Age and Isotope Evidence for the Evolution of Continental Crust [and Discussion]

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Age and isotope evidence for the evolution of continental crust

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Irreversible chemical differentiation of the mantle's essentially infinite reservoir for at least the past 3800 Ma has produced new continental, sialic crust during several relatively short (*ca.* 100–300 Ma) episodes which were widely separated in time and may have been of global extent. During each episode (termed 'accretion–differentiation superevent'), juvenile sial underwent profound igneous, metamorphic and geochemical differentiation, resulting in thick (*ca.* 25–40 km), stable, compositionally gradational, largely indestructible, continental crust exhibiting close grouping of isotopic ages of rock formation, as well as mantle-type initial Sr and Pb isotopic ratios for all major constituents. Isotopic evidence suggests that within most accretion–differentiation superevents – and especially during the earlier ones – continental growth predominated over reworking of older sialic crust.

Reworking of older sialic crust can occur in several types of geological environment and appears to have become more prevalent with the passage of geological time. It is usually clearly distinguishable from continental growth, by application of appropriate age and isotope data.

1. Introduction

The problem of the growth of the continents has divided geologists for many years. Many believe that most, if not all, continental, sialic material was formed early in the history of the Earth by rapid separation of core, mantle and crust, and that the sialic crust has been largely reworked or recycled ever since. Recent proponents of this view include Fyfe (1976), Hargraves (1976), Lowman (1976) and Shaw (1976).

In the influential model of Armstrong (1968), global Sr and Pb isotopic evolution is believed to indicate that crustal material is recycled through the mantle on an immense scale, implying vast scales of isotopic homogenization. In this model, the Earth's crust and upper mantle above about 500 km depth are 'in a steady-state system and the volumes and bulk compositions of ocean, continent and mantle have been nearly constant for at least the last 2500 Ma and probably for most of the Earth's history'. Nothing could be further from the conclusions of Hurley & Rand (1969), based on a consideration of Sr isotope evolution. They state that there was 'an accelerating generation of crustal material amounting to 20 km^2 Ma^{-2}, or about 600 km^3 Ma^{-2}, if it is assumed that the upper and lower crust are complementary parts of the differentiating crustal system' and, further, that 'the process would have started about 3800 Ma ago'.

The viewpoint of Hurley & Rand (1969) is, of course, in more general accord with those who consider that continents have grown throughout geological time as direct or indirect derivatives of the mantle as it undergoes partial melting, differentiation and degassing, possibly as the result of processes akin to modern global (plate) tectonics.

I now wish to review, briefly, some recently published works on the evolution of sialic crust which are essential for an understanding of the interpretation of radiogenic isotope studies which follows thereafter.

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2. Evolution of continental crust

(a) *Production of juvenile sial*

One of the principal consequences of the new global tectonics lay in the realization that generation of new sialic, calc-alkaline material occurs at destructive plate margins above or near Benioff zones by partial melting of subducted oceanic lithosphere and possibly also of the overlying wedge of mantle, followed by development along various fractionation trends (see, for example, Taylor 1967; Jakeš & White 1971; Brown 1973). The details of this complex process were reviewed by Ringwood (1974), who states that 'the residual refractory eclogite and peridotite in the lithosphere plates which sink below about 150 km have become irreversibly differentiated and never again are able to participate in the formation of basaltic magmas at mid-oceanic ridges. The complementary differentiate is, ultimately, the continental crust which grows through time by the accretion of island arcs and by the addition of the andesitic volcanic suite. It has been suggested that about 30–60 % of the volume of the mantle may have passed through this process of irreversible differentiation.'

The petrogenesis of Archaean calc-alkaline orthogneisses has received increasing attention (see, for example, Barker & Peterman 1974). Modern work on the problem of the predominant tonalites and trondhjemites stems from the recognition by Hanson & Goldich (1972) and Arth & Hanson (1972) of the significance of the depletion in heavy rare earth elements (r.e.e.) in 2700 Ma old tonalites from Minnesota. They suggested that these tonalites were generated at mantle depths by partial melting of quartz-eclogite and that garnet in the residuum caused the liquid to be depleted in heavy r.e.e. More recently, Barker & Arth (1976) and Arth & Barker (1976) have revised this view and now postulate that two processes of magma generation involving hornblende – with little or no garnet – produced most of both Precambrian and Phanerozoic continental margin trondhjemites, tonalites and extrusive equivalents. The first process is fractionation of wet basaltic liquid from which hornblende is a major cumulate phase, while the second process consists of partial melting of hydrous metabasalt or amphibolite in the lower crust, as previously suggested for the generation of calc-alkaline liquids by Green & Ringwood (1968). The model proposes (i) mantle upwelling and basic volcanism to form a thick pile (presumably such as a greenstone belt); (ii) metamorphism of the lower parts of this pile to amphibolite; (iii) partial melting of amphibolite to yield trondhjemitic and tonalitic liquids; (iv) ascent and intrusion or extrusion of these liquids into the upper crust before the melting fraction of parental amphibolite exceeds about 40 %; (v) transformation of the residue of partial melting to anhydrous, refractory assemblages; and (vi) continuation of mantle upwelling and basaltic volcanism as trondhjemitic–tonalitic liquids are being extruded.

A model for the evolution of the Precambrian crust of southern Africa, involving continental evolution through progressive transformation of mantle and mantle-derived rocks into calc-alkaline and granitic rocks via some early analogue of island-arc development was suggested by Anhaeusser (1973). It is broadly similar to an earlier model of Glikson (1971) which, however, did not involve island arcs or subduction. Both authors regarded the base of greenstone belts as 'primordial' oceanic type crust and did not accept the now indisputable fact that greenstone belts sometimes lie unconformably on older, sialic crust. However, this point matters little since most workers accept that basic rocks of the mantle and/or oceanic lithosphere *of any age* can be converted by partial melting and subsequent differentiation into more evolved sialic rocks.

There are many published models for the origin and evolution of Archaean greenstone belts. The one which seems to me, in principle, best capable of accounting for most of the observed characteristics as well as the complex and variable field relations with the juxtaposed gneisses is the so-called 'Marginal Basin' model of Tarney, Dalziel & de Wit (1976). A close analogy is drawn between a typical Archaean Greenstone belt and the Cretaceous 'Rocas Verdes' marginal basin complex of southern Chile. Taking into account the higher geothermal gradient in the Archaean, with its influence on lithospheric plate size and thickness, plate subduction and nature of the crust-mantle interface, Tarney *et al.* propose a geotectonic model for Archaean greenstone belts which is also reconcilable with the geochemical features of the principal rock types.

Windley & Smith (1976) have reviewed tectonic and chemical similarities between Archaean rock types and the rocks in Mesozoic and Cainozoic fold belts whose tectonic environments are better understood. More specifically, they suggest that Archaean quartzo-feldspathic gneisses and their enclosed remnants of layered igneous complexes and supracrustal rocks are metamorphosed and deformed equivalents of calc-alkaline batholiths in the Cordilleran fold belt of western North America and possibly of the similarly active plate margin of the Caledonian fold belt of Britain.

It is evident that in recent geological thinking there is a growing tendency towards a uniformitarian viewpoint involving some recognizable form of global tectonics throughout geological time. Some important differences, such as the common production of high-temperature ultramafic magmas (komatiites) in the Archaean, presumably reflect the considerably greater radiogenic heat production in the mantle at that time (Green 1975; McKenzie & Weiss 1975).

(*b*) *Geochemical differentiation of sial*

Since the demonstration from geochemical and heatflow measurements that rocks of increasing metamorphic grade in ancient shield areas are increasingly depleted in large-ion lithophile (l.i.l.) or 'incompatible' elements, including the heat-producing radioactive ones, it has become evident that the continental crust is strongly geochemically layered. The subject has been reviewed by Heier (1973*a*, *b*). The characteristic constituents of the deep continental crust appear to be dry, depleted, barren, intermediate to basic granulites. Seismic velocity studies support this hypothesis (Christensen & Fountain 1975). Heatflow studies have shown that even in geologically young igneous plutons, such as the Sierra Nevada and Idaho batholiths, there is an exponential decrease of heat production with depth (Lachenbruch 1968, 1970; Swanberg 1972). It is possible that the plutons pass downwards into high-grade, depleted metamorphic rocks which could be the deep-seated equivalents in time and origin of the overlying igneous plutonic and volcanic rocks. As far as I know, no young high-grade metamorphic rocks are yet exposed in the Cordilleras or Andes, but continued uplift and erosion may eventually uncover such rocks. A much greater crustal cross section is, of course, available for sampling and study in Precambrian terrains. There is much evidence that the processes leading to petrological and geochemical layering of the continental crust have occurred throughout geological time, which is strongly supported by the isotopic data to be discussed shortly. The upper continental crust is thus separated and insulated from the upper mantle, or from anomalous sub-continental mantle (see, for example, Jordan 1975*a*, *b*; Sipkin & Jordan 1975) by a permanent, refractory, dry, impervious layer of granulites which it is very difficult to melt under any but extreme and somewhat implausible circumstances (Brown 1970).

A dynamic view of the geochemical differentiation of continental crust has been given by Fyfe (1970, 1973*a*, *b*) and Brown & Fyfe (1970), who consider that granitic rocks result from the fusion of high-grade metamorphic rocks at depth and that an originally more homogeneous sialic crust will undergo petrological and geochemical differentiation by the influx of heat from below and/or within. The detailed mechanisms were not clearly specified. The reality of this phenomenon of crustal differentiation is beyond question, yet I find it difficult to reconcile its existence on general and isotopic (see below) grounds with Fyfe's (1976) view of a world-wide 'primordial' granitic crust which has been incessantly reworked from the beginnings of geological time.

3. Interpretation of Sr and Pb isotopic studies

The birth and differentiation of sialic crust, reviewed briefly above, have not often been discussed in the same breath. However, Taylor (1967), Jakeš & White (1971) and Jakeš (1973) have strongly hinted on general geological grounds that these two major processes may follow each other without any major break. Several years ago, it occurred to me that the best way of explaining much geochronological and isotopic data that had by then become available was, in fact, to postulate the occurrence of periodic 'accretion-differentiation superevents' in which the production of juvenile, mantle-derived sial is immediately followed by intense crustal differentiation in one immensely complex, multistage, semi-continuous (or semi-episodic!), continent-forming episode. I have presented detailed evidence and reasoning elsewhere (Moorbath 1975*a*, *b*, *c*, 1976, 1977), so that only a brief summary is given here, together with additional comments. Relevant isotope-evolution diagrams are given in most of the quoted references and are not reported here.

(*a*) Sr *isotopes*

Many major Archaean and Proterozoic calc-alkaline orthogneiss terrains yield good Rb-Sr whole-rock isochrons over vast areas, in which the initial $^{87}Sr/^{86}Sr$ ratios, $(^{87}Sr/^{86}Sr)_i$, either coincide with, or lie only slightly above, plausible upper mantle values as deduced from a hypothetically linear upper mantle $^{87}Sr/^{86}Sr$ growth line from 0.699 to *ca.* 0.703–0.704, extending over the past 4600 Ma. (The exact shape of the growth line has not yet been established, but most workers agree that any departure from linearity must be small.) As an example, most $(^{87}Sr/^{86}Sr)_i$ values for 2800–2500 Ma basement gneisses are in the range 0.701–0.702, averaging close to 0.7015. This is not significantly different from $(^{87}Sr/^{86}Sr)_i$ values for basaltic and metabasaltic rocks from greenstone belts of similar age (see, for example, Hart & Brooks 1969). Values of $(^{87}Sr/^{86}Sr)_i$ for 3700–3600 Ma basement gneisses are mostly in the range 0.700–0.701 (Moorbath *et al.* 1972; Moorbath, O'Nions & Pankhurst 1975; Hawkesworth, Moorbath, O'Nions & Wilson, 1975). It is not possible, of course, to measure isochron $(^{87}Sr/^{86}Sr)_i$ values as precisely as those of modern igneous rocks, but the data are nonetheless fairly conclusive. Thus, associated gneiss terrains and greenstone belt volcanics frequently yield closely grouped ages and essentially mantle-type $(^{87}Sr/^{86}Sr)_i$ values, suggesting that the entire sequence is part of one major crust-forming event. For example, in West Greenland such events occurred at around 3800–3650, 3000–2800 and 1900–1700 Ma ago (for summary, see Moorbath & Pankhurst 1976) and in Rhodesia at around 3600–3500 and 2800–2650 Ma ago (for summary, see Moorbath, Wilson, Goodwin & Humm 1977). Similar groupings of ages and $(^{87}Sr/^{86}Sr)_i$ have been reported from North America and elsewhere (for summary, see Moorbath 1976).

Crustal growth must dominate greatly over crustal reworking because $(^{87}Sr/^{86}Sr)_i$ values are low and uniform in the different rock types formed during each event at widely varying metamorphic grades. Regional metamorphic homogenization of Sr isotopes is unlikely to be significant because of the general observation in geochronology that even the highest grades of metamorphism will not usually cause isotopic homogenization between adjacent hand-specimen-size domains of whole rock (see, for example, Krogh & Davis 1973; Moorbath 1975*b*). Large scale Sr isotope homogenization under plutonic conditions undoubtedly requires the presence of a melt phase, although it is known to occur on a more modest scale during diagenesis and/or metamorphism of fine-grained sediments in the presence of much interstitial or chemically-bound water.

Some ancient igneous rocks are known to have high $(^{87}Sr/^{86}Sr)_i$ values. These are usually late, intrusive plutons of true granitic composition. A few examples, quoted with 2 standard deviations are the Qôrqut granite of West Greenland (2552 ± 16 Ma; $(^{87}Sr/^{86}Sr)_i = 0.7083 \pm 0.0004$; Moorbath & McGregor, unpublished data), the Mont d'Or granite of Selukwe, Rhodesia (3420 ± 120 Ma; $(^{87}Sr/^{86}Sr)_i = 0.711 \pm 0.002$; Moorbath, Wilson & Cotterill (1976)), the Prosperous Lake granite of the Yellowknife area, Canada (2575 ± 25 Ma; $(^{87}Sr/^{86}Sr)_i = 0.712 \pm 0.002$; Green, Baadsgaard & Cumming (1968)), and the so-called 'Undifferentiated gneisses' of Saglek Bay, Labrador (3120 ± 160 Ma; $(^{87}Sr/^{86}Sr)_i = 0.7064 \pm 0.0012$; Hurst *et al.* (1975)). I am convinced that many more examples will turn up with further search. Depending upon the regional setting, such granites are presumably the products of partial anatexis of older sialic crust probably pre-dating the granites by not less than about 100–200 Ma, and possibly by *much* more. However, present evidence suggests that such processes are quantitatively of secondary importance when compared with production of juvenile sial, especially during the earlier, possibly world-wide, Precambrian continent forming events which appear to peak at around 3800–3500, 2900–2600 and 1900–1600 Ma ago.

Several workers (see, for example, Bridgewater & Fyfe 1974; Hargraves 1976) have criticized the Sr isotope interpretation of crustal growth on the grounds that partial anatexis of a much older, sialic, Rb-depleted basement with very low Rb/Sr ratios could yield low-$(^{87}Sr/^{86}Sr)_i$ igneous rocks at any subsequent time. The difficulty then lies in accounting for the production of vast amounts of juvenile, calc-alkaline material from older continental-type crust which is already highly depleted in Rb and presumably, therefore, in other granitophile elements. This controversy has been particularly discussed in connection with the origin of the voluminous *ca.* 2850 Ma old Nûk gneisses of West Greenland (Bridgewater, McGregor & Myers 1974; Moorbath & Pankhurst 1976). Other critics have suggested the occurrence of Sr-isotopic mixing and homogenization between crust and mantle on a vast scale, so that the source region of most juvenile igneous rocks is essentially uniform and has low $(^{87}Sr/^{86}Sr)_i$ values at any given time because the mantle Sr reservoir greatly exceeds the crustal Sr reservoir (see, for example, Shaw 1976; Fyfe 1976). I regard such large scale mixing processes as highly implausible. As stated above, it is now beyond question that Sr does not diffuse in dry, crustal rocks over distances of more than a few centimetres (if that!) even under granulite conditions. Similarly, the long-standing (*ca.* 1000–3000 Ma) isotopic heterogeneity of the upper mantle on a scale in some cases down to a few kilometres has been established beyond any reasonable doubt from numerous isotopic measurements on modern oceanic volcanic rocks (Sun & Hanson 1975; Hofmann 1975; Hofmann & Hart 1975; Brooks, Hart, Hofman & James 1976). It is surely a logical proposition that if neither the crust nor the mantle can homogenize isotopically to any significant extent within themselves, then large scale isotopic mixing and homogenization between crust and mantle is implausible, to say the least.

(*b*) Pb *isotopes*

Many of the above considerations apply to Pb/Pb whole-rock isochron ages on ancient calc-alkaline orthogneisses which frequently agree with corresponding Rb-Sr whole-rock ages, although not nearly as many data have been published (see, for example, Moorbath, Welke & Gale 1969; Black *et al.* 1971; Black, Moorbath, Pankhurst & Windley 1973; Rosholt, Zartman & Nkomo 1973; Moorbath *et al.* 1975; Moorbath, Powell & Taylor 1975). Simplicity of Pb/Pb isotope systematics suggests derivation from a source region with rather uniform U/Pb ratio, approximating to single stage evolution from time of formation of the Earth to the measured isochron age. Consideration of the calculated $^{238}U/^{204}Pb$ (μ_1) value of the source region (*ca.* 7.5–8.0, with the use of model parameters of Oversby (1974)) for the appropriate single stage growth curve suggests that the source region of the gneiss precursors was either upper mantle, or upper mantle derived basic lithosphere.

Following closely upon generation of juvenile sial, geochemical differentiation of newly formed crust produces strong fractionation of U/Pb ratios at, or close to, the measured isochron age. The wide range of measured U/Pb ratios in many ancient calc-alkaline orthogneisses contrasts strongly with the relatively homogeneous U/Pb calculated for the source region of the gneiss precursors. Most ancient gneisses have undoubtedly suffered profound U depletion and frequently contain present-day unradiogenic Pb isotopic ratios on, or close to, an appropriate primary growth curve. Thus the Early Archaean Amîtsoq gneisses of West Greenland contain the most unradiogenic Pb yet measured for any terrestrial rock because of intense U depletion at about 3700 Ma ago (Black *et al.* 1971). Similarly, the least radiogenic Pb for the Late Archaean Scourian granulite gneiss basement of northwest Scotland lies almost on the single stage growth curve at about 2800 Ma (Moorbath *et al.* 1969; unpublished data).

In close analogy with the Rb-Sr decay scheme, approximate homogeneity of initial Pb/Pb isotope ratios in an ancient gneiss terrain is broadly regarded as inherited from the upper mantle source region of the igneous precursors of the gneisses. Penecontemporaneous crustal accretion and metamorphic/geochemical differentiation results in depletion in U (and other granitophile elements) by transport processes involving partial melting and dehydration, leading to dispersed (but generally low) U/Pb ratios. The necessary conditions for satisfactory isochron behaviour are thus fulfilled. A good Pb/Pb whole rock isochron can thus date the 'accretion–differentiation superevent'. In many cases the duration of the superevent probably does not exceed the uncertainty on the age measurements.

There is one fundamental difference between the application of Rb-Sr and Pb/Pb methods to problems of origin and development of sialic crust. As mentioned earlier, geochemical differentiation produces lower continental crust with an average Rb/Sr ratio not always sufficiently different from average Rb/Sr of upper mantle to make $(^{87}Sr/^{86}Sr)_i$ values unambiguous petrogenetic indicators of crustal or mantle derivation. In contrast, geochemical differentiation produces lower continental crust in which U/Pb ratios tend to be much lower than in the upper mantle, so that lower crustal Pb isotopic ratios for rocks of any age are on average *much* less radiogenic than for upper mantle. This very fundamental difference has clearly persisted throughout geological time. This makes it possible to distinguish between crustal accretion of mantle-derived juvenile sial and reworking of much older sialic crust. As an example, we consider again the problem of the origin of the igneous precursors of the *ca.* 2850 Ma old Nûk gneisses of West Greenland. Sr isotope data strongly suggest, but cannot by themselves confirm, that the Nûk gneisses represent juvenile, mantle-derived sial at or not long before *ca.* 2850 Ma ago and not reworked *ca.* 3700 Ma old Amîtsoq gneisses (Moorbath & Pankhurst 1976). Amîtsoq gneisses became severely depleted in U at *ca.* 3700 Ma ago, so that their average Pb isotopic composition thereafter remained highly unradiogenic (Black *et al.* 1971). Deeper level Amîtsoq gneisses than any now exposed would be even more depleted in U, if that were possible! Therefore, any subsequent partial melt of such a basement would similarly contain unradiogenic Pb whose crustal development began at about 3700 Ma ago. However, preliminary whole-rock Pb/Pb measurements on Nûk-type gneisses from areas some distance north and south of Godthaab demonstrate that the measured Pb isotope systematics developed in a crustal environment only since about 2850 Ma ago and not since 3700 Ma ago (Black *et al.* 1973).

4. General discussion of isotopes and crustal evolution

The fact that an immense, semi-continuous or semi-episodic burst of continental accretion and differentiation with a high degree of internal, multistage complexity often yields rather simple age and isotopic relations is a consequence of the relatively homogeneous (compared to continental crust) upper mantle as the major source region for igneous rocks, as well as the restricted time scale for the whole operation. The birth and 'ripening' of sial (to borrow a term from Jakeš (1973)) then, as now, can be measured in terms of tens or, at the most, a few hundreds of millions of years. It must be emphasized again that the isotopic data in no way imply *direct* derivation of new calc-alkaline sial from upper mantle in a one-stage process, although they do not rule out this possibility. Neither do they rule out derivation of new sial from continental or oceanic basic lithosphere of any age with mantle-like Rb/Sr or U/Pb ratios, nor in some cases reworking of *slightly* older ($<$ 100–150 Ma) sial with average upper crustal Rb/Sr or U/Pb ratios.

In this connection, reference was made earlier to post-tectonic granites (*sensu stricto*) with high, variable $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$ values, probably derived by partial anatexis of older sial. Furthermore, a newly formed sialic segment may itself continue to undergo internal, ensialic, metamorphic and geochemical differentiation for perhaps as much as several hundreds of millions of years. For example, Moorbath & Pankhurst (1976) thought they could detect a significant increase in $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$ from *ca.* 0.7015 for Nûk gneisses formed between *ca.* 2900 and 2650 Ma ago in different regions of West Greenland. Extrapolation backwards of average $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ development lines suggested that the new sialic segment could have separated from mantle or mantle-like source regions some 2900–3000 Ma ago.

Similarly, Davies & Allsopp (1976) report that Swaziland Precambrian gneissic rocks with Rb-Sr whole-rock ages in the range 3400–3140 Ma lie on a steep $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$ against time development line extending from 0.701 to 0.706 that intersects a linear upper mantle development line (or region) at *ca.* 3500 Ma ago. Their interpretation is that regionally, extensive juvenile sialic crust formed at about 3500 Ma ago and that the various gneissic rocks defining the steep development line attained their present state by repeated localized metamorphism and Sr isotopic homogenization within this early crust, although it is uncertain whether the metamorphism(s) proceeded to the state of anatexis. If it had proceeded that far, it would certainly be easier to envisage large scale Sr isotope homogenization in these rocks. The possibility of successive, ensialically derived, batches of magma actually seems to be more in accord with the field evidence summarized by Davies & Allsopp (1976).

My preferred model is that the birth of sial is rapid compared to its ripening. This latter process might be visualized as a kind of 'thermally self-sustaining, ensialic zone-refining' extending over as much as several hundreds of millions of years and probably helped along by repeated influx of heat, magma and volatiles from below. Thus the juvenile sialic crust gradually purges itself of incompatible, granitophile 'impurities' from the base upwards, involving a combination of partial melting and dehydration processes until a steady state is reached. Such a model can also easily explain the frequently observed phenomenon of retrograde metamorphism and metasomatism of rocks at higher crustal levels. I agree with Wells (1976*a*, *b*; and private communication) that metamorphism in a major gneiss terrain, such as the *ca.* 2850 Ma old Nûk gneisses of West Greenland, may occur quite soon after the emplacement of large amounts of mantle-derived, acid-to-intermediate magmas. Wells proposes a model for the Nûk gneisses from phase equilibrium studies suggesting that the mineral assemblages in these intrusive gneisses record progressive cooling conditions from magmatic maxima and that the restoration of a steady-state geothermal condition in the crust after emplacement of the mantle-derived gneiss precursors is responsible for the post-intrusion metamorphic evolution of this sector of Archaean crust. This model may have very wide applicability and is entirely consistent with observed isotopic evidence. A similar type of model was proposed by Spooner & Fairbairn (1970) who, on the basis of low $(^{87}Sr/^{86}Sr)_i$ values, favoured an igneous origin for several suites of Precambrian pyroxene-granulite grade gneisses, involving transfer into the crust of a mantle-derived magma of intermediate composition. They suggest that the part that reaches the upper crust will crystallize as normal intrusive and extrusive rocks, but that which is trapped in the lower crust at about 1 GPa (10 kbar) pressure or more will cool slowly to a minimum of about 500 °C and crystallize directly into plagioclase–pyroxene assemblages characteristic of the granulite facies.

Sr isotope data have been reported for much younger rocks than any so far discussed, which are consistent with the above closed-system, short term, crustal model of metamorphic/geochemical evolution within a juvenile sialic segment. Fullagar & Odom (1973) report whole-rock Rb-Sr data for gneisses in the Blue Ridge Province of North Carolina, Virginia and Tennessee which show an increase in $(^{87}Sr/^{86}Sr)_i$ from about 0.704 to 0.708 during the period 1250–1030 Ma. The crustal segment could have separated from mantle source regions around 1300–1400 Ma years ago. Vidal (1974, 1976) has reviewed all available Rb-Sr data on granites from western and central Europe in the age range 600–280 Ma and has demonstrated a statistically valid trend of increasing $(^{87}Sr/^{86}Sr)_i$ values from a mantle-like value of *ca.* 0.703 at 600 Ma ago to as high as 0.710–0.715 at 280 Ma ago. He attributes this to continuing closed-system crustal evolution over this period for the region, in which later granites are produced by partial melting of sialic crust which is not older than about 600 Ma. It is most improbable that any true granites were derived directly from the mantle, although the earliest ones at 600 Ma undoubtedly had only a very short crustal history.

So far we have discussed isotopic data in the context of generation and chemical evolution of juvenile sial. But the isotopic situation may get steadily more complex when ancient sial becomes involved in later rock-forming processes, as is so often the case. Only a brief mention of this extensive topic is possible here.

In the Central Andes between latitudes 26° and 29° S, McNutt *et al.* (1975) have reported that mid-Cretaceous to Quaternary intrusive and extrusive igneous rocks exhibit a systematic west-to-east increase in mean $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$ from 0.7022 to 0.7077 (although $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$ values of Jurassic plutons vary from 0.7043 to 0.7059, and do not correlate with age). The existence of unusually low $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$ values of 0.702–0.703 for several Mesozoic plutonic rocks implies a sub-crustal source for at least some of the Andean magmas. Similarly, in the Cordilleras of North America, Kistler & Peterman (1973) have reported an increase in $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$ from 0.7031 to 0.7082 for Sierra Nevadan plutonic rocks emplaced over a 130 Ma period. It would be tempting to interpret these data in terms of closed-system, short term evolution of sial, but for many of the rocks from the Cordilleran region there are ample Pb isotope measurements (Peterman, Doe & Prostka 1970; Doe & Delevaux 1973; Zartman 1974) proving that ancient crust with an approximate age of 2800 Ma has contributed a variable but significant proportion of Pb to the young igneous rocks. It even proved possible to contour the isotopic data in relation to crustal thickness, as well as to the age and nature of the crust in any given region. The quoted authors interpret their isotopic data in terms of a variety of subduction-related processes, while Kistler & Peterman (1973) state that 'the chemical and isotopic variations observed are best explained if the parent magma of the majority of granitic rocks investigated were derived in a region that was laterally variable in composition and in a zone of melting that intersected both upper mantle and lower crust'. They also state that 'some granitic rocks, with high Sr concentrations and low Rb/Sr ratios, suggest that deeper sources are also involved in the total spectrum of igneous rocks in the region'. However, the fact remains that the lowest $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$ values of calc-alkaline intrusive and extrusive igneous rocks at accreting continental margins are either identical to, or only marginally higher than, $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$ ratios for calc-alkaline rocks from island arcs that are entirely oceanic, such as the Marianas arc (Meijer 1976) or the Tanzawa plutonic complex of the Izu-Bonin arc of Japan (Ishizaka & Yanagi 1977) which are themselves almost indistinguishable from the range of $(^{87}\mathrm{Sr}/^{86}\mathrm{rS})_i$ values for many oceanic basalts.

There are two principal additional situations in which much older sial can contribute to the production of juvenile igneous magma. The first occurs when there is a close approach and subsequent collision of continental masses with resulting tectonic complications and associated crustal thickening (*ca.* 60–80 km). Under these conditions, extensive basement reactivation and crustal melting may be expected, leading to production of granitic magmas with high but variable $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$ values and typically crustal Pb isotope ratios. (Few Pb isotope data are yet available from such an environment.) An example is provided by the high $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$ values of 0.714–0.717 for 460–500 Ma old Caledonian granites of northeast Scotland (Bell 1968; Pankhurst 1974; Pankhurst & Pidgeon 1976). Rb-Sr systematics and U-Pb zircon dates indicate that the crustal source region of Caledonian granites may have separated from the upper mantle at least *ca.* 800 Ma ago and probably *ca.* 1300 Ma ago. The thermal logistics and subsequent feasibility of this process in the case of the Caledonian granites have recently been discussed by Richardson & Powell (1976). A spectacular example is provided by the Oligocene Manaslu granite from central Nepal in the Himalayas, with an age of 28 Ma and $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$ of 0.741 (Hamet & Allègre 1976) which these authors naturally interpret as the result of crustal anatexis. The Grenville Province of North America, which may be an old collisional suture (Dewey & Burke 1973), similarly exhibits much isotopic complication, presumably as the result of extensive basement reactivation.

The other principal environment of isotopic complication occurs during localized melting of older, sialic crust in the zone of heat transfer above large bodies of mantle-derived basic and ultrabasic magmas introduced into high crustal levels at accreting plate margins in major rift zones. For example, Lower Tertiary (*ca.* 60 Ma) granites of northwest Scotland, which were emplaced into thick Precambrian continental crust during the early stages of opening of the Atlantic Ocean, have high $(^{87}Sr/^{86}Sr)_i$ in the range 0.711–0.721 (Moorbath & Bell 1965) and contain a substantial proportion of unradiogenic Pb derived from underlying rocks which began their crustal history some 2800 Ma ago (Moorbath & Welke 1968). In contrast, plateau basalts of the area have much lower $(^{87}Sr/^{86}Sr)_i$ values in the range 0.703–0.705. However, even the plateau basalts contain some 'old' Pb, so that some kind of deep-seated contamination process between magma and ancient sialic crust must be envisaged.

In summary, Sr and Pb isotopic ratios of igneous rocks are highly sensitive, time-dependent indicators of geochemical differentiation process in crust and mantle and respond particularly readily to the presence of ancient sialic crust. In the latter's absence, they closely reflect the relatively straightforward isotopic condition of the upper mantle during the genesis of a new batch of sial of whatever geological age. On these criteria, massive additions of new sial appear to have occurred throughout most of the Earth's history, although this process may have reached its maximum development during late Archaean times at around 2600–2900 Ma ago. It is clearly still occurring at continental margins above or near subduction zones, although as geological time has progressed, initial Sr and Pb isotopic relations in igneous rocks have become more complex because of increasing interaction with, and participation of, pre-existing sialic crust, resulting from the more effective global operation of modern-type plate tectonics and the 'Wilson Cycle'.

As stated earlier, the mantle itself is now known to be isotopically and, therefore, geochemically heterogeneous on a scale of perhaps as little as several tens of kilometres, while it is quite certain that major heterogeneities have persisted for as long as 1500–2000 Ma, and possibly for 3000 Ma (Sun & Hanson 1975; Hofmann & Hart 1975; Brooks *et al.* 1976). It is tempting to suggest that the time of mantle differentiation measured from Pb/Pb and Rb/Sr linear arrays ('pseudoisochrons') on modern oceanic volcanics represents an averaged time-equivalent for the most rapid and voluminous rate of production of juvenile sialic crust. It is reasonable to suppose that depletion of the most accessible part of the mantle balances production of sialic crust.

There is growing evidence, not yet adequately reviewed in the literature, that the birth of new sial occurred episodically during the Earth's history. The major onset of accelerated crustal growth appears to have occurred very approximately at around 3800–3500, 2900–2600, 1900–1600 and 600–0 Ma ago. Relatively few intermediate, true rock-forming, episodes have been thoroughly documented, but it may eventually turn out that the above pattern results from inadequate sampling on a global scale. If the episodicity is eventually substantiated beyond reasonable doubt, it will provide a strong creative incentive for geophysicists studying the history of the Earth's thermal régime in relation to possibly periodic changes in the global convection pattern.

5. Conclusions

The above account is highly oversimplified. However, I believe that an immense amount of recent evidence from different branches of the Earth sciences is overwhelmingly in favour of evolution of juvenile continental sialic crust by, or through, (i) irreversible differentiation of the upper mantle throughout geological time – possibly episodically; (ii) global tectonics differing in degree rather than in kind over at least the past 3800 Ma; (iii) predominance of (possibly episodic) continental growth over continental reworking or recycling; (iv) penecontemporaneous continental accretion and petrological/geochemical differentiation of juvenile sialic crust within a time interval not usually exceeding about 200–300 Ma, and sometimes much less; and (v) indestructibility of continental sialic crust because of its relatively low density.

In addition, reworking of much older sialic crust can occur in several types of geological environment and becomes more common with the progressive build-up of continental crust over geological time. It is usually distinguishable from the accretion–differentiation régime by detailed age and isotope studies within a given terrain.

In summary, the picture that emerges is one in which the similarities in crustal evolution over the past 3800 Ma are greater than the differences.

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Discussion

R. B. McConnell (*Streatwick, Streat, Hassocks, Sussex, BN6 8RT, U.K.*). In a diagram of the periods of formation of sialic crust in the Precambrian of West Greenland, Dr Moorbath showed an anatectic granite 'E' dated about 2500 Ma, and with a slightly higher $^{87}Sr/^{86}Sr$ ratio than rocks of greater than 3000 Ma sialic crust formation. An age greater than 3000 Ma is indicated by structural and meagre isotope data for the origin of the Tanzania and Uganda–West Nile Shields of East Africa, although the ubiquitous granites and granite-gneisses which now form the predominant outcrops of these shields give firm isotopic ages of 2500–2550 Ma. Has Dr Moorbath studied the Sr isotope ratios of these granites? If so, how would he relate them to the geological history of East Africa?

S. Moorbath. No, I have not worked on these granites. Dr McConnell should discuss this point with Dr N. J. Snelling (I.G.S.) who is currently concerned with aspects of the geochronology of Africa.

G. C. Brown (*Department of Geophysics, Liverpool University*). I should like to make two points on Dr Moorbath's talk:

(1) The ripening process discussed by the speaker is probably the effect of rising isotherms as activity proceeds, such that crustal contributions to rising mantle magmas may become more significant with time, thus raising the ($^{87}Sr/^{86}Sr$) initial ratio.

(2) With reference to the strontium results from the Caledonian, many of the initial ratios from northern England and Ireland are of mantle-type whereas those published by Dr Pankhurst are from the North Scottish region and their higher ratios, reflecting substantial crustal contributions, may be exceptional – even for Caledonian granites.

S. Moorbath.

(1) I agree completely with Dr Brown's first point. There are a good many isotopic data indicating that successive bursts of progressively more granitic magma within a single continent-forming episode show an increasing involvement of old, sialic crust. Some of the evidence is briefly reviewed in the paper.

(2) I suspect that granitic rocks in orogenic belts will always tend to show variable Sr and Pb isotopic ratios, reflecting their mixed crust–mantle genesis. The more voluminous and deep-seated calc-alkaline magmas, however, will be dominated by mantle-type isotopic ratios. A search for possible correlation between isotopic ratios and chemical composition as well as sequence of intrusion of the Caledonian 'granites' could be most instructive.