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Accretion of continental crust: thermal and geochemical consequences

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The irreversible chemical differentiation of the Earth's mantle to produce sialic crust over the past 3900 Ma has most probably occurred during widely separated, but short-lived, accretion episodes. These episodes involved the massive addition of juvenile sialic magma to the Earth's surface, thickening pre-existing crust. Simple numerical simulations, based on tectonic, petrological and geochemical observations on Archaean high-grade orthogneiss terranes, have been used to explore the metamorphic and geochemical consequences of massive thickening of sialic crust during short-lived accretion episodes. The location of the main sites of magmatic addition within the crust exert a profound influence on the thermal régimes. Geochemical differentiation of the continental crust by partial-melt and vapour-phase-controlled processes, and the development of granulite facies mineral assemblages can be integrated with the simple numerical models. Finally, the survival of thick Archaean continental crust imples the contemporaneous stabilization of thick lithospheric substructures to the newly formed continental masses.

INTRODUCTION

Much evidence has been presented in recent years to support the thesis that the irreversible chemical differentiation of the Earth's mantle, to produce new continental crust, has occurred in several short, 100–200 Ma, episodes, widely separated in time throughout the past 3900 Ma (Moorbath 1978; Jakeš 1973). Archaean cratons must have been at least as thick (30–40 km) in the Archaean as at the present time, since mineral assemblages at the surface record Archaean metamorphic pressures of 10–15 kbar[‡] (Wells 1976, 1979; Wood 1975; Manna & Sen 1974; Windley 1977; Dickenson & Watson 1976). In addition these Archaean continental masses are strongly geochemically differentiated, the lower crust being depleted in H_2O, heat-producing elements and other large-ion lithophile (l.i.l.) elements (Moorbath 1978; Wells 1979; Heier 1973; Sheraton *et al.* 1973; Jakeš 1973; Lambert & Heier 1967, 1968; Collerson & Fryer 1978; Drury 1973). I present here a synthesis of the thermal and chemical processes associated with episodes of generation of stable differentiated sialic crust in the late Archaean, 2900–2600 Ma B.P., when the generation of juvenile sial appears to have been particularly vigorous (Moorbath 1978; Armstrong, this symposium).

The higher internal heat production of the Archaean Earth may have been partly dissipated by more vigorous surface tectonic processes, such as faster and more extensive ocean crust generation. However, these have physical limitations (Bickle 1978; Davies 1979; Oxburgh & Parmentier 1977), and it is unlikely that surface activity alone would have been completely effective in buffering the Earth's internal temperature fields to levels sufficiently low to prevent wholesale melting of sialic materials, and permit the preservation of any thick, fusible sialic

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[‡] 1 kbar = 10^3 bar = 10^8 Pa.

crust. There is therefore an apparent contradiction in the survival of thick Archaean continental crust and the prohibitively high conductive heat flow required by the higher internal heat production (Davies 1979). A resolution of this contradiction may be achieved by a coupling between sialic crust formation and the growth and stabilization of a thick subcontinental lithosphere, thus isolating the fusible sialic crust from the high mantle temperatures (Jordan 1978; Davies 1979). I have attempted to integrate thermal models for the accretion of sialic crust with plausible thermal and chemical processes in the underlying mantle.

Crustal thickening

Evidence review

The detailed study of Archaean calc-alkali orthogneisses, presently exposed worldwide, has considerably increased our knowledge of the petrogenesis and evolution of continental crust (Drury 1973; Sheraton *et al.* 1973; Wells 1979, 1980*a*; Heier 1973; Lambert & Heier 1967, 1968; Jakeš 1973; Arth & Hanson 1972, 1975; Arth & Barker 1976; Barker & Arth 1976; Collerson & Fryer 1978; Burke *et al.* 1976; Burke & Kidd 1978). Many geochemical studies of the dominant tonalite–granodiorite–trondjhemite lithologies have shown that much of the Archaean continental crust was derived by short-lived partial-melting episodes (maximum 100–200 Ma) acting either directly on fertile upper mantle ultramafic rocks, or on short-lived metabasic rocks (Moorbath 1978; Arth & Hanson 1975; Arth & Barker 1976; Barker & Arth 1976; Compton 1978; Moorbath 1978). It is fair to point out contrary interpretations by Collerson & Fryer (1978).

Analysis of metamorphic mineral assemblages in these Archaean terranes suggests a minimum Archaean crust thickness of 30–40 km 2800 Ma ago, comparable to that of the present day, (Wells 1976, 1979; Wood 1975; Manna & Sen 1974; Windley 1977; Dickenson & Watson 1976). Since these high-pressure mineral assemblages are at the present surface of continental crust of normal thickness, parts of the Archaean sialic crust, 2800 Ma ago, must have been at least 60–80 km thick. Pressure–temperature (P–T) estimates indicate modest thermal gradients of 20–40 °C/km in parts of the continental crust (Wells 1979; Wood 1975; Windley 1977).

A number of geochemical and tectonic models have been proposed for the generation and evolution of Archaean sialic crust. On the basis of studies of rare earth elements, Hanson & Goldich (1972) and Arth & Hanson (1972) suggested that the precursor liquids to the tonalitic orthogneisses were produced within the mantle by partial melting of quartz–eclogite, generated by subduction in a plate tectonic regime. Arth & Barker (1976) and Barker & Arth (1976) have subsequently revised this interpretation and they now favour a two-stage magmatic process acting on tectonically thickened, metamorphosed basic crust, not necessarily within a plate tectonic setting. Anhaeusser (1973) and Windley & Smith (1976) have suggested broadly similar models based on island-arc and Pacific-type continental margins. Windley & Smith (1976) present persuasive evidence for Archaean calc-alkali orthogneisses representing the more severely metamorphosed and deformed equivalents of the Mesozoic calc-alkali batholiths of the western Cordilleras of North and South America.

If the behaviour of the Archaean lithosphere was influenced by processes of the plate tectonic type, it is probable that zones of accretion of continental crust in the Archaean would resemble island arcs of Pacific continental margins (Wells 1980*a*; Bickle 1978; Davies 1979; Burke *et al.* 1976). Such an interpretation is in line with the uniformitarian application of contemporary plate tectonics to Archaean geology, which is receiving growing support (Moorbath 1978; Davies 1979; Bickle 1978). Certainly, plate tectonic processes are the most efficient means of converting, by partial-melting episodes, fertile ultramafic mantle into sialic magma and continental crust. I present models for the accretion and differentiation of sialic crust that, while being compatible with, are not restricted to, plate tectonic régimes.

Geochemical investigations have shown that Precambrian shields are increasingly depleted in heat-producing and other l.i.l. elements with increasing metamorphic grade. This evidence demonstrates that the continental crust has a well developed geochemical layering, the lower crust commonly developing granulite facies mineralogy (Wells 1976, 1979; Drury 1973; Sheraton *et al.* 1973; Heier 1973; Lambert & Heier 1967, 1968; Collerson & Fryer 1978; Fyfe 1973; Windley 1977). Moorbath (1978), Taylor (1967), Jakeš (1973), Jakeš & White (1971) and Wells (1979, 1980*a*) have suggested that the generation, accretion and differentiation, or ‘ripening’ of continental crust must have followed each other very closely in time. Much of the isotope and geochronological data, reviewed by Moorbath (1978), are consistent with this concept of a rapid production of juvenile sial, followed by its geochemical differentiation and metamorphism.

Thermal models

Thickening of continental crust in Phanerozoic, Mesozoic and Cainozoic times has occurred at convergent plate boundaries by tectonic and/or magmatic thickening. Tectonic thickening, exemplified by the Western Alpine zone, occurs where thrust sheets, nappes and slices of obducted continental crust become piled up along a collision zone (Bickle *et al.* 1975; Oxburgh & Turcotte 1974; England & Richardson 1977). Magmatic thickening, by the accretion of juvenile sialic magma into new continental crust, has been identified with thermally active island arcs and some Pacific-type continental margins, e.g. the Andean zone (Oxburgh & Turcotte 1970, 1971; England & Richardson 1977). The new continental crust stems from the differentiation of upper mantle, and little or no recycling of older continental material need occur.

I have presented simple models for the massive magmatic thickening of continental crust, in particular for the episode occurring 2900–2600 Ma ago (Wells 1980*a*). Wells (1980*a*) performed numerical simulations of the accretion and thickening of the crust by the pulsed addition of recumbent sialic magma bodies. This model is supported by structural and isotopic investigations of the Archaean of west Greenland (Bridgwater *et al.* 1974, 1976; Chadwick *et al.* 1973; Chadwick & Nutman 1979; Coe *et al.* 1976; Moorbath 1978; Moorbath & Pankhurst 1976; Wells 1979). Apart from the amount and duration of accretion, the intrusive pattern of the sialic magma bodies was shown to influence the modelled thermal evolution of the thickening crust. Two main possibilities were identified:

(1) overaccretion; each new magma body was added at the same depth in the crust so that it displaced previously accreted bodies to lower levels; and

(2) underaccretion; new magma pulses were added beneath the earlier bodies, and the accretion zone descended in depth as accretion proceeded.

Wells (1980*a*) examined and compared simulated thermal histories of continental crust accreted by these models. Underaccretion, involving the addition of magma at the base of the crust, does not greatly affect the overall thermal evolution of previously added material, since this becomes progressively further removed from the magmatic heat source as the crust thickens. The layers of new sialic crust cool nearly isobarically from their magmatic intrusion temperatures. The overall slow cooling régime of continental crust generated in this way is not influenced by accretion rates, intrusion temperatures or variations in modelled thermal properties, although the cooling rate is affected.

Models of crustal thickening by predominantly overaccretion are more influenced by the model parameters. The thermal history of the thickened crust is controlled by the location of the transient magmatic heat sources close to the surface, and previously added layers descend from the accretion zone, becoming buried by the subsequent accumulations. Each newly accreted layer cools immediately after its emplacement and initially during burial, but two effects lead to an increase in temperature of the buried layer: first, the transient heat associated with the pulsed addition of magma; secondly, the long-term warming resulting from the burial of the layer in the accreting crust. These long-term effects are the same as the thermal processes controlling metamorphism of buried cold rocks in sedimentary basins and tectonic nappe and thrust sheet complexes (England & Richardson 1977). The relative importance of these effects on the simulations depends on the rate of accretion.

The pulsed addition of magma causes oscillations in the temperature of the layers of crust being buried beneath the accretion zone. These oscillations become damped as the layer is removed from the accretion zone, and the damping is accompanied by a progressive increase in time between emplacement of magma and the associated thermal effect induced in the buried layer. The amount of time depends on the thickness and diffusivities of the intervening rocks. For the faster accretion models, lasting less than 35–50 Ma, the effects of the individual transient heat pulses become indistinguishable and cumulative once *ca.* 20 km of crust separates the buried layer from the accretion zone. An important consequence of this increased delay time between heat input and temperature response of the buried layer is that the cumulative temperature maxima in the deeply buried crust occur some time (2–10 Ma) after accretion has ended. These temperature maxima are reached at later times with increasing depth, so that the metamorphic mineral assemblages exposed by differential erosion would be polychronic. Simple isochronic interpretations of isograds and P–T data are impossible.

If accretion lasts longer than 35–50 Ma, the rate of accretion is slower than the rate of conductive transfer of the magmatic heat, and this heat is almost completely conductively dissipated during accretion. The buried crust below 25 km progressively warms over a period of 40–100 Ma, extending from the end of accretion, in response to equilibration of temperature fields with the heat supplied to the base of the crust. These long-term effects take substantially longer to cause temperatures to rise in the middle–lower crust than the more rapidly developed cumulative temperature maxima generated by faster magmatic accretion.

Numerical simulations (Wells 1980*a*) have shown that non-ordered emplacement patterns for the accreting magma bodies generate thermal regimes broadly similar to the overaccretion models. The overaccretion simulations seem the most plausible on relative density considerations, and they are more efficient in generating P–T régimes suitable for crustal differentiation (see later). However, underaccretion may be favoured by magmatic accumulation along a plane separating crustal materials with markedly different rheological properties (Stainforth 1977).

Discussion

Simulated thermal profiles in the models of crustal accretion by magmatic thickening are markedly convex towards the temperature axis, being thus characteristic of profiles for crust thickened in this manner, and quite different to the concave thermal profiles produced during the erosion-dominated metamorphism of tectonically thickened crust (England & Richardson

1977; Wells 1980*a*, *b*). In the numerical simulations performed by Wells (1980*a*) parts of the thermal profiles became inverted during accretion, this effect being particularly well developed in the more rapid overaccretion models.

The influence of syn-metamorphic erosion, so important in the metamorphic evolution of tectonically thickened crust, will not be so significant in the magmatic thickening models unless erosion is very rapid. Rapid erosion in the latter stages of, and after, accretion causes the lower crust to decompress along near-isothermal *P–T* paths, which may lead to the development of prograde dehydration reactions, decompression melting, and some polymorphic transitions. However, with modest erosion rates, post-accretion metamorphism will be dominated by conductive relaxation and mineral reactions would correspond to slow near-isobaric cooling, as described in granulite facies rocks by Manna & Sen (1974), Wells (1979) and Morse & Talley (1971).

Intracrustal Rayleigh–Benard type convective instabilities may be important in the lower–middle crust near the end of, and immediately after, accretion (Stainforth 1977; Wells 1980*a*; Chadwick & Nutman 1979; Talbot 1968). The relaxation of the unstable thermal profiles towards thermal equilibrium may have been accompanied by gravitational instabilities generated by hot, light, partially crystalline material underlying denser, cooler assemblages. The diapiric ascent of the still warm partially molten sialic material, and the associated descent of cooler dense crystalline rocks would have led to considerable local modification of regional metamorphic *P–T* regimes generated by the thermal relaxation following the massive convective addition of heat during the accretion. In particular, mineral assemblages from antiformal zones may preserve evidence for higher metamorphic temperatures than do adjacent cooler synformal areas. Relic mineral assemblages may indicate local retrogression from high *P–T* conditions in antiformal areas, although some prograde dehydration reactions and even melting may have occurred. Conversely in synformal areas relic mineral assemblages may indicate prograde *P–T* conditions, but hydration reactions may have occurred. Percival (1979) has described *P–T* regimes from Archaean gneisses in Canada that may be the products of deep crustal convective processes. The tectonic manifestations have been described by Stainforth (1977) and Chadwick & Nutman (1979) for west Greenland Archaean terranes and have been generally discussed by Talbot (1968).

Geochemical fractionation of the continental crust during and immediately after accretion would be facilitated by the progressive addition of magma pulses. The pulsating temperature fields sustained by the older, deeper crust would tend to initiate melting of the affected layers. The removal of these successively generated liquid fractions would deplete the lower crust in l.i.l. heat-producing elements and H_2O. These relatively volatile elements would ascend to the upper crust in the rising secondarily generated magmas. Residual vapour phases in the lower crust would be enriched in CO_2 relative to H_2O. Successive melting episodes during accretion would be extremely efficient in differentiating upper and lower crust in the latter stages of continent generation. The refractory rocks, depleted in l.i.l. elements left at the base of the crust would be thermally inert, magmatically infertile and suitable for the generation of granulite facies mineral assemblages under the appropriate metamorphic conditions.

The complexity and diversity of chemical trends and calc-alkali affinities in orthogneiss complexes may have been caused by the recycling of the crystalline products in an 'accretion–differentiation engine'. The continental crust generated in the accretion phase would comprise rocks derived by partial fusion of a number of distinct geochemical sources: primary, associated with upper mantle or short-lived intermediatory upper-mantle products; pre-existing local lithologies at the site of accretion; and calc-alkali orthogneisses crystallized from melt products of the former sources.

Apart from this differentiation and ripening of the juvenile sial by multistage melting within the accretion zone, further post-accretion geochemical fractionation of the crust may have occurred by dehydration and fluid migration from deep-seated high-grade granulite facies complexes. Compelling evidence for such metasomatic processes are presented by Wells (1979), Drury (1973), Sheraton *et al.* (1973) for Archaean granulite facies terranes in west Greenland and northwest Scotland. I shall return to this topic and the formation and role of granulite facies rocks later in this paper.

The rapid addition of thermal energy by convective transfer during accretion in ascending and crystallizing magmas from the source region(s) generates strongly perturbed thermal profiles in the thickening crust. The geochemical differentiation and 'ripening' of the sial would occur during accretion and during the thermal relaxation of the perturbed thermal conditions. If the buoyant thickened crust was eroded, or heat flows from the upper mantle fell after the accretion phase, the duration of the ripening process would probably have been limited to a few tens of millions of years, because temperatures would have been falling. If erosion was inhibited *and* heat supplies from the mantle were maintained, then high temperatures would have been sustained in the lower crust and the ripening process may have extended for 50–100 Ma after the end of accretion. Under these conditions considerable blurring of the isotope systematics would seem likely (Wells 1980*a*). The highly consistent isotopic data and well constrained isochrons of many Archaean orthogneiss terranes testify to the short duration of the ripening phase (Moorbath 1978). In addition to this evidence a reduction in the thermal energy of the crustal system might be expected for a number of reasons, as, for example, the cessation of supply of convective heat transferred in the ascending magmas from the source region(s), and the growth of a stable thermally inactive and insulating lithospheric 'root' to the new continental crust (Davies 1979; Jordan 1978).

The granulite facies

The development of granulite facies minerals in the deep crust has been closely linked with the differentiation and geochemical 'ripening' of Archaean sialic crust (Tarney 1976; Wells 1979; Heier 1973; Drury 1973; Sheraton *et al.* 1973; Jakeš 1973; Lambert & Heier 1967, 1968; Moorbath 1978; Fyfe 1973). Based on the magmatic crustal accretion models for Archaean sialic crust formation and growth presented here I identify two main locations where granulite facies may develop. Apart from local preservation of granulite mineralogies generated by direct magmatic crystallization and not attributable to subsequent metamorphism, these are as follows. First, the simulations of rapid magmatic growth and thickening, with accretion lasting less than 35–50 Ma, generate sustained high temperatures (700–900 °C) in the upper crust, where thermal gradients are steep, *ca.* 10 °C/km (Wells 1980*a*). Low-pressure granulite facies minerals may grow in this upper crustal régime and be exposed by subsequent erosion (see Lambert & Heier 1968). Secondly, and of greater importance in the geochemical differentiation of the sialic crust, medium–high pressure granulite facies minerals may develop in the lower crust under moderate thermal gradients (20–40 °C/km) (Wells 1979, 1980*a*; Wood 1975; Windley 1977), provided that temperatures are sufficiently high and water activities sufficiently low (see Wells 1979). These Archaean medium–high pressure granulites have a worldwide distribution and have an important role in the maturation and stabilization of Archaean continental crust. These two potential granulite zones sandwich a middle crust, where the balance between temperature and water activity conditions is not conducive to the extensive development of granulite facies, and predominantly amphibolite facies minerals are stabilized.

From a tectonothermal viewpoint two types of régime suitable for lower crustal granulite facies may be distinguished, namely decreasing pressure and constant, or increasing, pressure. First, decreasing pressure, near-isothermal regimes may be identified with the erosion-controlled metamorphic models presented by England & Richardson (1977) and Wells (1980*b*). Intra-crustal tectonic movements, possibly associated with convective instabilities in the hot plastic crust, may also produce isothermal, falling-pressure conditions similar to those of the erosion-controlled models (Wells 1980*a*; Stainforth 1977). Solid–solid dehydration reactions with positive $\mathrm{d}P/\mathrm{d}T$, producing pyroxenes from hydrous minerals, would be penetrated during decompression (Wells 1979). Water-undersaturated partial melting, also through positive $\mathrm{d}P/\mathrm{d}T$ reaction curves, may also occur during decompression.

Secondly, isobaric or prograde pressure together with prograde temperature regimes may be associated with the sort of magmatic crustal accretion and thickening mechanisms, namely overaccretion, described in this paper and elsewhere (Wells 1979, 1980*a*). Tectonic thickening, acting alone, or in concert with magmatic thickening, may lead to broadly similar prograde P–T mineral reactions and assemblages (England & Richardson 1977) provided that erosion is inhibited.

I consider that granulite mineral assemblages are the natural culmination of high P–T, low P_{H_2O}, prograde crustal metamorphism. Considerable petrological evidence lends credence to this view (Wells 1976, 1979; Manna & Sen 1974; Wood 1975; Morse & Talley 1971). The geochemical changes that may accompany the mineralogical transformations result from the removal of l.i.l. elements and H_2O, either in locally generated mobile partial melts, perhaps stimulated by the H_2O released by dehydration reactions, or dissolved in mobile vapour phases (Wells 1979; Drury 1973; Heier 1973; Sheraton *et al.* 1973; Collerson & Fryer 1978). I associate Archaean granulite facies metamorphism and the culmination in P–T conditions in the deep crust with the period immediately succeeding, perhaps within 10–20 Ma, of the massive magmatic thickening and accretion of that part of the Archaean sialic crust itself (Moorbath 1978; Wells 1979, 1980*a*).

These views are in contrast to the interpretation that anhydrous granulite facies mineral assemblages were caused by the slow geochemical changes that dehydrated the lower crust and depleted it in l.i.l. elements, namely the removal of partial melts and the movement of vapour phases. Sheraton *et al.* (1973), Drury (1973) and Tarney (1976) associate the geochemical transformations in the lower crust, leading to granulite facies rocks, with similar changes in the underlying mantle. They envisage the chemical changes in these zones to result from the upward migration of vapour phases rich in CO_2 and selectively dissolved species, which become stabilized in appropriate mineral facies régimes throughout the continental crust. Granulite facies minerals are stabilized by the reduction in H_2O activity brought about by the invasion of CO_2-rich vapour from the upper mantle into the lower crust. Wells (1979) has placed a different interpretation on the evidence cited for these large-scale vapour migration systems, principally, CO_2-rich fluid inclusions with carbon isotopes indicating upper-mantle sources (Touret 1977; Hoefs & Touret 1975; Collerson & Fryer 1978), and selective element enrichment and depletion patterns in granulite facies minerals and rocks (Sheraton *et al.* 1973; Drury 1973; Collerson &

Fryer 1978; Tarney 1976). In the context of the accretion–differentiation process, supported by Moorbath (1978), Jakeš (1973) and myself (Wells 1978, 1980*a*), the juvenile sialic magmas would carry with them free, evolved and dissolved CO_2–H_2O vapour phases, which would be derived within a few tens of millions of years during partial melting of upper-mantle sources or short-lived upper-mantle products (Moorbath 1978; Moorbath & Pankhurst 1976). The isotopic character of samples of these fluids, sealed in fluid inclusions, would correspond to that of upper-mantle fluids at the time of crystallization (Wells 1979). The selective geochemical differentiation of lower crustal rocks may occur by removal of secondarily generated partial melts, the squeezing out of late-stage l.i.l. and volatile-rich liquid residues from the crystallization of the lower crust, and the local migration of vapour phases (Wells 1979). Wells (1979) suggested that the geochemistry of high-grade orthogneisses from the Archaean (2900–2700 Ma) of west Greenland indicated two-stage chemical fractionation of lower crustal rocks. A later vapour-phase-controlled chemical fractionation, associated with granulite facies metamorphism, was superimposed on earlier melt-dominated element fractionation patterns. In terms of the numerical simulations of accretion of sialic crust presented here and by Wells (1980*a*), I associate partial melt-dominated crustal differentiation with an early hot juvenile period during the crustal ripening, extending throughout the thermally energetic accretion phase. Vapour-dominated crustal differentiation would occur in association with post-accretion metamorphism of the lower crust, during predominantly conductive thermal relaxation and in a more mature phase of the evolution of the continental crust.

Development of Archaean continental lithosphere

The paradox presented by the survival of thick, 20–40 km, Archaean continental crust, with modest palaeothermal gradients, 20–40 °C/km (Wells 1979; Wood 1975; Windley 1977), and the much higher internal heat production, two to three times that at present, of the Archaean Earth may be resolved by associating the generation and stabilization of Archaean sialic crust with the formation and stabilization of a stable lithospheric substructure to the continents.

The thermal arguments for this concept have been presented by Sclater & Francheteau (1970), Jordan (1978) and Davies (1979). Briefly, since the rheology of mantle materials is strongly temperature-dependent (Stocker & Ashby 1973; McKenzie 1967; McKenzie & Weiss 1975), the higher internal heat production within the Archaean Earth and the associated greater heat flux through its surface layers may be accommodated by only a small increase in the mantle temperature. Davies (1979) has estimated a 10–20 °C rise in mantle temperature to be sufficient to compensate for an increase in internal heat production to three times that at present. The slightly increased mantle temperatures cause a large decrease in mantle viscosity, thereby encouraging more vigorous mantle convection, and some of the excess heat is mechanically dissipated. Additional substantial losses of the extra heat occur through increased tectonic and magmatic activity in the oceanic lithosphere, through which most of the excess heat is transferred. The thermal boundary defining the base of the oceanic lithosphere would have been at lesser depths than at present; i.e. the Archaean oceanic lithosphere would have been hotter, thinner and relatively young compared to the present day (Sclater & Francheteau 1970; Bickle 1978; Oxburgh & Parmentier 1977; Davies 1979; Jordan 1978). In contrast, thermal gradients within a stabilized relatively immobile subcontinental lithosphere would have been only slightly higher than present, due to the small rise in temperature of the underlying mobile mantle. This immobile substructure armours and insulates the fusible sialic crust from the hot vigorously convecting mantle. The survival of thick Archaean sial requires a thick stable subcontinental lithospheric 'root' zone to be generated contemporaneously with the formation of the continental crust. Sclater & Francheteau (1970), Jordan (1978) and Davies (1979) estimate 200 km for the thickness of the stable subcontinental lithospheric 'root' zone.

Stable insulating lithospheric substructures beneath the growing Archaean continents may have formed in place, by transformation of fertile mobile upper mantle materials, or have been emplaced ('underplated'?) diapirically on to the base of continental crust by the ascent of buoyant depleted infertile ultramafic bodies carried down into the mantle by subduction (Oxburgh & Parmentier 1977). A simplistic model would associate the generation of the lithosphere with that of the sialic crust. Fertile upper mantle is converted by partial fusion into buoyant sialic liquids, which ascend to the surface, leaving a residual, refractory, upper mantle zone depleted in l.i.l. and heat-producing elements. In the context of contemporary global tectonics this processing is effected in the upper mantle wedge overlying active subduction zones.

CONCLUSIONS

I have presented a simple integrated model for the magmatic growth and thickening of Archaean continental crust, its geochemical differentiation and metamorphism. These processes occur within a maximum time span of 100–200 Ma, and most probably within a few tens of millions of years at any one location of sial formation.

Two main sial accretion mechanisms have been examined based on magmatic accumulation coeval with recumbent tectonic deformation: over- and underaccretion. Both are characterized by the massive addition of juvenile magma and associated heat to the Earth's surface layers. Thermal régimes generated by underaccretion would have been dominated by slow conductive cooling. Those generated by rapid, not exceeding 35–50 Ma, overaccretion would have been more strongly influenced by the combination of the progressive convection of heat, by the rising and consolidating juvenile sialic magma bodies, and the inability of conductive transfer to dissipate this heat during accretion. Successive temperature maxima would have been experienced by the lower crustal rocks, culminating in post-accretion temperature maxima in the deep crust.

The rapid and progressive addition of magma and heat would have caused partial melting of the more 'primary' products emplaced in the earlier stages of accretion. This recycling of sialic material by the upward transfer of buoyant partial-melt fractions presents a potent mechanism for geochemical differentiation of sial within the short-lived accretion–differentiation episode. During accretion crustal differentiation would have proceeded mainly by the ascent of successively generated partial melts from the lower to the upper crust. In the more mature post-accretion phase, during conductive thermal relaxation, the activity of mobile vapour phases with dissolved species would have become more important (Wells 1979).

Within the context of the relatively rapid growth of continental crust the granulite facies would have been confined to two separate régimes: (i) the upper crust, where temperatures and thermal gradients were high; and (ii) the lower crust, where temperature were sufficiently high, water activities were sufficiently low, but thermal gradients were probably quite modest. I view the Archaean medium–high-pressure granulite facies as the natural culmination of crustal metamorphism, resulting from thermal relaxation following the massive magmatic thickening of sialic crust. Careful examination of mineral assemblages in Archaean orthogneiss terranes should determine the relative importance of (i) dehydration reactions and decompression melting in near-isothermal falling-pressure régimes, associated with metamorphism dominated by uplift and erosion, and (ii) prograde dehydration reactions during prograde P–T conditions occurring in the sort of magmatic accretion models described here (Wells 1980*a*).

The survival of thick (not less than 30–40 km) Archaean continental crust implies the formation of a thick (not less than 200 km) stable lithospheric 'root' zone to the continents coeval with their formation and thickening. In a plate tectonic setting the site of growth of this 'root' zone could be identified with the upper mantle wedge overlying an active subduction zone.

The simple model that I have presented for the formation of Archaean sialic crust is consistent with the operation of plate tectonic processes in the Archaean. Specifically, I identify sialic crustal accretion sites with island-arc and Pacific-type continental margins associated with extensive calc-alkali magmatic activity (Moorbath 1978; Burke *et al.* 1976; Burke & Kidd 1978; Windley & Smith 1976). The progressive vertical and lateral accretion of the continental masses in island-arc régimes would have been accompanied by the vertical and lateral growth of the lithosphere beneath the continental crust. Without developing this subject further, I record my awareness that Archaean global tectonics may not have resembled modern plate tectonic régimes, but note that it is difficult to ignore the familiar plate tectonic régimes that are so highly efficient in the magmatic and tectonic processing of Earth materials.

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