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The Initiation and Thermal Diversity of Granite Magmatism

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The initiation and thermal diversity of granite magmatism

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Notions of batholith magma generation in crustal thermal environments are countered by the consanguinity of intrusive and extrusive magmas at destructive plate margins, their overlapping mantle-type initial strontium isotope ratios and by their contribution to observed crustal thickening in the absence of significant shortening. Conductive heat modelling produces geotherms which do not intersect the field of crustal fusion. However, crustal scavenging by ascending melts, initiated in the mantle, is a distinct possibility in most tectonic environments. Scavenging occurs more effectively at modern plate margins as activity continues to increase crustal thicknesses, temperatures and acidity of magmas. However, evidence from British Caledonian granites, an older Cordilleran suite, shows the opposite crustal cooling trend probably linked to younger granite formation after subduction processes ceased. Mantle derived Cordilleran magmas contribute to contemporary crustal growth at 0.1–0.5 $\mathrm{km^3\,a^{-1}}$ – a decreasing rate, proportional to the Earth's decaying thermal output, which has controlled the changing style of tectonics and granitic activity during geological history.

GRANITE DIVERSITY AND CRUSTAL MELTING EXPERIMENTS

During this meeting we have heard about the distribution of near-surface temperatures in the Earth and the generation and subsequent thermal history of various kinds of mantle melt, and several contributors have touched on the geochemical evolution of the crust and mantle. Our purpose now is to summarize evidence bearing on the origin of granitic rocks which, together with lower crustal granulites, make up the majority of the Earth's continental crust and whose presence usually controls the distribution of heat-producing elements. Contemporary granites are found in a number of tectonic situations ranging from Andean-type destructive plate margins to those developed during continental rifting at constructive margins such as the British Tertiary granites of Skye, Arran and the Mourne Mountains. A few examples of Phanerozoic intracontinental granites are also known and the extensively studied Nigerian Jurassic intrusions can be interpreted in terms of melting within an abortive rift system having only temporarily stabilized high heat flow conditions (Van Breemen & Bowden 1973).

Volumetrically, the vast majority of modern granites are found in Cordilleran settings, yet there is much evidence that in Archaean times granitic crust was formed at intracontinental locations as a response to penetrative convection in the underlying mantle, operating at relatively shallow levels (see, for example, Windley 1973; Fyfe 1973). The ratio of marginal to intracontinental granite generation has increased with time and the vast span of the Proterozoic marks the transitional thermal régime during which time the balance changed in favour of marginal heat focusing (Fyfe 1976; Watson, this volume, pp. 431–440). In this paper we argue that the addition of new intermediate and acid plutonic rocks to the continental crust represents a continuing process of crustal growth whose rate has been controlled by the Earth's decaying

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thermal output during its 4500 Ma history. To explain the existence of any Archaean granitic crust it is necessary to postulate that granites were produced direct from the mantle or by partial melting of contemporary, more basic mantle fractionates. However, there is some controversy (Heier, this volume, pp. 393–400) as to whether accretion of continental crust still continues. While it is difficult to find a source for plate margin basalts and andesites other than in the mantle (Dickinson 1970; Ringwood 1974), the traditional theory of crustal melting to produce granites has received much experimental support in recent years (Brown & Fyfe 1970; Robertson & Wyllie 1971; Presnall & Bateman 1973).

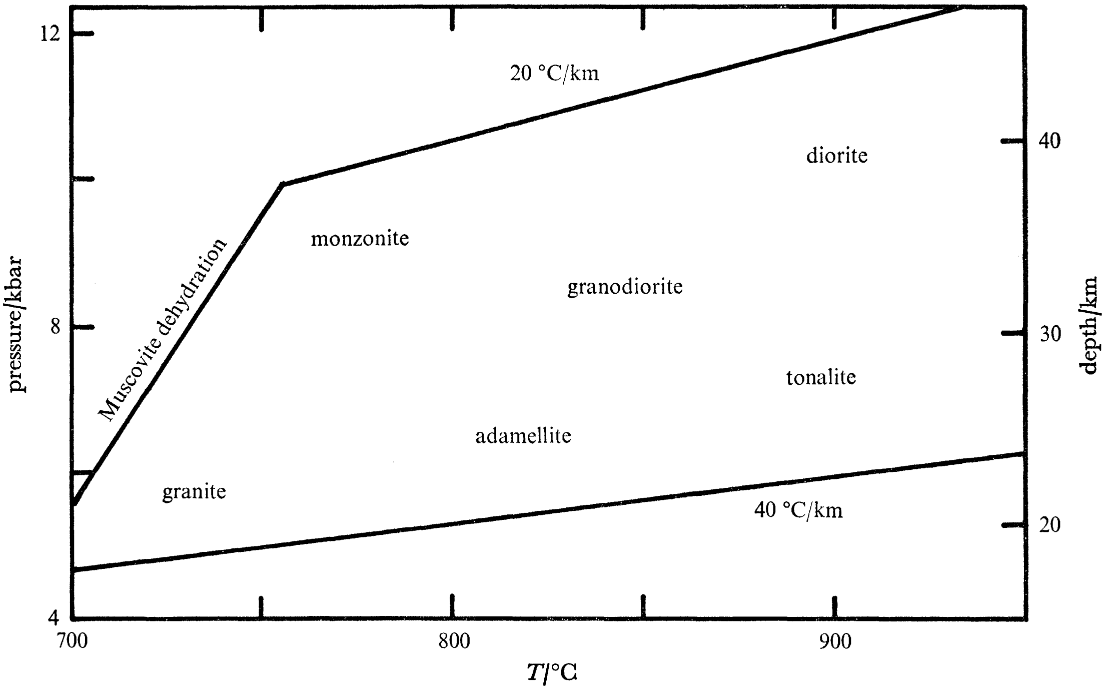

FIGURE 1. Composition of liquids produced by experimental melting of crustal metasediments between 20 and 40 °C/km with muscovite dehydration as a lower temperature limit (after Brown 1973).

Although rocks of the granite family have been produced in a wide variety of tectonic and thermal environments, there are certain minimum pre-requisite pressure–temperature–composition relations (figure 1) which seem necessary for melting. Indicated temperatures are a minimum for each rock type: experimental liquidus temperatures are some 200 °C higher (Presnall & Bateman 1973) and it may be more appropriate to consider higher temperatures of crustal fusion than indicated on figure 1. The starting materials must be fusible metamorphic rocks rather than the anhydrous granulites inferred at depth beneath many batholiths. However, it is demonstrable that a thickening volcanic–sedimentary pile, developed at a plate margin, may eventually undergo partial melting due to the continuing thermal input of andesitic liquids from the vicinity of a mantle subduction zone (Brown 1973; Younker & Vogel 1976). Cordilleran intrusive sequences encompass a range of compositional variants, and the time–composition relations are nowhere better displayed than in the Peruvian coastal batholith (Pitcher 1974) (table 1). To account for this intrusive cycle it is necessary to invoke melting first at the base of the crust to give dioritic magmas at the highest P–T conditions, followed by the production of successively lower temperature granodiorite and adamellite melts at higher crustal levels (figure 1). The very nature of this cycle emphasizes the genetic relation between Cordilleran granite magmas and the products of mantle melting which could initiate the crustal melting cycle. Consequently, experimental results are consistent with the crustal generation of granites.

More recently, our attention has been drawn to evidence that places severe constraints on crustal melting models; this will be considered in two main sections and extended from modern Cordillera back to the British Caledonian. Initial strontium isotope ratios and consideration of crustal thicknesses, deformation and accretion rates led Brown (1977) to conclude that much of the voluminous Cordilleran granites are mantle derived. Furthermore, normal crustal temperatures are well below experimental anatectic conditions (700–900 °C at geothermal gradients between 20 and 40 °C/km; figure 1) and the introduction of mantle magmas may be insufficient to initiate *large scale* crustal melting on the 10^8 a active cycle normally observed.

Table 1. Variation with time of the primary magmas recognized in the Peru coastal batholith by Pitcher (1974)

adamellite	youngest intrusions
↑	↑
granodiorite	
↑	
microtonalite–granodiorite	
↑	
tonalite	80 Ma
↑	
quartz diorite	
↑	
diorite	
↑	↓
gabbro–meladiorite	oldest intrusions

CRUSTAL TEMPERATURES AND GRANITE MELTING

The basis of former arguments favouring crustal melting was that in regions of plate destruction geothermal gradients would be higher, in proportion to observed higher heat flow, compared with normal crust (Brown & Fyfe 1970). Gradients measured in boreholes and estimated using eroded greenschist facies mineral geothermometers were then extrapolated downwards to meet experimentally determined melting curves. From figure 1 we observe that even high-temperature diorite magmas would be generated from appropriate metasediments if they reached 45 km depth. Crustal thicknesses of this order are not uncommon at Andean-type plate margins.

Research into radioactive heat-producing element distributions has now shown that an invariant thermal gradient throughout the continental crust cannot necessarily be assumed. Heier (1973) showed that granulitic lower crust is depleted in heat productivity and we can add Lauchenbruch's (1970) observation that heat-producing elements are logarithmically distributed in the crust with the highest concentrations near the surface. This arises from the linear heat productivity (A)/heat flow (Q) correlation for individual continental provinces (Birch, Roy & Decker 1968). To maintain the relation $Q = bA + q$ (where b and q are constants) during differential erosion, Lauchenbruch (1970) found that heat productivity $A(z)$ at depth z is described by $A(0)\exp(-z/b)$, where $A(0)$ is the measured surface radioactivity. There is some controversy about how this distribution is created from a homogeneous state; whereas Lauchenbruch (1970) considered that magmatic fractionation is responsible, Albarede (1975) preferred a dissolution and reprecipitation process during crystallization and subsequent cooling of intrusions. Our view, amplified later, is that rising magmas scavenge these geochemically leachable elements during ascent, reprecipitating them on crystallization. However, all these mechanisms are a product of magmatism whereas we wish to examine the *initiation of melting*, i.e. the thermal situation before magmatic events have redistributed radioactive elements and before the ascent of thermal/magmatic plumes.

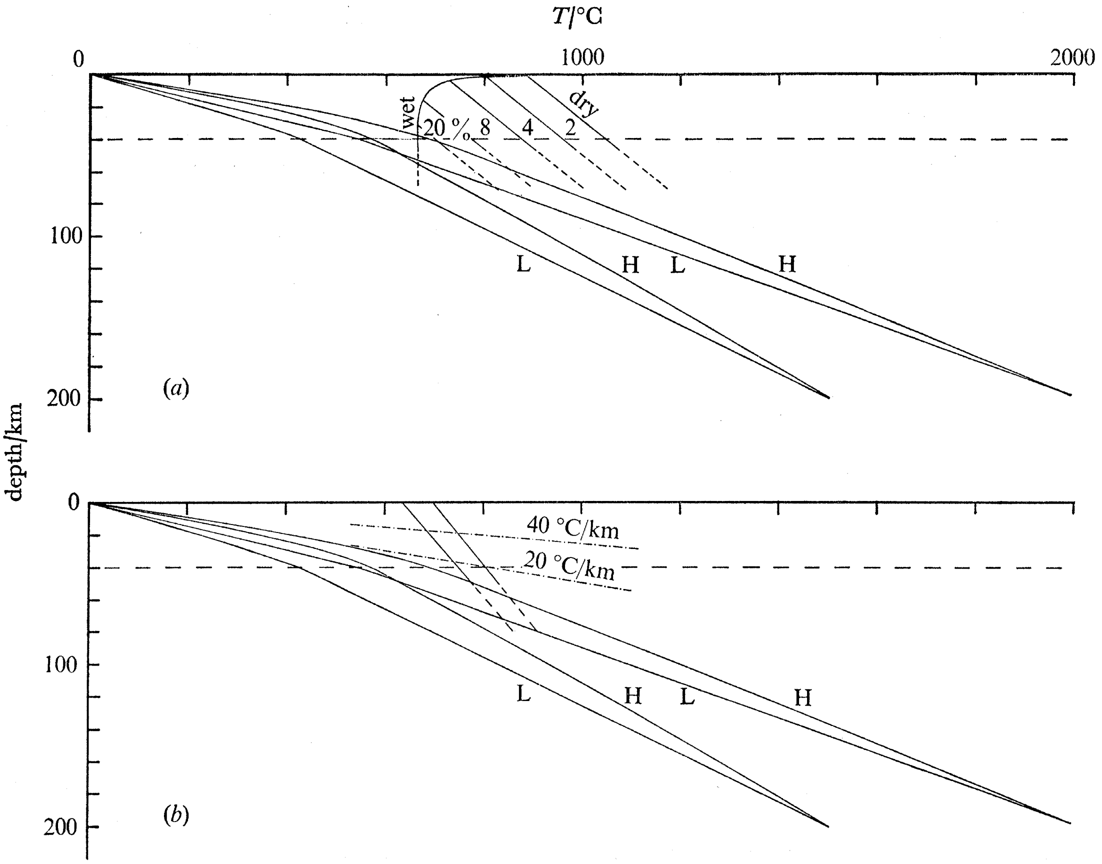

Figure 2. Crust and upper mantle geotherms calculated using a two-layer heat productivity model with a 40 km crust and basal isotherms of 1500 and 2000 °C at 200 km depth. Curves L are based on Sclater & Francheteau's (1970) heat productivity values; curves H on twice these values. The upper diagram (*a*) also schematically illustrates water contents required to saturate acid liquids (Brown 1970). In the lower diagram (*b*) 20 and 40 °C/km gradients are compared with calculated geotherms. The position of the muscovite and biotite dehydration curves in order of increasing temperature are also shown (cf. Brown & Fyfe 1970).

The thermal model we shall describe assumes a homogeneous distribution of heat-producing elements which applies to a crustal metasedimentary pile only before magmatism disturbs this homogeneity by concentrating radioactive elements upwards. Geothermal gradients previously applied to granite melting have been observed after magmatism when near-surface gradients are increased at the expense of those in lower crustal regions. Of course, some crustal segments may have experienced previous magmatism and already have non-homogeneous heat productivity but in such regions the lower crust would be relatively refractory. In any case, Smithson & Decker (1974) and Balling (1976) have shown quite convincingly that mature, layered crustal segments have Moho temperatures between 350 and 500 °C, well below granite melting conditions, with lower crustal thermal gradients of 5 °C/km.

Turning to our homogeneous model: before any melt is transferred through the crust, to determine a temperature profile we must add the heat being conducted from below to that generated from within. To estimate continental lithosphere temperatures as they might appear before subduction or melting commenced we assume a 40 km thick crust with uniform heat productivity $4.5 \times 10^{-7}\,\mathrm{W\,m^{-3}}$ and conductivity $2.6\,\mathrm{W\,m^{-1}\,K^{-1}}$ (Sclater & Francheteau (1970); values for upper and lower crust are homogenized). There follows a solid ultrabasic mantle, 160 km thick, with heat productivity $0.085 \times 10^{-7}\,\mathrm{W\,m^{-3}}$ and conductivity $3.4\,\mathrm{W\,m^{-1}\,K^{-1}}$. At 200 km depth an isothermal boundary is assumed, maintained at constant temperature by asthenospheric convection. Calculations for two basal temperatures of 1500 °C and 2000 °C are shown as curves L in figure 2: the latter is also equivalent to raising the isothermal boundary to 120 km below the surface. On the basis of normal asthenosphere depths and basalt melting relations (Ringwood 1975) upper mantle temperatures would not exceed these values without magma ascent. Curves H, based on doubling Sclater & Francheteau's (1970) heat productivity values, provide a reasonable upper limit to crustal temperatures: clearly, the basal isotherm controls crustal temperatures more significantly than does its radioactive content.

Figure 2*a* shows water-saturated and dry solidi for granite melting together with water solubility curves for acid melts (Brown 1970). Only the relatively unrealistic high basal temperature–high heat productivity curve intersects the field of melting in a 40 km crust. Little melt could be produced with 20 % water and ascent to cooler regions would be curtailed rapidly by P–T conditions falling back to the solidus. In any case, free water would be unavailable at depth and melting, delayed until muscovite or biotite dehydrate (Brown & Fyfe (1970); see figure 2*b*), could not occur in the crust on this basis. The previously extrapolated thermal gradients (20–40 °C/km) are shown to be gross overestimates except for upper crustal regions.

This discussion indicates that granite melting does not occur in normal crust without an increased thermal input exceeding the normal conductive heat transfer. So far we have not excluded crustal fusion in regions of high magma flux from mantle subduction zones. Calculations by Hodge (1974) and Younker & Vogel (1976) show that, when a mantle derived magma (1200–1400 °C) intrudes lower crust at 500 °C, a limited bordering zone of partial melt, initiated at 800 °C, is produced on time scales between 10^4 and 10^6 a. For example, a 6 km wide magma conduit has partial melt zones 1 and 2.2 km wide for initial country rock tempeatures of 500 and 600 °C (Hodge 1974). Such models assume a static, cooling intrusion but in a dynamic model, where magma continues rising towards the surface, the conduit will stay hot until the magma pulse dies away. Magma pulses probably last until some melt crystallizes or is extruded thus causing pressure release. Marsh's (this volume, pp. 611–625) ascent rates (10^{-9} to $10^{-8}\,\mathrm{m\,s^{-1}}$) imply that andesite magmas generated at 100 km depth reach the surface in 3×10^4 to 3×10^5 a. It follows that the magma conduit stays hot on a time scale similar to that required for partial melting in the static model (see above) so the partial melting front is unlikely to advance much further in a dynamic system.

These calculations show that, at best, about 100 % volume increase in mantle melts may be achieved by crustal fusion. In these circumstances, Younker & Vogel (1976) considered that efficient mixing of crust and mantle melts 'can produce compositions similar to those observed in calc-alkaline batholiths'. However, there are certain assumptions which, if questioned, further constrain the crustal melt contribution:

1. Andesite melts may reach the crust at a temperature lower than 1200 °C: the wet andesite liquidus occurs between 1000 and 1200 °C for crustal pressures (Green 1972).

2. The majority of batholith magmas (granodiorites, diorites and tonalites, whose phase equilibria approximate those of andesite) require temperatures above 800 °C for initiation – see figure 1.

3. An ample reservoir of potentially fusible lower crust is not necessarily present.

To conclude: while thermal analysis does not exclude the possibility of crustal melting we are of the opinion that mantle derived melts undergo only small increases in volume within the lower crust.

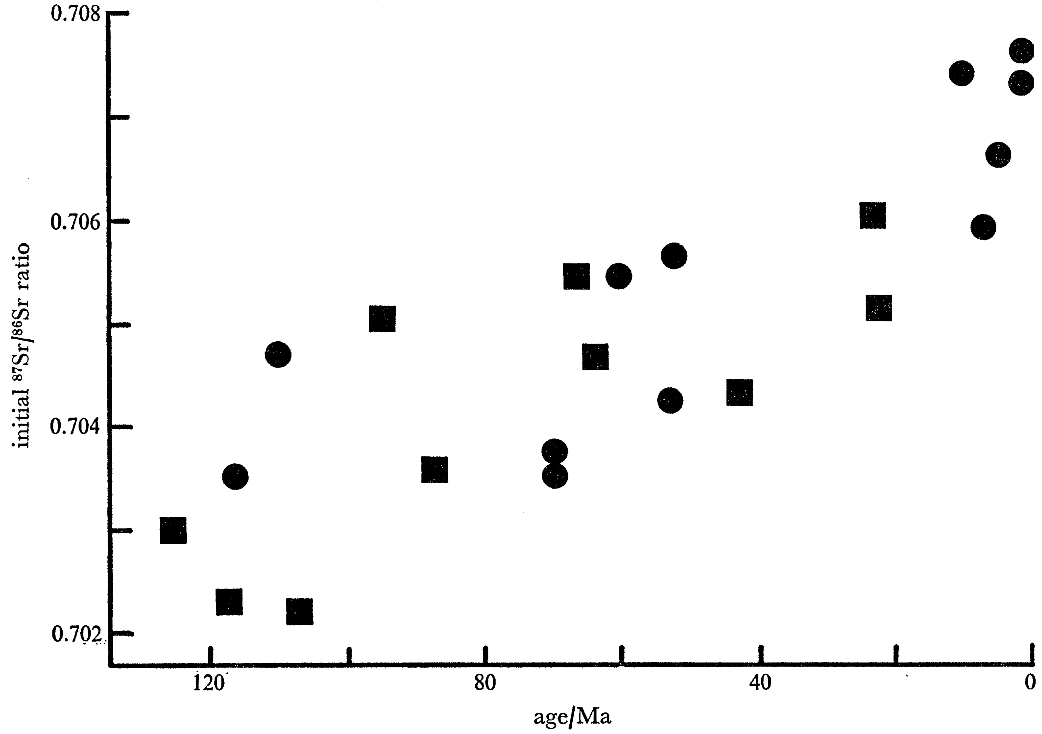

Figure 3. The trend of increasing strontium isotope ratio with *decreasing age* for igneous rocks of the central Andes (after McNutt *et al.* 1975). In general terms the distance from the Pacific margin also increases from left to right. ●, volcanics; ■, intrusives.

Modern Cordilleran granites: additional constraints on the melting zone

The widespread occurrence of mantle type initial strontium and lead isotope ratios in all components of accreting continental crust throughout geological time has received competent coverage by Moorbath (1975 and this volume, pp. 401–413). In modern Cordillera, $^{87}Sr/^{86}Sr$ initial ratios for igneous rocks range from 0.703 to 0.708 (cf. Brown 1977) and a recent illuminating study of Peruvian igneous rocks by McNutt *et al.* (1975) has revealed the striking correlation of isotopic ratio with age plotted in figure 3. The authors concluded that partial melting occurred first in subducted oceanic lithosphere and then in overlying mantle peridotite of slightly higher isotopic ratio. Incorporation of sialic crustal fragments in the down-going slab and some degree of basal crustal melting were both admitted as possibilities. In this context, we maintain that strontium isotopes preclude ancient crystalline basement rocks, preserved unmodified in the lower crust, from producing the bulk of batholithic magmas. For example, $^{87}Sr/^{86}Sr$ ratios of old gneisses from coastal Peru, also thought to underlie the Cainozoic Andean batholith (figure 4), range from 0.732 to 0.774 (Pitcher 1974): partial melting products would inevitably inherit these ratios. It could be argued that prior upward migration of heat producing elements might have depleted the lower crust of rubidium leaving less mature ^{87}Sr/^{86}Sr ratios. However, the close proximity of eroded high ratio gneisses to the thickening axis, as in Peru, suggests that the depletion process occurs during crustal thickening, i.e. during magma ascent. We return to the concept of a scavenging mantle melt phase which removes rubidium and other radioactive elements leaving a lower crustal layer in refractory granulite facies. After limited partial melt extraction, these granulitic residua may retain much of their original strontium partitioned into high temperature feldspar–pyroxene minerals (Hart & Brooks 1974). This makes it difficult to quantify the lower crustal contribution to the melt but the argument that Cordilleran granites contain strontium predominantly of recent mantle derivation remains valid and this precludes their production in the lower crust alone.

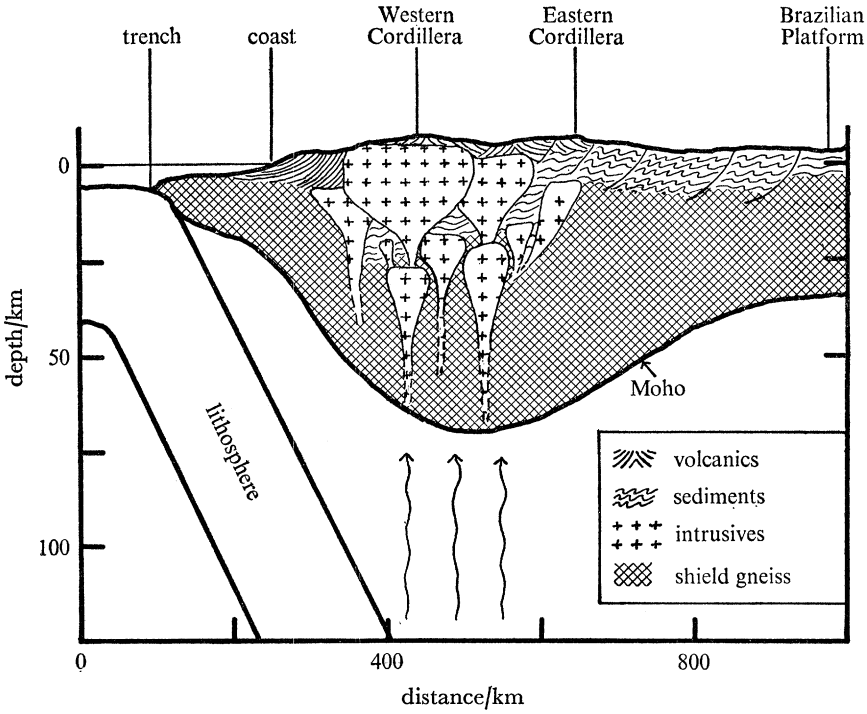

Figure 4. Schematic east-west cross section through the central Andean destructive margin after James (1971), Myers (1975) and Francis & Rundle (1976).

Another striking feature of figure 3 is the overlap of intrusive and extrusive rock age-isotope trends. This is compelling evidence that both the granite batholiths and the andesitic extrusives of Peru have a common origin and it adds weight to the observation (Myers 1975) that the most common intrusive rock type, tonalite (58% by area of the coastal batholith; Cobbing & Pitcher 1972) crystallized in andesite volcano conduits. Were we not so hide-bound by the traditions of igneous rock terminology, the consanguinity of these magmas, which are closely related spatially (Myers 1975), geochemically (W. S. Pitcher, personal communication) and temporally (figure 3), might have become more widely recognized earlier. In addition to the production of low initial ^{87}Sr/^{86}Sr ratios we have a second difficulty for the crustal granite model, that of generating a genetically related suite of intrusives and extrusives. We noted earlier that Cordilleran extrusives, the continental equivalent of oceanic destructive margin island arc magmas, are predominantly mantle derived: a predominantly mantle origin for intrusive magmas is implied.

A third line of reasoning which constrains crustal melting is based on the amount of crustal thickening at destructive margins. Geophysical studies suggest the cross section for the central Andes illustrated in figure 4. Axial crustal thicknesses reach 70 km, twice the average for adjacent shield areas (James 1971). It is conceivable that crustal shortening and consequent thickening would be a natural product of convergence between plates but nowhere along the margins of Western America do we find the necessary degree of compressive folding and overthrusting. These features are confined to identifiable continent–continent convergence zones, between two plates of similar density, such as the former Tethyan line (Bird, Toksöz & Sleep 1975). Reworking of continental crust at modern destructive margins is untenable as a means of crustal thickening; therefore, thickening occurs by the addition of both plutonic and volcanic suites vertically from the mantle. This concept receives further support from the 'permissive' *tensional* features associated with granite emplacement in Peru (Myers 1975).

We have drawn extensively on evidence from the Andes. Similar observations of isotope ratios, magma types, their interrelations and crustal thicknesses apply to other Mesozoic and Cainozoic Cordilleran margins, e.g. western North America (Hietanen 1973), Alaska (Reed & Lanphere 1973) and the Hellenides (Dercourt 1972).

AN OLDER CORDILLERAN SUITE: BRITISH CALEDONIAN GRANITES

Granites from the British Caledonian ranging in age from 390 to 560 Ma have received extensive petrographic study over the years (e.g. Pitcher & Berger 1972) and there are several models for magma generation commensurate with plate tectonic theory (e.g. Dewey 1974; Phillips, Stillman & Murphy 1976). Outcropping granites in northern England, Scotland and Ireland are the surface expression of an underlying batholith of Caledonian age. This granitic basement was probably developed above destructive plate margins flanking a proto-Atlantic ocean (Wilson 1966) which closed along a NE–SW line through the Southern Uplands and Northern Ireland – the precise location of the suture is still debated. If we remove the post-Caledonian effects of sea-floor spreading, we find a continuum of sedimentary, volcanic and plutonic rock types, from eastern Greenland and Scandinavia down to the Southern Appalachians, which are strongly reminiscent of modern Cordillera.

Allowing for the fact that we are observing an intra-continental mountain belt, there are some important features which contrast with modern plate margins. For example, granites south of the Southern Uplands fault intrude Lower Palaeozoic sediments deposited during the latter stages of proto-Atlantic closure. These low grade slates and greywackes contrast with strongly deformed, high grade metasediments of the Alpine–Himalayan mountain chain where frictional heating and overthrusting of radioactive upper crustal layers might well have sufficed to initiate crustal melting (Oxburgh & Turcotte 1974). Moine and Dalradian rocks of the northern proto-Atlantic margin encountered greenschist metamorphism after deposition in an ensialic basin (Phillips *et al.* 1976): they attained P–T conditions intermediate between the Southern Caledonian province and the Alps. The differing grade between Dalradian greenschists and Lower Palaeozoic greenstones either side of the proto-Atlantic suture suggests that the early Ordovician metamorphic climax on the northern foreland (500 Ma) might have preceded closure of the proto-Atlantic to the south (Brown & Hughes 1973). This northern peak of metamorphism also preceded emplacement of many granites south of the suture zone where Caledonian plutonic activity was short-lived (*ca.* 400 Ma) and non-diastrophic. A passive demise for this former ocean is recorded, resulting from a slowing of the spreading rate after the early Ordovician as resistance to subduction occurred first at the northern margin. Palaeomagnetic data (Morris 1976) also indicate relatively little post-Ordovician movement between opposing forelands.

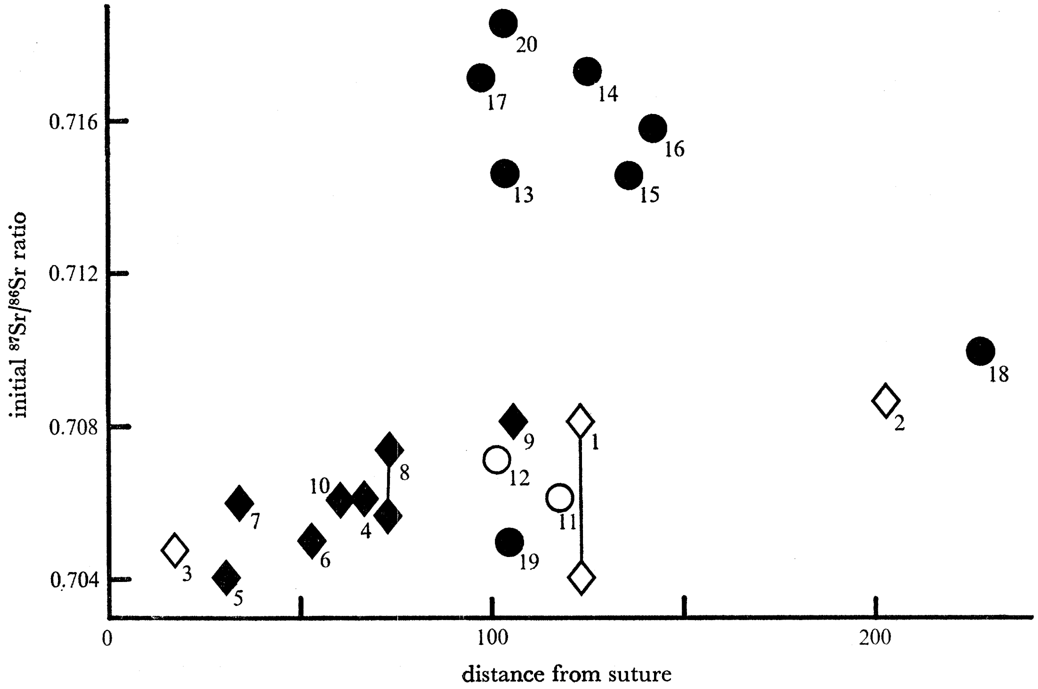

FIGURE 5. Variation of initial strontium isotope ratios with distance from a supposed Caledonian suture zone near the Southern Uplands fault (see O'Connor, Brown & Max, in preparation, for full reference). There are two groups of granites: *a*, a high ratio cluster of Aberdeenshire intrusions and *b*, a trend of increasing ratio with distance from the suture which also correlates broadly with *age increase* from left to right. ●, N Scotland; ○, N England; ◆, N Ireland; ◇, S Ireland. Intrusions are numbered as follows: 1, Leinster; 2, Carnsore; 3, Galway; 4, Omey; 5, Inish; 6, Roundstone; 7, Oughteraard; 8, Ox Mountains; 9, Donegal; 10, Newry; 11, Weardale; 12, Threlkeld; 13, Glencroft-Ardlethan; 14, Strichen; 15, Kennethmont; 16, Aberchirder; 17, Peterhead; 18, Carn Chuinneag; 19, Garabel Hill; 20, Dunfallandy Hill. The Glen Clova granite for which $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_{\mathrm{init}}$ = 0.729 has not been plotted.

Phillips *et al.* (1976) have argued that a lower Caradocian (473 Ma) termination of Lake District volcanism marked the end of southerly subduction and thus closure of the adjacent ocean. If so, the N England Caledonian granites were intruded after closure. This could also apply to the Galloway granites even if the Southern Upland sequence were thrust north from England over the Solway suture as suggested by Mitchell & McKerrow (1975). If we consider a suture zone near the Southern Uplands fault rather than the Solway line of Phillips *et al.* (1976) the Southern Uplands sediments could be of the marginal basin type, formed behind a southerly dipping Benioff zone. This would remove the necessity for thrust translation but would still imply that granite emplacement postdated closure (cf. ages of 390–403 Ma for Galloway granites; Brown, Miller & Grasty 1968).

We have indicated that the maximum metamorphic temperatures of exposed crustal rocks considerably exceed the melting temperatures of associated intrusions especially in the Southern

Caledonian province. Further evidence for magma provenance comes from a limited collection of strontium isotopic data which will be reported elsewhere in detail (O'Connor, Brown & Max, in preparation). A useful correlation between initial $^{87}Sr/^{86}Sr$ ratios and distance perpendicular to the Southern Uplands fault (our estimate of the proto-Atlantic suture based on these data) is illustrated in figure 5. A group of high initial ratio granites, mainly from Aberdeenshire, are separated from the otherwise convincing trend which embraces the initial ratio range of modern Cordilleran granites (figure 3). A major crustal melt contribution to the Aberdeenshire acid intrusions is implied – a feature attributable to increased crustal temperatures associated with basic magma penetration into already high grade Dalradian metasediments, or to overthrusting of radioactive layers in the early evolution of the northern province (cf. Oxburgh & Turcotte 1974).

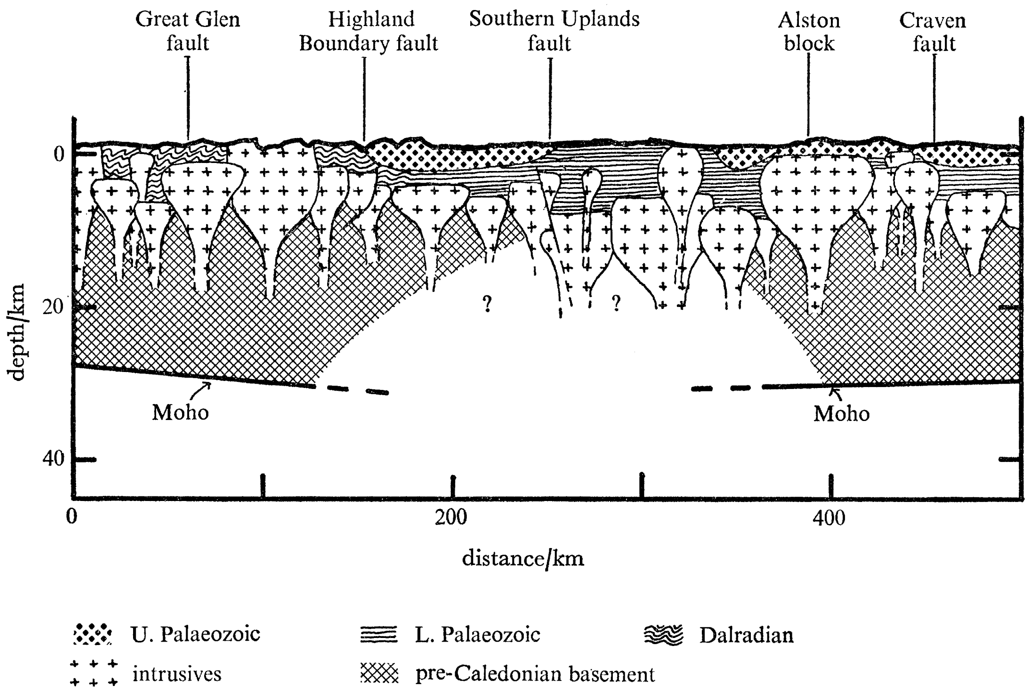

Figure 6. Schematic north–south cross section through the proto-Atlantic suture zone, at present erosion levels, along the lithospheric seismic profile of Britain line incorporating boundaries based on seismic (see text), gravity (D. Powell, personal communication) and other geological data.

In their appraisal of Peruvian initial ratios, McNutt *et al.* (1975) (see figure 3) found that the correlation with decreasing age could be extended spatially: ratios increase with distance from the Pacific margin. The main Caledonian trend (figure 5) shows an identical spatial–initial ratio variation but we find the opposite correlation with age. Although data are sparse, Caledonian granite initial ratios vary sympathetically with age which increases from left to right in figure 5.

The observation that the youngest Caledonian granites, close to the supposed suture zone, have the lowest initial ratios uncovers a fundamental difference between their genesis and that of granites formed at modern destructive margins. Further light on this subject comes from the lithospheric seismic profile of Britain project interpretation (Bamford *et al.* 1976; D. Bamford & C. Prodehl, in preparation and personal communication) which shows a seismic change at the Moho beneath central Scotland (shown in figure 6). A sharp boundary is defined to the north with a more diffuse transition to the south: on both sides a lower crystalline granulite basement yields characteristic P wave velocities of 6.3–6.4 km s^{-1}. These geophysical data confirm a basement discontinuity centred at the Southern Uplands fault which was predicted by the suture position used in figure 5.

Returning to granite petrogenesis we propose the following model (see also figure 6). Early Caledonian intrusive magmas were formed by the processes described earlier for contemporary destructive margins. These magmas scavenged to various degrees as they rose through warm crustal metasediments and basement gneisses of the proto-Atlantic foreland regions. These intrusions preserve the highest initial $^{87}Sr/^{86}Sr$ ratios in the main trend of figure 5 (approaching 0.710, e.g. Carnsore and Carn Chuinneag intrusions: 551 and 557 Ma old respectively). Successively lower ratio granites followed closer to the suture zone as spreading rates slowed and crustal temperatures fell, following the metamorphic climax, together with the potential for crustal scavenging. Granites near the central suture zone were not emplaced until closure was complete and mantle partial melting, adjacent to the former thermally active spreading ridge, was aided by the thermal insulation of a crustal sedimentary cover. These magmas penetrated relatively thin, cool crust and preserved their $^{87}Sr/^{86}Sr$ initial ratios near 0.704 (e.g. intrusions at Leinster, Inish and Weardale dated at 430, 428 and 410 Ma respectively). No strontium results are available for Southern Upland granites but we expect comparably low initial ratios. However, all granites remote from the suture zone will not necessarily include a crustal component in their initial ratios. For example, the Garabel Hill intrusion gives $(^{87}Sr/^{86}Sr)_{init.} = 0.705$ which reflects its passage through the crust with relatively little contamination.

We conclude that although British Caledonian granites have many of the features described for modern Cordilleran batholiths, they have retained a unique age–isotope–spatial relation which indicates passive continental collision followed by magma injection into the suture zone. The earlier conclusions concerning magma genesis by partial melting at mantle depths followed by limited crustal contamination are common to both modern granites and most of the Caledonian suite.

CONCLUSIONS

The thermal, tectonic, isotopic and other constraints on granite melt initiation and diversity discussed in this paper lead to the following conclusions:

1. Former notions that near-surface crustal geotherms intersect the partial melt field for sialic metasediments were erroneous. Voluminous crustal granite magmas are not spontaneously generated but can occur under the influence of high temperature mantle liquid invasion. Even so, thermal calculations for Cordilleran margins, the sites of compressive stress, suggest that crustal fusion is restricted to scavenging by mantle magmas which may increase their volume given a suitable melt reservoir.

Regions of high thermal and magma flux from the mantle under significant tensional stress might more easily generate crustal melts (cf. the continuing controversy over the crust or mantle origin of the Skye granites).

2. The nature of the crustal thickening process at Cordilleran margins, largely the result of magma emplacement and extrusion, again precludes a major crustal melt contribution. Mantle-type initial strontium isotope ratios for plutonic and volcanic suits overlap and emphasize their geochemical and spatial relations: the ratios increase with crustal maturity, temperatures and thickening during the active tectonic cycle (*ca* 10^8 a) as limited crustal fusion by mantle-derived

melts becomes increasingly effective. A further aspect is the temporal trend towards increasingly acid intrusives illustrated in table 1. The compositional diversity of Cordilleran intrusives thus reflects the degree of crustal assimilation involved – a process which will increasingly silicify parental liquids of andesitic affinity as the tectonic cycle proceeds.

The parental consanguineous suite of andesite–diorite–tonalite magmas found at modern destructive margins is predominantly the result of partial melting within and above a subduction zone (cf. Ringwood 1974; Thorpe, Potts & Francis 1976).

3. While noting that early Precambrian tectonic styles are inconsistent with continental-margin granite production, many of the Lower Palaeozoic granites in Britain were developed after the Proterozoic change to marginal tectonics. Caledonian granites were formed first by the destructive margin processes just described and later were injected through marginal basin sediments near the suture zone after ocean closure. These magmas have their origin by mantle melting and crustal scavenging in common with modern Cordilleran granites but, in contrast, their initial isotope ratios follow a crustal cooling trend by evolving towards lower ratios in the latter stages.

4. A mantle origin for Cordilleran magmas implies that crustal growth still occurs at modern destructive margins. On this assumption Brown (1977) calculated a global contemporary growth rate of $0.5\,\mathrm{km^3\,a^{-1}}$ which is a fraction higher than the 0.1–$0.4\,\mathrm{km^3\,a^{-1}}$ deduced from Francis & Rundle's (1976) figures based on magma production estimates in Peru and the Sierra Nevada. It would take between 10 and 50 Ga to 'grow' all of the Earth's continental crust at these rates and a higher accretion rate in the past is implied. Accretion would have been more rapid during early geological history when growth by underplating and intracontinental penetrative convection reflected the higher output of the Earth's heat engine. We suggest that not only the style of continental accretion through the diverse forms of granite magmatism but also the accretion rate is observed to be a function of the progressively decaying thermal output of the Earth.

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