferred from one plate to another without any spontaneous and unpredicatable wholesale reorganizations of plate boundaries being necessary. This point is considered here to have important implications for the evolution of the Archaean crust (see next section).

One of the most obvious ways in which individual skimming orogeny may be brought to a close would be when a large sialic mass incorporated in the subduced plate gives the subduction zone indigestion. Orogens which end with the closure of an ocean will be referred to here as suturing orogens following Tuzo Wilson's (1966) suggestion that the Appalachians may have sutured together two continents formerly on either side of a proto-Atlantic. Dewey & Horsfield (1970) called one very important class of suturing orogens the Himalayan type. Suturing orogeny is a special case of skimming orogeny (being a comment on how it ends). Himalayan type orogeny is in turn a special case of suturing orogeny in which the sutured sialic accumulations are sufficiently extensive for significant portions to survive as recognizable cratons.

Himalayan type orogeny cannot have occurred in Archaean times as defined here because no Archaean cratons have been recognized (but see Goodwin 1968). Cratons may have existed for long intervals of Archaean time, possibly formed by progressive cratonization as early island arc type orogens evolved to Cordilleran type, but if any did develop they cannot have escaped subsequent suturing orogenies on a large scale until the end of the Archaean.

As a more or less continuous process, skimming orogeny presumably results in broadly conformable lateral accretions of sialic crust. The various interruptions to skimming orogeny, and suturing orogeny in particular, might be represented in the geological record as marked disconformities and unconformities in the tectonic grain of laterally accreted crust. It is these disconformities and unconformities, which imply periods of independent mobility and development following fragmentation of old sialic accretions, which were missing from the classical picture of continents symmetrically accreted around old nuclei (Dewey & Horsfield 1970; but see also Hurley & Rand 1969).

Almost imperceptibly, stratigraphy, one of the oldest branches of geology, has been changed by the findings of the last decade. Vertical superposition of sediments is now matched by lateral accretions of igneous simatic crust, and if the ideas expressed here are anywhere near correct, then the majority of the crystalline sialic crust must also accumulate with a crude lateral stratigraphy. Just as lateral unconformities in simatic crustal stratigraphy imply development associated with different spreading poles, so unconformities in the lateral stratigraphy of crystalline sialic masses indicate intervals during which individual sialic concentrations may have developed oceans apart. A complete description of the stratigraphic relationships of any rock unit must now include not only its time and environment of formation, but also its position in space relative to the spin-poles of the Earth and to the geography of the sialic crustal accumulations of the time.

Archaean tectonics

Figure 3 is an attempt to illustrate how Archaean tectonics could be so distinctive despite the tectonic processes having been similar to those still in action. The effects of transform faults and other complications implied by the dynamics of plate junctions (McKenzie & Morgan 1969; Uyeda 1971) have been ignored in the construction of figure 3 for the sake of simplicity.

It is necessary for large sialic concentrations to exist on subduced plates for skimming orogenies to end in suturing orogeny. Unless, therefore, the first set of plates and their boundaries were established on a static planet which already had surface concentrations of sialic crust (a possibility for which the existence of a sialic crust on the Moon would be very relevant), no suturing orogeny would have occurred and no ocean floor would have been entrapped as a future greenstone belt, until at least two complete oceanic plates had been entirely subduced.

Figure 3 shows the first concentrations of sialic crust as island arc type skimming orogens. The first primary sialic bodies differentiated at plate accreting margins may have been small enough to have been carried quite far into the mantle, before they rose to intrude the overlying calc-alkaline volcanics to form the precursors of the Archaean granitoid strips. The first island arc type-skimming orogens cannot have been diluted by many sediments for few of the early sialic concentrations could have had sufficient mass to rise isostatically above the wave base. While the sialic crust was so restricted, the oceans would have been larger and, if the rates of the early plate motions were anything like those of the present, and if the plates were much the same size as now, the life-cycle of the various facies of an ocean (i.e. the geosynclines) may have been far longer than in more recent times. Such Archaean sediments as there were might therefore have remained undeformed for very long intervals of time.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Figure 3. If the volume of sialic crust has increased with time the six possible stages in early Earth history shown here are suggested by extrapolating plate tectonics back to Archaean times.

Sialic crust already at the surface is joined by small acid or intermediate bodies differentiated at the plate accreting zones. These bodies are eventually skimmed onto the leading edges of expanding plates (which have arrows on them) to form concentrations of orogenic sial. This continuous process would be interrupted at any one plate margin if it is driven over a plate accreting zone onto a shrinking plate (top left of diagrams 1 and 2). Suturing and reorganization of the simatic subducing and sialic skimming plate margins may follow (diagram 4). Fragmentation may occur as the larger sialic accumulations are driven over plate accreting zones (diagram 4). The end of Archaean times is marked by the survival of undeformed cratons involved in the first suturing orogeny of Himalayan type.

The first suturing orogeny became inevitable after the first skimmed orogens were transferred to plates in the process of being subduced (see diagram 3 on figure 3). Because the first suturing orogens involved such small sialic concentrations they may have been very different from those involving larger concentrations. They may not, for instance, involve noticeable unconformities in the tectonic trends on either side of the entrapped ocean floor if the early sialic concentrations were transferred from plate to plate without fragmentation. If the subduction of such small sialic concentrations were to occur down Benioff shear zones at a shallow angle they may have been taken far behind the even smaller island arc type orogens to which they were being sutured before they rose as buoyant plastic diapirs through the oceanic plate behind. Such a process could obviously account for the lack of conglomerates at the base of most greenstone belts. The suturing of small slabs of sialic crust might therefore generate the gravitationally unstable sections invoked in model 1 of this work – at least locally. The incorporation of model 1 into model 3 might account for how the symmetry planes of the structures in so many greenstone belts are vertical despite their formation being associated in model 3 with asymmetric subduction zones. Other greenstone belts may have formed as island arc calc-alkaline volcanics or as fragments of ocean floor scraped from the subduced plate during more general skimming orogeny. Yet others might be the volcanic rocks recording the transit of early sialic concentrations over plate accreting zones with or without any fragmentation and separation (see figure 3).

The high proportion of basic volcanic rocks in the Archaean crustal remnants is therefore interpreted in model 3 as reflecting both the small size of the early sialic concentrations and the large number of suturing orogenies which occurred before the concentrations became extensive enough for cratons to survive.

The lateral unconformities in the type of tectonics and their trends around many of the remnants of Archaean crust are interpreted here as implying that Archaean times ended with the first suturing orogeny of the Himalayan type. Large traces of almost undisturbed shelf type sediments between 2300 and at least 1200 Ma are known and probably rest on the first extensive cratons. Examples of these are:

In southern Africa: Transvaal sequence < 1950 to > 2300 Ma (Button 1971); Umkondo sequence < 1785 to > 2050 Ma (Vail & Dodson 1969).

In South America: Roraima sequence *ca.* 1700 Ma (McConnel & Williams 1970).

In Canada: Helikean strata < 1800 to ≫ 1200 Ma (Fraser *et al.* 1970).

There are problems associated with the plate tectonic model suggested here to account for Archaean tectonics. Not the least of these is that it must be adaptable enough to account for the relationships emerging from Archaean terrains characterized by anorthosites and pyroxene granulite metamorphism. Metamorphism in the blueschist facies appears to have been associated with Phanerozoic subduction zones and it is not obvious why this type of metamorphism should apparently be missing from Archaean rocks even though the sialic concentrations were so small and the effects of reworking so general.

Possible tests of models of Archaean tectonics

The most distinctive differences between any model invoking a form of plate tectonics and the alternatives described earlier is the continual geographic mobility of every element and the amount of horizontal shortening of (mainly simatic) crustal segments implied in the plate tectonic model. If the Archaean granitoid strips formed as simple remobilized gneiss domes, convection cells, or as fault blocks, then no large horizontal changes were necessarily involved in the development of the Archaean tectonic patterns. The plate tectonic model suggested here raises the spectre of the Archaean granitoid strips having been skimmed off vast areas of different lithospheric plates before eventually being sutured together by the loss of very extensive areas of igneous ocean floor.

The problem of orogenic shortening has been debated using the geometry of strain structures characteristic of the central parts of so many orogens – similar folds. Their presence is often assumed to prove large shortening strains between opposing cratons, but Carey (1962) demonstrated their geometric similarity to folds in flowing fluids due, not to lateral shortening, but merely to slight differences in rates of flow over large distances. The geometry of similar folds is ambiguous to discussions of shortening of the crust because there is as yet no simple way of measuring any degree of shortening involved in their genesis. A glance at the top row of diagrams in figure 2 suggests that the geometry of similar folds is not only ambiguous, but that any shortening they might record is irrelevant to discussions of shortening of the complete crust if model 1 has any credibility at all. This is because rock layers originally at any one level of the crust must be shortened in some places but extended in others during movements to restore gravitational stability – but there is no necessary implication that the crust as a whole has changed in length. The greenstone belts in model 1 of figure 2 are only likely to be preserved where they have been severely shortened, any intervening areas of extension might have been represented by gaps in formerly continuous greenstone sequences even before any erosion took place.

The answer to the problem of whether shortening occurred across the greenstone belts lies not in the belts themselves – but in tracing the paths of the intervening granitic strips in space and time. Some sort of palaeogeographical markers are necessary. Palaeoclimatology might eventually serve as a useful check to any answer but is unlikely to be sufficiently accurate or definitive to be of much use alone (but see Meyerhoff & Harding 1971).

Palaeomagnetism is the obvious tool to try. It is already being applied to older and older orogenic belts (see, for example, Briden 1970; Hamilton 1970; Kropotkin 1971) and if these are found to have involved large lateral motions they can be used as circumstantial evidence for earlier and earlier lateral mobility in the crust.

The movement of cratons relative to each other and to the magnetic poles is represented in apparent polar movement paths for each craton by relative convergences, divergences and shared paths. Most Earth scientists are familiar with the converging paths of the apparent magnetic poles recorded as the present continents separated during and since the Mesozoic – but then every palaeomagnetic pole position ever determined in unstrained or untilted rocks are relevant to this separation. As the possibility of older lateral motions comes to be tested the source of the data must be restricted to the relevant cratons only, and for each successively older tectonic pattern the surviving cratons or palaeomagnetic blocks will be smaller and smaller and less likely to have survived the vicissitudes of a mobile crust. Instead of the spot checks at present being carried out across the obvious Himalayan type suturing orogens it is likely that apparent polar movement paths will have to be carefully constructed for each craton if the possible activities of former plate tectonics are to be disentangled.

Because of the definition of the Archaean chosen for this work, no extensive cratons can have survived from Archaean times. The recognition of units in which the palaeomagnetic latitude records have not been reset by close association with plate subduction zones, might be very difficult in Archaean rocks therefore.

If the Archaean tonalitic migmatic and gneissose masses have always formed a more or less continuous sialic crust, without large changes in the distance between each body having occurred, then the cumulative, structural, and metamorphic histories might be broadly similar, or at least continuous, from one to another. Such similarities should be comparatively obvious if the oldest granitoid masses are simple fault blocks remobilized and strained only by the intrusions of magma from below. Such similarities would be less obvious if the same masses had developed as mantled gneiss domes. None the less, the structures and lithological banding of the oldest granitoid rocks might be expected to be still visible, possible with some radial or concentric components in such a case. The continual circulation in the oldest granitoid layer implied by the thermal convective variant of model 1 would presumably result in comparative homogeneity of each mass. Classical geological studies might also allow views on whether the roots of the greenstone belts are associated with fault zones – or with either closed oceans or parts of the ocean floor perched on top of temporarily subducted sialic slabs.

In any study designed to decide the relative usefulness of the multiple working hypotheses described here, the most critical areas are surely the junctions between the oldest granitoid masses, where they are unobscured by any rocks of a greenstone belt. For the time being, a geologist standing on such a junction has the choice of interpreting it as the welded or transcurrent junction between two plasticized microcontinents, a simple dyke or fault zone, or the junction between two frozen convection cells down which cooler, denser rocks may have sunk, perhaps even the site down which a greenstone belt has fallen.

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Discussion

Dr B. J. Walton (*Department of Chemistry and Geology, Portsmouth Polytechnic*) suggested that some of the amphibolite-agmatite gneisses characteristic of the Archaean might represent metamorphosed and migmatized equivalents of Phanerozoic orogenic mélanges. If it is true that sediments were less extensive in the Archaean, mélanges of this age should consist mainly of oceanic basalts subsequently converted to amphibolites.