# Chemical and Isotopic Systematics of the Caledonian Intrusions of Scotland and Northern England: A Guide to Magma Source Region and Magma-Crust Interaction

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# Chemical and isotopic systematics of the Caledonian intrusions of Scotland and Northern England: a guide to magma source region and magma–crust interaction

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Chemical and O-, Sr-, Nd-, and Pb-isotope relations for the British Caledonian granitoids exhibit systematic variations that are attributed to derivation from both mantle and crustal sources. The 'older' (more than *ca.* 470 Ma) pre- and syn-tectonic granites were the product of local anatectic melting of Late Proterozoic metasedimentary upper crust ($\delta^{18}\mathrm{O} \approx 8$ to 14‰, $^{87}\mathrm{Sr}/^{86}\mathrm{Sr} > 0.710$, $^{206}\mathrm{Pb}/^{204}\mathrm{Pb} \approx 18.1$–19.2) during the peak thermal conditions of the Grampian Orogeny. The 'younger' (less than *ca.* 440 Ma) post-tectonic granitoids have a complex origin which, in individual cases, involved at least four different source regions: (i) the upper mantle or subducted oceanic crust ($\delta^{18}\mathrm{O} \approx 5.7$ to 7.0‰, $^{87}\mathrm{Sr}/^{86}\mathrm{Sr} \approx 0.7035$–0.7040, $^{206}\mathrm{Pb}/^{204}\mathrm{Pb} \approx 17.9$ to 18.1) and (ii) Lower Palaeozoic geosynclinal sedimentary upper crust ($\delta^{18}\mathrm{O} \approx 11$ to 14‰, $^{87}\mathrm{Sr}/^{86}\mathrm{Sr} \approx 0.705$–0.711, $^{206}\mathrm{Pb}/^{204}\mathrm{Pb} \approx 18.4$) within the paratectonic Caledonides in the Scottish Midland Valley and Southern Uplands and in Northern England or (iii) Middle Proterozoic (?) mafic to intermediate granulitic lower crust ($\delta^{18}\mathrm{O} \approx 8$ to 10‰, $^{87}\mathrm{Sr}/^{86}\mathrm{Sr} \approx 0.705$–0.707, $^{206}\mathrm{Pb}/^{204}\mathrm{Pb} \approx 16.5$–17.0) and (iv) Middle to Late Proterozoic metasedimentary upper crust ($\delta^{18}\mathrm{O} \approx 8$ to 14‰, $^{87}\mathrm{Sr}/^{86}\mathrm{Sr} > 0.710$, $^{206}\mathrm{Pb}/^{207}\mathrm{Pb} \approx 18.1$–19.2) in the Scottish Highlands. Mantle-derived magmas or their direct derivatives were likely involved in the development of all of the 'younger' granitoids, either as end-member components or as the source for a substantial part of the heat required for crustal melting and assimilation. Although the Lower Palaeozoic was a time during which a large amount of igneous material was introduced into the upper crust in Britain, it was not a major crust-forming period because the Caledonian granitoids are dominated by recycled continental crust.

## INTRODUCTION

The 'British Caledonian Granitoids' (B.C.G.) are a chemically and isotopically diverse group of intrusions which were emplaced across the northern half of the British Isles during Early Palaeozoic time and define a unique class of granitic rocks in the genetic classification scheme of Pitcher (1979). Details of the geology, petrology, and major element chemistry of the B.C.G. have been reviewed recently by Pankhurst & Sutherland (1982) and will not be restated here. This work discusses the petrogenesis of the B.C.G. in the light of their isotope systematics and trace element character. Over the past century favour has fluctuated between the hypothesis that the B.C.G. evolved largely as a result of varying degrees of fractional crystallization of primary mafic parent magmas (Harker 1895; Nockolds 1941) and the idea that the B.C.G. were produced entirely by crustal anatexis (Barrow 1893; Read 1961). Recent geochemical, geophysical and isotopic investigations (see, for example, Hall 1972; Richardson & Powell 1976; Pidgeon & Aftalion 1978; Blaxland *et al.* 1979; Brown & Locke 1979; Halliday *et al.* 1979; Pankhurst 1979; Simpson *et al.* 1979; Halliday *et al.* 1980; Hamilton *et al.* 1980; Harmon & Halliday 1980; Clayburn *et al.* 1983; Halliday & Stephens 1983; Harmon 1983) have cited data interpreted to support one side or the other of this debate.

Studies of contemporary or younger granite provinces have drawn attention to the different processes and source regions which may be involved in the generation of granitic magmas. These include:

(i) closed system fractionation of mafic partial melts produced by variable degrees of melting of the upper mantle (Chivas *et al.* 1982);

(ii) partial melting either of subducted oceanic lithosphere or of intercalated sediment or both (Dickinson 1979);

(iii) derivation from isotopically heterogeneous upper mantle and lower crust (Domenick *et al.* 1983);

(iv) upper crustal contamination of melts generated in the mantle (DePaolo 1981) or granulitic lower crust (Albarède *et al.* 1980); and

(v) derivation largely within the crust from protoliths of varying composition (Allègre & Ben Othman 1980; Wenner 1981; McCulloch & Chappell 1982).

At the outset we state our convictions that (i) simple classification schemes based upon bulk composition are not especially revealing because the B.C.G. are predominantly of a single granite type (Stephens & Halliday 1984); (ii) the largest volume of plutonic activity within the British Caledonides was post-tectonic, and much post-dated oceanic closure, such that a direct cause and effect relation between B.C.G. magmatism and subduction is by no means certain; and (iii) the petrogenesis of the B.C.G. was complex and involved both mantle and crustal sources.

## Geological setting

The British Caledonides (figure 1) comprise one of the primary segments of the North Atlantic Caledonian Orogenic Belt. Caledonian magmatic activity in Britain largely postdates the polyphase deformation and metamorphism of the Grampian Orogeny, a major Late Proterozoic–Early Palaeozoic tectonic event attributed by many plate-tectonic models to convergent plate-margin processes accompanying progressive closure of the Iapetus Ocean (see, for example, Dewey 1971; Lambert & McKerrow 1976; Phillips *et al.* 1976; Leggett *et al.* 1979; Longman *et al.* 1979; Thirlwall 1981). Mafic magmas (the 'Newer Gabbros') which are considered by Pankhurst (1970) and Yardley & Senior (1982) to be the deep roots of an island arc, were emplaced in northeastern Scotland *ca.* 490 Ma. Granitoid magmas were emplaced throughout northern England and Scotland over a long interval from *ca.* 515–390 Ma. The main phase of granitoid emplacement occurred after *ca.* 440 Ma following the peak Grampian tectonic activity, which was diachronous from northeast to southwest across the orthotectonic Caledonides and reached a climax between *ca.* 480–460 Ma (Pankhurst 1974; van Breemen *et al.* 1978), although a few plutons predate the main orogenic event and a second group are essentially contemporaneous with it.

The region of B.C.G. magmatism, which extends between the Archaean Lewisian Foreland of northwestern Scotland and the Upper Palaeozoic Variscan fold belt of southwest England, is subdivided into three basic structural-stratigraphic provinces (figure 1). Northwest of the Great Glen Fault, a marginal zone of parautochthonous nappes is developed within a highly deformed basement of Archaean granulites and gneisses (the Lewisian) and the thick sequence of Proterozoic sediments (the Moinian) which forms an unconformable cover. Between the Great Glen Fault and the Highland Border Fault Zone in south-central Scotland lie the orthotectonic Caledonides, a structurally complex alpinotype metamorphic fold belt of highly deformed and variably metamorphozed late Proterozoic to early Palaeozoic supercrustal rocks (the Dalradian). Southeast of the Highland Border Fracture Zone in the Southern Uplands of Scotland, in northern England and Wales, and in eastern Ireland is a wide, non-metamorphic region of weakly deformed pelitic rocks, the paratectonic Caledonides, which were deposited during early Palaeozoic geosynclinal sedimentation. The Midland Valley is considered a link zone between these two Caledonian tectonic provinces.

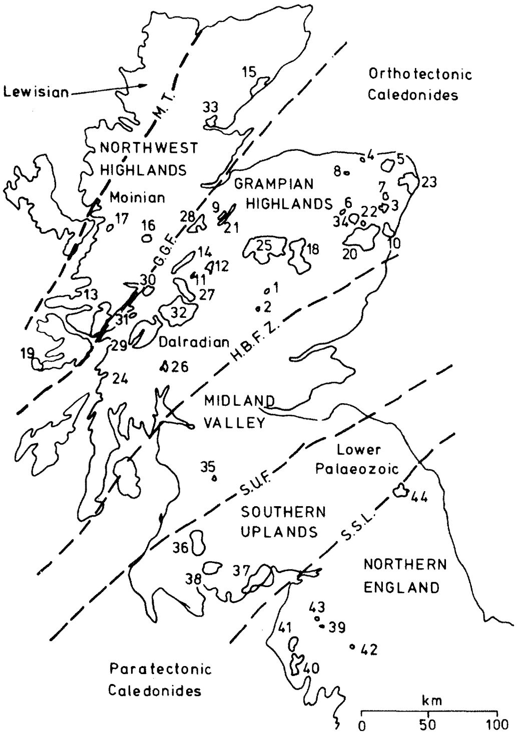


FIGURE 1. Partial outline map of the British Isles showing: (1) major geographic and structural-stratigraphic provinces in northern England and Scotland; (2) the distribution of Caledonian granitoids; and (3) the location of important structural features (M.T., Moine Thrust; G.G.F., Great Glen Fault; H.B.F.Z., Highland Border Fault Zone; S.U.F., Southern Uplands Fault; and S.S.L., Solway–Shannon Line (the probable trace of the Iapetus suture). The numbers assigned to the intrusions correspond to those in table 1.

More than a hundred granitoid intrusions, ranging in size from small sheets, vein complexes, and stocks to large plutons are exposed in the British Caledonides; the majority are concentrated in the Grampian Highlands. In general, there is a lack of extensive hydrothermal alteration of the Caledonian intrusions. Such alteration is a common feature of the Mesozoic granitoids in the Cordillera of the western Americas and the Hercynian granites of Europe; its general absence, except at the margins of a few high-level sub-volcanic centres in the British Caledonides, is generally attributed to the anhydrous nature of the pre-Caledonian crust through which many of the B.C.G. magmas were emplaced (Plant *et al.* 1983).

The earliest phase of Caledonian plutonic activity was the pre-$F_3$ development of small migmatitic and sheeted complexes of biotite or muscovite granite in the Central Highlands which date from $514 \pm 7$ Ma to $491 \pm 15$ Ma (Pankhurst & Pidgeon 1976). These older, pre-tectonic granites were converted largely to foliated augen gneiss or schistose granite during the climax of Grampian deformation and metamorphism at *ca.* 480 Ma. Toward the end of this main phase of tectonism small bodies of relatively homogeneous biotite granite and two-mica granite were emplaced in the northeastern Grampian Highland and extensive migmatites and vein complexes were developed in the Grampian Highlands and northwest Highlands in the areas of most intense regional metamorphism. The former, which yield a variety of Rb–Sr ages (Bell 1968; Pankhurst 1974), have been affected by pneumatolysis to varying degrees during later metamorphic activity; therefore, the concordant monazite U–Pb data of $475 \pm 5$ Ma for the Strichen granite (Pidgeon & Aftalion 1978) is probably the best estimate of the actual emplacement age of this group of intrusions. The main phase of Caledonian plutonism occurred from $439 \pm 7$ to $390 \pm 6$ Ma (Clayburn 1981; Pidgeon & Aftalion 1978) with the post-$F_4$ emplacement of undeformed vein complexes in the central Grampian Highlands and the intrusion of large intrusions of variable composition throughout northern England and Scotland.

The subsurface geology in the British Caledonides has been inferred from geophysical studies and indirect geological evidence. The 25–35 km of continental crust above the Moho in the orthotectonic Caledonides and adjacent areas is best described in terms of a three-component structure (Bamford 1979). A lower crust characterized by P-wave velocities of *ca.* 7 km $s^{-1}$ is separated from an upper crust with P-wave velocities of *ca.* 6.1 km $s^{-1}$ by a pre-Caledonian basement with P-wave velocities of *ca.* 6.5 km $s^{-1}$. The upper crust is considered to consist largely of Moinian and Dalradian metasediments, felsic gneisses, and younger granitoid intrusions. Harris *et al.* (1978) estimate that the total thickness of this basement cover is in excess of 25 km, and seismic data indicates that some 14 km of such crust underlies the greater portion of the Grampian Highlands (Bamford *et al.* 1977). The pre-Caledonian basement, which forms the middle crust, varies in thickness from about 6 km under the Grampian Highlands to greater than 12 km to the north and south. This crust has the seismic character of intermediate granulite (Hall & Al-Haddad 1976). The lower crust is a 6–15 km thick layer presumed to be granulite facies metaigneous rock gradational between gabbro and eclogite in composition (Hall & Simmons 1979). This lower crust is generally inferred to be of Archaean age because P- and S-wave velocities for Lewisian granulites have yielded Poisson's ratios similar to those for the 7 km $s^{-1}$ layer (Hall & Simmons 1979); granulite xenoliths have been observed to occur in the Carboniferous lavas for the Midland Valley (Upton *et al.* 1976); and Pb-isotope data have been interpreted to indicate a Lewisian component in the sediments of the Southern Highland group (Dickin 1980).

Although the geophysical character of the continental segment of the paratectonic Caledonides south of the Highland Border Fault Zone is less well defined, this region is considered to have a distinctly different crustal structure than that to the north beneath the orthotectonic

Caledonides (Bamford *et al.* 1977). Lower Palaeozoic geosynclinal sediments derived from the uplifted areas of the orthotectonic Caledonides, with P-wave velocities of 5.9 km $s^{-1}$, overlie a pre-Caledonian basement with P-wave velocities which vary between 6.5 km $s^{-1}$ in the Midland Valley to 6.3 km $s^{-1}$ in the Southern Uplands and Northern England. Notably absent south of the Southern Uplands Fault is the granulitic lower crust recognized to the north. This evidence is consistent with the heat flow data of Richardson & Oxburgh (1978) which suggests that the basement across most of England and Wales consists of low-grade metamorphic rocks and felsic plutonic rocks to a depth of *ca.* 15 km.

Thus, available geophysical evidence indicates a distinct difference in the nature of the continental crust in the orthotectonic and paratectonic Caledonides. An outstanding question, however, is the identity of the pre-Grampian basement which underlies the British Caledonides. The fact that the general lithologies and metamorphic grade of the major crustal units within the orthotectonic and paratectonic Caledonides may be relatively uniform does not necessarily imply that each is of the same age (Watson & Dunning 1979). Smith & Bott (1975) and Hall & Al-Haddad (1976) have speculated on the basis of similarity in seismic velocities that it might be entirely Archaean granulite.

However, any younger granulite terrain of similar composition would be seismically indistinguishable from Archaean granulites. It is therefore possible that a large portion of the continental crust beneath the British Caledonides is comprised, at least in part, of Proterozoic granulite. Shackleton (1979) has interpreted the seismic data of Bamford *et al.* (1978) to indicate that there is a progressive decrease in basement age from Lewisian to Grenvillian, to Morarian, and to Caledonian from northwest to southeast across the Caledonides. Similarly, Watson & Dunning (1979) have noted that the seismic data of Bamford *et al.* (1978) is consistent with a pre-Caledonian basement that consists partly or largely of a Grenvillian structural province in which crust-forming processes, not manifest on the Archaean craton, led to the formation of gneisses and granulites, as well as the emplacement of granites, during middle Proterozoic time. If such were the case, this Grenvillian province would lie to the southeast of the Lewisian front in the northwest Highlands and could be an important basement component beneath the orthotectonic Caledonides.

Three major, post-Scourian (*ca.* 2900 Ma) orogenic events have been identified in northern Britain. The Laxfordian at *ca.* 1800 Ma, which involved the reconstitution of older Archaean crust (Bickerman *et al.* 1975), and the Morarian at *ca.* 800 Ma, which involved some crustal remobilization (van Breemen *et al.* 1978; Piasecki & van Breemen 1979), are considered to be very restricted and weak metamorphic events. By contrast, the Grenvillian event at *ca.* 1200–1000 Ma is recognized in eastern North America (Krogh & Hurley 1968; Odom *et al.* 1973), Scandinavia (Priem *et al.* 1973), and East Greenland (Rex *et al.* 1976) as a time of high-grade metamorphism and the large-scale addition to new continental crust (McCulloch & Wasserburg 1978). Palaeomagnetic and geochronological evidence (Piper 1974; Patchett & Bylund 1977; Patchett *et al.* 1978) from Canada, East Greenland, and Sweden support the hypothesis of Dewey & Burke (1973) that the middle Proterozoic collision of the North American and Baltic continents represented a Himalayan-type collision which produced the Grenville–Gothide Orogenic Belt, a broad and arcuate super continent which encompassed the British Caledonides near its centre. This idea is supported by the Grenvillian ages observed in the Ox Mountains of Ireland (van Breemen *et al.* 1978) and for the Rockall Bank (Miller *et al.* 1973), the similarity in pre-Caledonian lithology, deformation, and metamorphism between East Greenland and the Scottish Caledonides (Higgins & Phillips 1979), and the structural complexity of rocks of Grenville age in Scotland (Brewer *et al.* 1979; Piasecki *et al.* 1981).

Rocks of Grenvillian age were first identified in Britain when Brook *et al.* (1976) dated the Ardgour granite gneiss, on the west side of Loch Linnhe within the Moinian metasedimentary sequence, at 1028 ± 45 Ma. This unit is post-$F_1$ and pre-$F_2$ in structure (Dalziel & Johnson 1963), but is nowhere cut by younger rocks, suggesting that a Grenvillian front must lie between it and Lewisian inliers within the Moinian province, identified by Moorbath & Taylor (1974), which outcrops to the northwest. There is also recent evidence of a Grenville age for the early metamorphism and deformation of the metasediments of the Glenfinnan Division in the northwest Highlands (Piasecki & van Breemen 1982) as well as for the Highland Division rocks of the Glen Kyllachy area (Piasecki 1980), which are the oldest rocks to outcrop south of the Great Glen Fault. Thus, there is reasonable evidence to expect that there should be a significant Grenvillian component to the continental basement beneath the British Caledonides despite the paucity of surface manifestation.

The character of the subcrustal mantle across the British Caledonides is even more highly speculative. It is unlikely to be homogeneous if current thinking regarding the geodynamics of global tectonics is correct. Recent isotopic studies (Hawkesworth *et al.* 1979; Thirlwall 1982) have shown that the dehydration of subducted oceanic lithosphere may modify significantly the chemical composition of the overlying lithospheric mantle wedge in destructive plate margin environments. Also, differential partial melting over long periods of time (DePaolo & Wasserburg 1976) or contamination by the subduction of continental sediments (White & Hoffman 1982; Dupré & Allègre 1983) are envisaged to produce large-scale heterogeneities in the mantle.

The ophiolitic rocks of the Ballantrae Complex (Church & Gayer 1973) and the Highland Border Fault Zone (Henderson & Robertson 1982; Ikin 1983) formed contemporaneously with deformation and metamorphism to the north in the orthotectonic Caledonides (Bluck *et al.* 1980) and indicate the presence of oceanic crust derived from an isotopically depleted mantle source (Jacobsen & Wasserburg 1979) which was obducted or thrust on to continental crust during the Grampian Orogeny. This, plus the recognition of the Lower Palaeozoic Southern Uplands sediments as a fossil accretionary prism (McKerrow *et al.* 1977), together with a wide variety of other geological evidence (see summary in Leggett *et al.* 1979), suggests that there was subduction-related oceanic closure of the Iapetus Ocean at this time. Therefore, a significant amount of oceanic crust may have been subducted and accreted as a basaltic underplate to the lower crust or returned directly to the mantle during Iapetus closure.

## CHEMISTRY

Overall, the B.C.G. are a group of calc-alkaline to alkalic plutonic rocks, falling largely within the fields of high-K calc-alkaline magmas defined by Peccerillo & Taylor (1976), which cover the compositional spectrum from ultramafic rocks with less than 40% $SiO_2$ to extremely leucocratic rocks with more than 70% $SiO_2$ (Pankhurst & Sutherland 1982). The B.C.G. exhibit an extreme degree of textural, mineralogical, and compositional variation, both across the province as a whole, as well as within individual intrusions, e.g. Garabal Hill: augite peridotite to porphyritic biotite granodiorite (Nockolds 1941); or the Etive complex: quartz diorite to leucocratic granite (Anderson 1937). Therefore, any consideration of regional chemical variability must first take into account such inter-pluton effects and then only compare petrographic or major-element oxide characteristics for plutons of similar age. An additional constraint for trace-element studies is that only rocks of similar major-element composition be compared because many trace elements are extremely sensitive to processes such as crystal fractionation, which can produce large differences in bulk chemistry and result in marked covariation of trace elements with major elements.

Previous classifications of the B.C.G. according to mechanism of emplacement (Read 1961) or geophysical expression (Brown & Locke 1979) have proven unsatisfactory as a basis for chemical comparison. The regional comparisons presented here are based either upon age or upon structural criteria or both (table 1). Ages derived from K–Ar (Brown *et al.* 1968) or fission-track (Hurford 1977) techniques are not considered because these represent cooling rather than emplacement ages. The principal division of the B.C.G. adopted here is into pre- or syn-tectonic '*older*' (more than *ca.* 440 Ma) and post-tectonic '*younger*' (less than 440 Ma) intrusions. This follows the original broad grouping of Read (1961) into 'Older Granites', which were emplaced before the principal Grampian deformation (pre-$F_3$), and the 'Newer Granites', which post-date the main tectonic activity (post-$D_3$ or post-$D_4$). The subdivision of the later intrusions on the basis of emplacement character is disregarded because there is no compelling evidence to indicate that intrusive style is a temporally or petrogenetically diagnostic feature. It is difficult to identify correctly the category to which any individual pluton belongs without firm chronological control because classification solely on the basis of observable tectonic structure can be misleading.

The 'older' pre- and syn-tectonic (pre-$F_3$) granitoids are those plutons for which there is good evidence for an emplacement age of greater than *ca.* 440 Ma or for which there is a regional tectonic foliation. These include the post-$F_2$ Perthshire granites Ben Vuirich and Dunfallandy Hill (Bradbury *et al.* 1976), respectively dated at $514 \pm 7$ and $491 \pm 15$ Ma (Pankhurst & Pidgeon 1976), as well as the post-$F_3$ granites of northeastern Scotland which include Kennethmont, Glencroft, Aucheldy, Aberchirder, Longmanhill, and Strichen, which have slightly reset Rb–Sr ages of greater than 440 Ma (Pankhurst 1969, 1974, 1982), the Glen Kyllachy portion of the Findhorn complex dated at $443+5$–$15$ Ma (van Breemen & Piasecki 1983), and Adclach and the major portion of the Moy complex (Zaleski 1982). Omitted from consideration here are Carn Chuinneag because of its great age ($555 \pm 10$ Ma: Pidgeon & Johnson 1979) and the Glen Dessary intrusion as it is syenitic rather than granitic. The Aberdeen intrusion is somewhat problematic, but is included in this group as suggested by Halliday *et al.* (1979).

The 'younger', post tectonic (post-$F_3$ or $F_4$) granitoids are far more numerous and widely distributed, ranging from the early post-tectonic vein complexes of the Central Highlands (e.g. Strathspey and Corrieyarrack) formed at $437 \pm 8$ Ma (Clayburn 1981) to the Distinkhorn intrusion in the Midland Valley emplaced at $390 \pm 6$ Ma (Pidgeon & Aftalion 1978). Omitted from consideration here are the alkaline rocks of the Loch Borralan complex in the Northwest Highlands and the appinites: ultramafic and mafic rocks which typically occur as small satellite bodies associated with the 'younger' granitoids in the orthotectonic Caledonides.

Chappell & White (1974) have classified granitic rocks into two primary groups based upon mineralogy and chemistry. Those hornblende-bearing granites with accessory sphene and normative diopside and high $Na_2O$ and low (less than 1.1) molecular $Al_2O_3/(CaO+Na_2O+K_2O)$ ratios are termed I-type. By contrast, those predominantly biotite- or muscovite-bearing granites having accessory monazite and normative corundum and low $Na_2O$ and high (greater

TABLE 1. SUMMARY OF GEOCHRONOLOGICAL, STRUCTURAL, AND COMPOSITIONAL CHARACTERISTICS OF THE BRITISH CALEDONIAN GRANITOIDS

| | intrusion‖ | age/Ma | rock type† | structural setting | reference§ | comments‡ |
|---|---|---|---|---|---|---|
| | | Scottish Highlands | | | | |
| *'older' (pre- and syn-tectonic) intrusions* | | | | | | |
| 1 | Ben Vuirich | 514 ± 7 | b gr | pre-F$_3$ | 1 | (A) |
| 2 | Dunfallandy Hill | 491 ± 15 | b gr | pre-F$_3$ | 1 | — |
| 3 | Glencroft | (482 ± 28) | 2m gr | post-F$_3$ | 2 | (B) |
| 4 | Longmanhill | (480 ± 50) | b gr | post-F$_3$ | 3 | (B) |
| 5 | Strichen | 475 ± 5 | b gr | post-F$_3$ | 4 | (B) |
| 6 | Kennethmont | (463 ± 4) | b gr | post-F$_3$ | 3 | (B) |
| 7 | Auchedly | (462 ± 10) | b gr | post-F$_3$ | 2 | (B) |
| 8 | Aberchirder | (454 ± 9) | b gr | post-F$_3$ | 3 | (B) |
| 9 | Glen Kyllachy | $443^{+5}_{-15}$ | b gd-2m gr | post-F$_3$ | 5 | — |
| 10 | Aberdeen | (>420) | 2m gr | post-F$_3$ | — | (C) |
| *'younger' (post-tectonic) intrusions* | | | | | | |
| 11 | Loch Laggan | 439 ± 7 | b gr | post-F$_4$ | 6 | — |
| 12 | Strathspey | 439 ± 9 | 2m gr | post-F$_4$ | 6 | — |
| 13 | Strontian | 435 ± 10 | t–b gr | post-F$_4$ | 4 | — |
| 14 | Corrieyairack | 434 ± 9 | h–b gr | post-F$_4$ | 6 | — |
| 15 | Helmsdale | (420) | 2m gr | post-F$_4$ | 4 | (D) |
| 16 | Cluanie | 417 ± 4 | h gd | post-F$_4$ | 4 | — |
| 17 | Ratagain-Glenelg | 415 ± 4 | d–b gr | post-F$_4$ | 7 | — |
| 18 | Lochnagar | 415 ± 5 | h gd–b gr | post-F$_4$ | 8 | — |
| 19 | Ross of Mull | 414 ± 3 | b gr | post-F$_4$ | 8 | — |
| 20 | Hill of Fare | 413 ± 3 | b gr | post-F$_4$ | 8 | — |
| 21 | Findhorn | 413 ± 3 | b–h gd | post-F$_4$ | 5 | — |
| 22 | Kemnay | (411 ± 7) | 2m gr | post-F$_3$ | 9 | (E) |
| 23 | Peterhead | (411 ± 7) | b gr | post-F$_3$ | 9 | (E) |
| 24 | Kilmelford | 410 | d–gd | post-F$_4$ | 10 | — |
| 25 | Cairngorm | 408 ± 3 | b gr | post-F$_4$ | 11 | (A) |
| 26 | Garabal Hill | 406 ± 4 | um–gd | post-F$_4$ | 12 | — |
| 27 | Strath Ossian | 405 ± 9 | h gd | post-F$_4$ | 6 | — |
| 28 | Foyers | 404 ± 8 | t–b gr | post-F$_4$ | 6 | — |
| 29 | Etive | 400 ± 5 | d–b gr | post-F$_4$ | 13 | — |
| 30 | Ben Nevis | (400) | d–b gr | post-F$_4$ | 14 | — |
| 31 | Ballachulish | (400) | t–b gr | post-F$_4$ | — | (D) |
| 32 | Rannoch Moor | (400) | h gd | post-F$_4$ | — | (D) |
| 33 | Bonar Bridge | (400) | b gr | post-F$_4$ | — | (D) |
| 34 | Bennachie | (399 ± 8) | b gr | post-F$_3$ | 9 | (E) |
| | | Scottish Midland Valley and Southern Uplands | | | | |
| 35 | Distinkhorn | 390 ± 6 | t | — | 6 | — |
| 36 | Loch Doon | 408 ± 2 | d–b gr | — | 15 | — |
| 37 | Criffell-Dalbeattie | 397 ± 2 | h gd–2m gr | — | 15 | — |
| 38 | Cairnsmore of Fleet | 392 ± 2 | b gr–2m gr | — | 15 | — |
| | | Northern England | | | | |
| 39 | Threlkeld | 461 ± 15 | b gd | — | 16 | — |
| 40 | Eskdale | 429 ± 4 | b g gd–m gr | — | 17 | — |
| 41 | Ennerdale | 420 ± 4 | gry | — | 17 | — |
| 42 | Shap | 392 ± 2 | b gr | — | 4, 18 | — |
| 43 | Skiddaw | 392 ± 5 | 2m gr | — | 19, 20 | — |

For footnotes, see opposite.

Table 1. *(cont.)*

† um: ultramafic; d: diorite; t: tonalite; gd: granodiorite; gr: granite; gry: granophyre; h: hornblende; b: biotite; m: muscovite; g: garnet.

‡ (A) Contains secondary muscovite. (B) The best age for these intrusions is the U–Pb monazite age of 475 ± 5 (Pidgeon & Aftalion 1978) as Rb–Sr isochrons have been reset during $F_3$ deformation and metamorphism (Pankhurst 1982). (C) Halliday *et al.* (1979) have suggested that the Aberdeen intrusion may be significantly older than 420 Ma and therefore it has been included here with the 'older' granitoids. (D) Estimated. (E) Minimum age; *ca.* 50 Ma younger than local mica K–Ar ages (Dewey & Pankhurst 1970).

§ 1, Pankhurst & Pidgeon (1976).
2, Pankhurst (1970).
3, Pankhurst (1974).
4, Pidgeon & Aftalion (1978).
5, van Breemen & Piasecki (1983).
6, Clayburn (1981).
7, Thirlwall (personal communication).
8, Halliday *et al.* (1979).
9, Bell (1968).
10, Halliday *et al.* (in preparation).
11, Pankhurst (1982).
12, Summerhayes (1966).
13, Clayburn *et al.* (1983).
14, Hamilton *et al.* (1980).
15, Halliday *et al.* (1980).
16, Wadge *et al.* (1974).
17, Rundle (1979).
18, Wadge *et al.* (1978).
19, Shepherd & Darbyshire (1981).
20, Shepherd *et al.* (1976).

‖ See figure 1 for location.

than 1.1) molecular $Al_2O_3/(CaO+Na_2O+K_2O)$ ratios are designated S-type. The I-type granites are considered to have been produced by the melting of an igneous protolith, whereas the S-types are attributed to the anatexis of reworked metapelitic crustal material that has been through a cycle of chemical weathering and sedimentation at the Earth's surface.

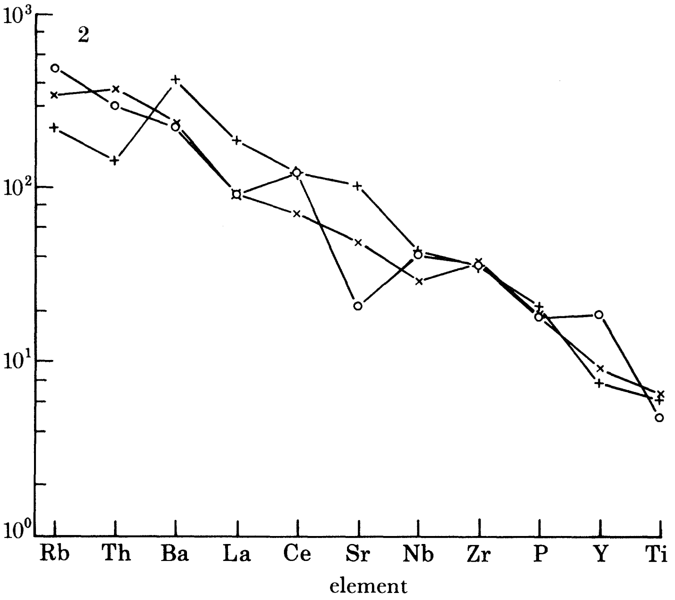
The 'older' Caledonian granitoids are small plutons that tend to be internally homogeneous but compositionally variable as a group. Chemically they tend to be peraluminous with low Na/K and K/Rb ratios. Compositionally they are mainly two-mica granites, although andalusite may replace muscovite on rare occasions (e.g. at Moy; Zaleski 1982). Cordierite has not been recorded in any of the 'older' granites. As a group the 'older' granites cluster close to the low-temperature minimum in the quartz–albite–orthoclase–water system and, in most respects, have the characteristics of S-type granites, which we consider to be primary features inherited from a metasedimentary protolith.

The 'younger' Caledonian granitoids, by contrast, are extremely diverse chemically, ranging in composition from diorites to two-mica granites. As a group they exhibit a trend on an a.f.m. diagram very similar to that for the southern Californian batholith (Larsen 1948), which is often referred to as the 'calc-alkaline' trend. However, the 'younger' granitoids are also strongly enriched in $K_2O$ relative to modern calc-alkaline volcanics such that the majority fall into the high-K calc-alkaline series of Peccerillo & Taylor (1976) as shown by Halliday & Stephens (1983).

For purposes of discussion here we subdivide the 'younger' granitoids into three groups on the basis of tectonic setting (table 1). The first includes those plutons north on the Highland Border Fault Zone in the Grampian and Northwest Highlands of Scotland which were emplaced into the stabilized, northerly continent. The second comprises those plutons in the Midland Valley and Southern Uplands of Scotland emplaced on the northern continental margin of the Iapetus Ocean. The third includes those plutons in Northern England, which were emplaced into the southern continental margin of the Iapetus Ocean. This simple, threefold division is justified for the following reasons. Only first-order variations in chemistry are being considered here, and following the proposal of Chappell (1979) that granites are images of their source regions, then such variations should correlate directly with major differences in tectonic domain. Secondly, the Highland Border Fault Zone and the Solway–

Shannon Line (figure 1) appear in geophysical studies as major lineaments defining prominent crustal discontinuities. Finally, most models casting B.C.G. magmatism in a plate tectonics framework make important interpretations of these boundaries.

In comparison with the 'older' granites, the 'younger' granitoids do not conform well to the I–S classification. The intrusions south of the Shannon–Solway Line tend to be significantly more peraluminous for a given $SiO_2$ value than those to the north and, indeed, many of the Lake District plutons fit into the S-type category. Exceptions to this S-type assignment are Shap and (to some extent) Ennerdale. By contrast, the vast majority of the 'younger' B.C.G. north of the Shannon–Solway Line are metaluminous, except for felsic derivatives which may become mildly peraluminous (e.g. the Starav phase of the Etive complex in the Southwestern Highlands and the Cairnsmore of Fleet granite in the Southern Uplands).



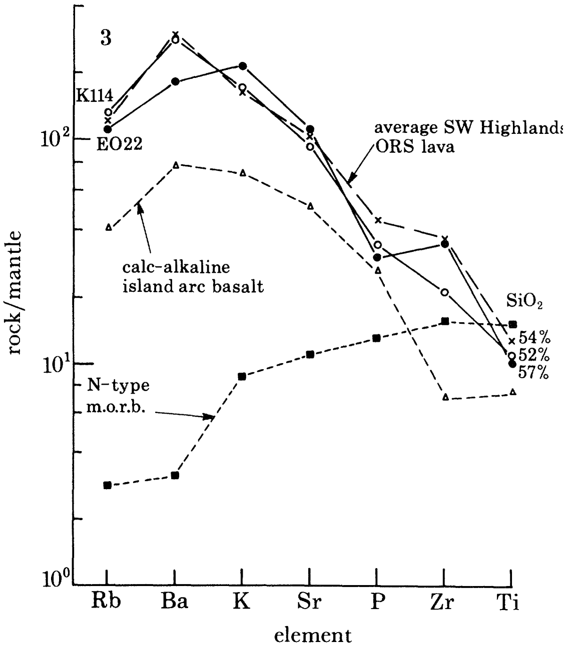


FIGURE 2. Incompatible element variations in the 'younger' (post-tectonic) British Caledonian granitoids averaged for the Scottish Highlands (+), the Southern Uplands and Scottish Midland Valley (×), and Northern England (o) at 65 ± 2% $SiO_2$. The normalizing parameters used are those of Sun *et al.* (1979).

FIGURE 3. Comparison of incompatible element variations in representative Caledonian diorites from the Kilmelford (K114; Halliday *et al.* 1984) and Etive (E022; Brown 1975) complexes in the Scottish Highlands with N-type m.o.r.b. (Sun 1980), a typical calc-alkaline island arc basalt (Sun 1980), and the average south-west Highlands 'Old Red Sandstone' andesitic lava (Thirlwall 1982).

Trace-element variations within the B.C.G. reveal more substantial differences. Figure 2 is a plot of various incompatible trace elements normalized to chondrite abundance following the procedure of Sun *et al.* (1979). The examples shown in figure 2 have been taken from a data base of nearly 500 analyses from all the major Caledonian intrusions in Scotland and Northern England. The plutons have been sampled as representatively as possible on the basis of available petrologic information, and it is considered that all principal phases of the major Caledonian intrusions have been analysed. A window of 65 ± 2% $SiO_2$ content has been used as the basis for comparison in figure 2 so as to compare only relatively primitive granitoids which have not been greatly affected by fractional crystallization and yet include a substantial number of intrusions from a wide geographic area.

These results are summarized in table 2. The majority of the 'younger' intrusions fall within a narrow band which is well represented by the mean trends shown in figure 2. The most notable features of the trace-element comparisons shown in figure 2 are large differences seen in Sr, Ba, Rb, La, Ce, and Th. The 'younger' Granitoids of the orthotectonic Caledonides are markedly enriched in Sr, Ba, and the l.r.e.e. but depleted in Rb and Th compared with those of the paratectonic Caledonides. All three groups exhibit very similar patterns for the high-field-strength elements Nb, Zb, P, and Ti. The l.r.e.e.-like element Y is similar for both granitoid groups north of the Solway–Shannon Line, but significantly enriched in those in Northern England, whereas these same English granitoids are severely depleted in Sr and enriched in Rb relative to their counterparts in Scotland.

TABLE 2. MEAN VALUES FOR SELECTED TRACE ELEMENTS FOR ALL SAMPLES WITH $SiO_2$ IN THE RANGE 63–67 % IN A COMPILATION OF 500 ANALYSES FOR THE 'YOUNGER' BRITISH CALEDONIAN GRANITOIDS

| element (μg/g) | Scottish Highlands | Scottish Midland Valley and Southern Uplands | Northern England |
|---|---|---|---|
| Rb | 78 | 122 | 175 |
| Th | 7 | 19 | 15 |
| Ba | 1490 | 845 | 795 |
| La | 60 | 30 | 30 |
| Ce | 100 | 57 | 99 |
| Sr | 1161 | 548 | 232 |
| Nb | 17 | 12 | 17 |
| Zr | 202 | 214 | 206 |
| P (%) | 0.22 | 0.20 | 0.19 |
| Y | 17 | 20 | 42 |
| Ti (%) | 0.63 | 0.69 | 0.50 |

Gill (1974) and Hawkesworth *et al.* (1979), among others, have called attention to the fact that magmas generated in destructive plate margin environments are enriched in elements with low ionic potential (the l.i.l. elements) relative to those of high ionic potential (the rare-earth and high-field-strength h.f.s. elements) when compared with magmas of equivalent bulk chemistry from the mid-ocean ridges or continental rift environments. This feature is thought to reflect a subduction-zone component in the magmas produced by selective enrichment of their mantle source region by aqueous fluids derived from dehydration of oceanic crust during subduction. Mantle-normalized plots of incompatible element abundances in the most mafic portions of the 'younger' B.C.G. composite and zoned intrusions are shown in figure 3. The Sr-, K-, and Ba- rich nature of these low-$SiO_2$ end-members is well illustrated. Also, the incompatible-element patterns for these two samples are coincident with that for the Southwest Highlands 'Old Red Sandstone' andesitic lavas. These lavas are temporally and spatially related to the B.C.G. in the Southwest Highlands and considered by Thirlwall (1981) to be derived from a mantle source similar to that giving rise to andesitic lavas in modern island arcs. Therefore, figure 3 implies that a similar mantle source may likely have played a predominant role in the generation of the more mafic of the 'younger' B.C.G. magmas.

The high Sr and Ba contents of the 'younger' granitoids of the Scottish Highlands are anomalous by comparison with the B.C.G. as a whole, the enrichment being approximately twice that observed in the Southern Uplands intrusions (figure 2). Except for the plutons in the Northeast Highlands, this enrichment is persistent throughout the compositional range of the Scottish Highlands granitoids on diagrams similar to figure 2 for small intervals from 55–75 % $SiO_2$. Therefore, this feature is most likely to be a characteristic imposed upon the 'younger' granitoids of the Scottish Highlands by the magma source region rather than a manifestation of fractional crystallization processes. Also, the differences in overall trace element composition of the B.C.G. illustrated in figure 2 indicate that the source region(s) for the 'younger' granitoids of the Scottish Highlands is compositionally distinct from that for the Southern Uplands granitoids, and that both are distinct from the source region for the Northern England granitoids.

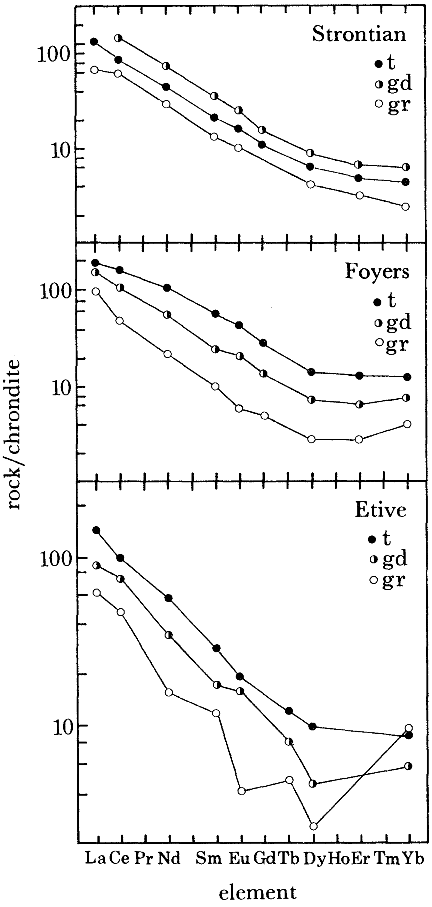


FIGURE 4. Representative chondrite-normalized rare earth element abundances for the Strontian, Foyers, and Etive intrusions of the Scottish Highlands (after Pankhurst 1979; and Pankhurst, unpublished data).

Halliday & Stephens (1983) have shown that the high Sr and Ba contents of the 'younger' granitoids of the Scottish Highlands are also anomalous when compared with other granitoid provinces (e.g. Southeastern Australia). This unique feature, if persistent along strike to the north in East Greenland and Scandinavia or to the west in North America, should be recognizable and provide a means for distinguishing the unusual source regions from which the high-Sr and high-Ba magmas were derived. Indeed, the continuity of this chemical province across the Grampian and Northwest Highlands is strong evidence against the ideas of Piper (1974) and

TABLE 3. SUMMARY OF AGES, RANGES AND MEAN VALUES OF O-, Sr-, Nd-, AND Pb-ISOTOPE RATIOS FOR BRITISH CALEDONIAN GRANITOIDS†

(The upper and lower line correspond to the range and mean respectively.)

| location | age/Ma | $\delta^{18}O$ (‰ s.m.o.w.) | $\left(\frac{^{87}Sr}{^{86}Sr}\right)_i$ | $\left(\frac{^{143}Nd}{^{144}Nd}\right)_i$ | $\frac{^{206}Pb}{^{204}Pb}$ | $\frac{^{207}Pb}{^{204}Pb}$ | $\frac{^{208}Pb}{^{204}Pb}$ |
|---|---|---|---|---|---|---|---|
| Scottish Highlands | 514–400 | 7.1–14.4 | 0.7035–0.7190 | 0.51214–0.51144 | 16.51–18.10 | 15.28–15.53 | 36.21–37.70 |
| | | 9.3 | 0.7072 | 0.51183 | 17.35 | 15.44 | 37.63 |
| ‘older’ granitoids | 514–443 | 8.0–12.1 | 0.7106–0.7190 | 0.51169–0.51142 | | | |
| | | 10.0 | 0.7169 | 0.51151 | 17.76 | 15.42 | 37.63 |
| ‘younger’ granitoids | 435–400 | 7.1–14.4 | 0.7035–0.7174 | 0.51214–0.51146 | 16.51–18.10 | 15.28–15.49 | 36.21–37.70 |
| | | 9.2 | 0.7067 | 0.51186 | 17.35 | 15.44 | 36.91 |
| NE Highlands | 413–*ca.* 400 | 9.0–11.0 | 0.7057–(0.718) | — | 17.96 | 15.46 | 37.60 |
| | | 9.8 | 0.7147 | | | | |
| C Highlands | 439–404 | 7.5–10.3 | 0.7044–0.7174 | 0.51181–0.51146 | 16.51–18.10 | 15.28–15.33 | 36.21–37.70 |
| | | 9.1 | 0.7075 | 0.51166 | 17.48 | 15.49 | 37.10 |
| SW Highlands | 410–400 | 7.2–10.7 | 0.7035–0.7074 | 0.51214–0.51162 | 16.71–17.81 | 15.31–15.49 | 36.28–37.64 |
| | | 8.9 | 0.7047 | 0.51193 | 17.15 | 15.39 | 36.65 |
| NW Highlands | 435–*ca.* 400 | 7.1–14.4 | 0.7048–0.7066 | 0.51210–0.51144 | 16.97–17.97 | 15.29–11.45 | 36.46–37.47 |
| | | 9.9 | 0.7059 | 0.51188 | 17.47 | 15.37 | 37.00 |
| Scottish Midland Valley and Southern Uplands | 408–390 | 7.8–11.9 | 0.7041–0.7109 | 0.51220–0.51197 | 17.91–18.35 | 15.46–15.58 | 37.55–38.09 |
| | | 10.1 | 0.7062 | 0.51205 | 18.15 | 15.54 | 37.86 |
| Northern England | 461–392 | 9.0–13.0 | 0.7055–0.7099 | 0.51203–0.51182 | | | |
| | | 10.7 | 0.7077 | 0.51193 | 18.27 | 15.65 | 38.23 |

† Data from this study and Clayburn *et al.* (1983), Halliday (1983), Hampton & Taylor (1983), Harmon (1983), van Breemen & Piasecki (1983), Clayburn (1981), Shepherd & Darbyshire (1981), Halliday *et al.* (1980), Hamilton *et al.* (1980), Harmon & Halliday (1980), Blaxland *et al.* (1979), Halliday *et al.* (1979), Pankhurst (1979), Pankhurst & Pidgeon (1976), Wadge *et al.* (1974), Pankhurst (1970), G. Davies (personal communication), R. Pankhurst (personal communication), Halliday *et al.* (1984).

van der Voo & Scotese (1981) that the Northwest Highlands might represent an 'exotic' terrain thrust into its present position by more than 2000 km of transcurrent sinistral movement along the Great Glen Fault (Halliday & Stephens 1983).

It is not clear at present whether the source for the Sr- and Ba-enriched magmas of the Scottish Highlands was the crust or the mantle. This feature does not persist to very low $SiO_2$ contents in the range of 45–55% $SiO_2$ except for Ratagain-Glenelg, Kilmelford, and the Quarry diorite phase of the Etive complex, suggesting that it is of crustal origin. However, Noble *et al.* (1975) have attributed similar strong Sr- and Ba-enrichments to mantle processes.

Rare-earth data are useful in this context, but are extremely limited. Pankhurst (1979) has shown that the 'younger' B.C.G. of the Scottish Highlands are characterized by l.r.e.e. enrichment with relatively constant Ce/Yb ratios, which are enriched by a factor of 2–3 over calc-alkaline magmas from modern destructive plate margin environments (Thorpe & Francis 1979). It is clear from figure 4 that individual intrusive centres are characterized by distinct r.e.e. patterns which reflect their different histories. The lack of a major Eu anomaly in the more mafic phases of the Etive, Strontian, and Foyers complexes indicates that the source region, be it mantle or crust, must have been feldspar-free, or had a very high oxygen fugacity, thus providing a mechanism for producing the extremely high Sr and Ba contents observed in these intrusions (Halliday & Stephens 1983). The fact that a significant Eu anomaly is only observed in only the low-Sr Meall Odhar member of the Etive complex, the evolved chemical character of which Brown (1975) and Clayburn *et al.* (1983) attribute to low-pressure fractional crystallization of plagioclase and biotite, indicates that other low-Sr intrusions such as Cairngorm, Lochnagar, and Hill of Fare have likely been derived through similar differentiation processes as suggested by Halliday (1981). There is, therefore, no chemical argument for attributing the slightly different geochemical character to these granitoids to a distinct source region as advocated by Brown (1979) or Brown & Locke (1979), and Plant *et al.* (1980).

## Isotope geochemistry

Table 3 presents a summary of stable and radiogenic isotope variations for the B.C.G. from the literature and some of our unpublished data. In a majority of cases, stable and radiogenic isotope measurements have been made on the same samples, thus providing an internally consistent set of data upon which to base the observations and speculations which follow. Many more O- and Sr-isotope analyses have been made than have Nd- and Pb- isotope analyses. Therefore, the data points shown in some of the figures that follow do not necessarily correspond to the full ranges for these isotopic parameters summarized in table 3. Note, at the outset, the extremely large ranges recorded for individual isotope parameters across the British Caledonides as a whole: $\delta^{18}O = 7.1$ to 14.4‰, respective initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios $= 0.7035$ to 0.7190 and 0.51144 to 0.51214, and respective age-corrected $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios $=$ 16.51 to 18.35, 15.28 to 15.65, and 36.21 to 38.23. The lower portion of the O- and Sr- isotope ranges for the B.C.G. just overlaps that of mantle-derived granitoids in oceanic island-arc areas where continental crust is absent, such as the Koloula Igneous Complex of Guadalcanal which Chivas *et al.* (1982) consider to be entirely mantle derived. The highest O- and Sr- isotope values observed for the Caledonian granitoids are typical of granites attributed to anatexis of old, radiogenic upper crust, such as the Hercynian granites of western Europe (Albarède *et al.* 1980; Michard-Vitrac *et al.* 1980; Sheppard 1977). The overall range of

O- isotope ratios for the B.C.G. (7.1 to 14.4‰) is much larger than, and totally encompasses, that for the Lower Palaeozoic granitoids of the Lachlan Fold Belt of Southeastern Australia (8.6 to 11.6‰) documented by O'Neil & Chappell (1977), whereas the initial Sr-isotope ratios and Nd-isotopic compositions of the B.C.G. ($Sr_i = 0.7035$ to $0.7190$; $\epsilon_{Nd} = +0.4$ to $-11.3$) are essentially equivalent to those determined by McCulloch & Chappell (1982) for the Australian granitoids ($Sr_i = 0.7045$ to $0.7184$; $\epsilon_{Nd} = +0.4$ to $-9.7$). This wide range in isotope composition suggests that both primary mantle or mafic lower crustal sources as well as metasedimentary upper crustal reservoirs have played an important role in the generation of the B.C.G.

It is also seen from table 3 that there are clear geographic differences in granitoid isotopic composition which are equivalent to those noted in table 2 for the 'younger' granitoids on the basis of trace element composition. Although the 'older' granitoids of the Scottish Highlands are isotopically distinct from the 'younger' granitoids, their number is so small that they do not significantly affect the provincial averages. Note that the 'younger' granitoids, which were intruded into the stabilized craton of the Scottish Highlands, have lower O-, initial Nd-, and Pb- isotope ratios than those emplaced into the thick accretionary prism of sediments at the continental margins. Also, there is a general tendency toward decreasing O-, initial Sr-, and Pb- isotope ratios, but increasing initial Nd- isotope ratios, from northeast to southwest across the orthotectonic Caledonides, a feature which contrasts sharply with the general north to south increase in all four isotopic parameters observed across the British Caledonides as a whole. This suggests that (i) pre-Caledonian, high-grade metamorphic crust was an important component in the petrogenesis of the granitoids in the Scottish Highlands, whereas immature geosynclinal sediments were the primary crustal component to the intrusions of the paratectonic Caledonides, and (ii) there was a difference either in the composition of the primary magma source region or in the extent of crustal involvement of magmas derived from the same source region from northeast to southwest across the Scottish Highlands.

The isotopic trends observed in table 3 for the B.C.G. are consistent with the observation of Pidgeon & Aftalion (1978), that many of the granitoids north of the Highland Border Fault Zone contain zircons with a component of inherited Pb, whereas those to the south do not. The zircon data emphasize the considerable involvement of pre-Caledonian crust in the generation of the granitoid magmas of the Scottish Highlands and Lower Palaeozoic crust in those of the Paratectonic Caledonides, but do not alone determine the nature of that involvement nor do they rule out a juvenile mantle component to the magmas. It is clear, however, that the extensive set of B.C.G. isotopic data in table 3, especially when considered on an individual pluton basis, do not indicate any correlation between distance from the Iapetus suture (Shannon–Solway Line in figure 1) and initial $^{87}Sr/^{86}Sr$ ratio (Brown & Hennessy 1978) or Pb-isotope ratios (van Breemen & Bluck 1981; Blaxland *et al.* 1979).

## DISCUSSION

Consideration of multi-isotope variations in unaltered igneous rocks provides powerful insight into both magma origin and subsequent evolution. The various radiogenic isotope systems will be influenced by the degree to which the individual parent–daughter elements have been fractionated in the source region, the age of the source, and the degree to which a magma produced within any particular source region has interacted with reservoirs of differing chemical and isotopic composition before final emplacement, crystallization, and cooling. For example the Sr- isotopic composition of a magma derived from a high-Sr source region will be dominated almost entirely by that particular source characteristic throughout its history, provided Sr is partitioned into the melt or a considerable amount of restite is carried with the melt, despite what may be significant contamination by a low-Sr reservoir of much different Sr-isotopic composition. By contrast, the Pb- isotopic composition of that same magma may be totally dominated by the contaminant if it happens to be strongly enriched in Pb relative to the source region.

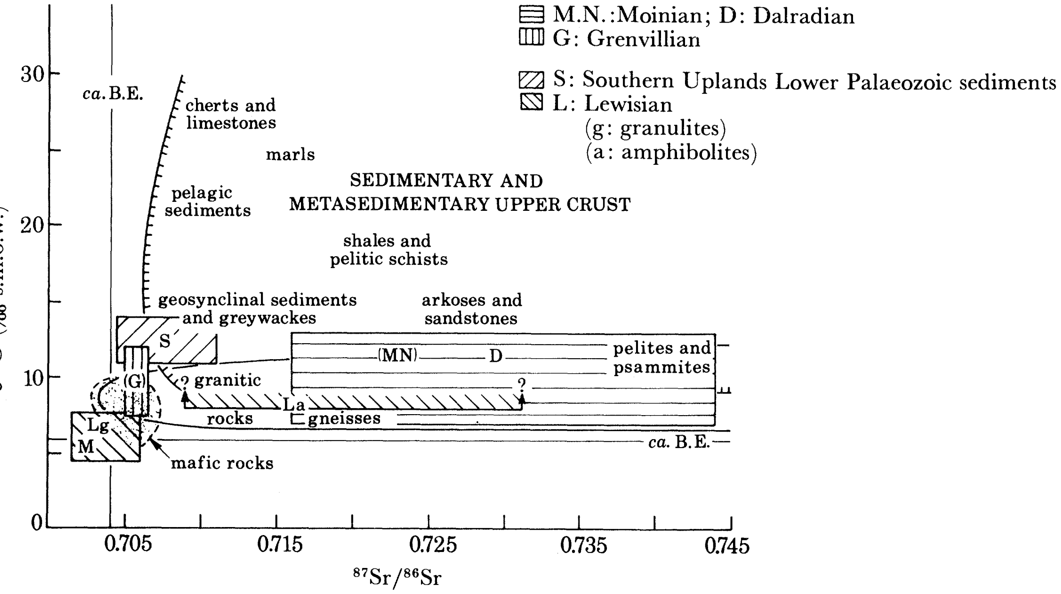


Figure 5. Schematic diagram of generalized O- and Sr-isotope variations in some terrestrial rocks (modified from Taylor 1980). Also shown are the range of isotopic compositions (rectangular fields) observed at 400 Ma for the various reservoirs which might have contributed to the petrogenesis of the British Caledonian Granitoids (data from Clayburn 1981, and references cited therein; Graham, personal communication; Halliday *et al.* 1980; Harmon 1983; Kay 1980; Krogh & Hurley 1968; and Shieh & Schwarcz 1982). The bold letters denote the mean value for each reservoir. The Grenvillian data are for the 1200 Ma 'Grenville Province' in Canada and the Moinian O-isotope value is inferred from Dalradian metasediments of equivalent metamorphic grade. M: m.o.r.b. type mantle; B.E.: bulk Earth.

The O-isotopic composition of an igneous rock is dependent largely on whether or not the source region or contaminant(s) have been through a cycle of crustal residence at one or more times in its history. Sedimentary rocks and their metamorphic counterparts are substantially enriched in $^{18}O$ relative to primary igneous material appearing at the Earth's surface for the first time because they contain large proportions of constituent components formed during low-temperature surficial processes such as weathering, chemical sedimentation, and diagenesis (Savin & Epstein 1970). However, there is a tendency for $^{18}O/^{16}O$ ratios to decrease during prograde metamorphism from $\delta^{18}O \approx 16$ to 20‰ for low-grade rocks to values of about 8‰ for very high grade rocks (Shieh & Schwarcz 1974; Harmon 1983). This feature is well illustrated for the upper crustal sediments and metamorphic rocks of the British Caledonides (figure 5). Dalradian rocks are observed to have an O-isotope character typical of low–intermediate grade metasedimentary upper crust and exhibit a systematic decrease in $^{18}O/^{16}O$ ratio from greenschists and pelites of the Knapdale area of the Southwest Highlands to the high-grade gneisses

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of Aberdeenshire in the Northwest Highlands (Kay 1980; Graham, personal communication; Harmon, unpublished data). By contrast, the greywackes of the Lower Palaeozoic accretionary prism in the Southern Uplands have the O-isotope composition expected of immature geosynclinal sediments (Halliday *et al.* 1980). Archaean granulites of the Lewisian Foreland in northwestern Scotland are significantly $^{18}$O-depleted relative to amphibolite-facies rocks of the same age (Harmon 1983).

It is therefore possible to infer the source region for a pristine plutonic rock based upon its stable and radiogenic isotopic composition because the mantle and various crustal reservoirs can generally be discriminated on multi-isotope diagrams such as figure 5. Also, one can, in certain instances, use theoretical mixing models to identify whether or not a magma was emplaced as an uncontaminated, partial melt isotopically representative of its source region, as a hybrid magma affected by bulk mixing processes, or as a magma whose composition had been highly altered by assimilation-fractional crystallization processes (Taylor 1980; James 1981).

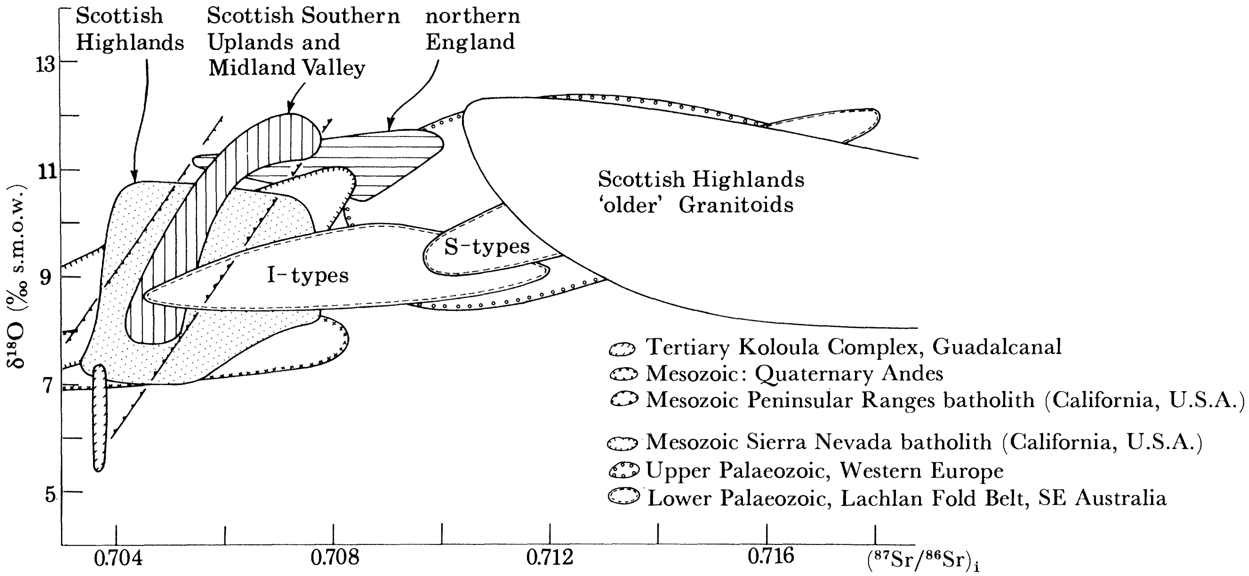


FIGURE 6. Plot of $\delta^{18}O$ against $(^{87}Sr/^{86}Sr)_i$ for the British Caledonian granitoids subdivided according to the primary geographic groupings in table 2. Also shown are the $\delta^{18}O$–$(^{87}Sr/^{86}Sr)_i$ fields for the Lower Palaeozoic Berridale and Kosciusko Batholiths of the Lachlan Fold Belt of southeastern Australia (O'Neil & Chappell 1977; McCulloch & Chappell 1982), the Hercynian Fold Belt of western Europe (Albarède *et al.* 1980; Michard-Vitrac *et al.* 1980), the Mesozoic Peninsular Ranges and Sierra Nevada Batholiths of the western United States (Kistler & Peterman 1973; Silver & Taylor 1978; DePaolo 1981; Masi *et al.* 1981), Mesozoic–Quaternary plutonic rocks of the central Andes (Longstaffe *et al.* 1983) and the Tertiary Koloula Igneous Complex, Guadalcanal (Chivas *et al.* 1982).

As illustrated in figure 5 for the O–Sr system, the mantle and different crustal reservoirs which may have produced or interacted with B.C.G. magmas are largely distinct isotopically in terms of their O–Sr characteristics. For example, the isotopic composition of granitoids produced by the contamination of a mafic melt produced in the mantle or lower crust would follow different evolutionary paths if intruded into the Precambrian Moinian or Dalradian metamorphic upper crust of the Scottish Highlands north of the Highland Border Fault Zone than if emplaced into the Lower Palaelozoic sedimentary crust of the Southern Uplands to the south. Therefore, arrays of data for individual intrusions on multi-isotope diagrams, such as figure 5, provide a useful guide to magma origin and subsequent evolution before crystallization and cooling.

The O–Sr isotopic data for the B.C.G. are compared with those for other granitoid provinces in figure 6. The 'older' granites of the Scottish Highlands define an isolated field, distinct from those for the 'younger' granitoids (except the Strathspey vein complex) by virtue of their high (over 0.710) initial Sr-isotope ratios. This field overlies that for the Australian S-type granites and the Hercynian granites of western Europe, supporting the prevailing view that these plutons were produced from the partial melting of local metasedimentary upper crust (see, for example, Pankhurst 1979; Harmon 1983). The 'younger' granitoids lie in three fields in figure 6, the array for the Southern Uplands overlapping those for the Scottish Highlands and Northern England which are otherwise separated. The overall field for the 'younger' B.C.G. is similar to, but not entirely coincident with, those bserved for calc-alkaline granitoids in destructive plate margin environments such as the Cordillera of the western Americas (Kistler & Peterman 1973; McNutt *et al.* 1975; Taylor & Silver 1978; Masi *et al.* 1981; Longstaffe *et al.* 1983). There

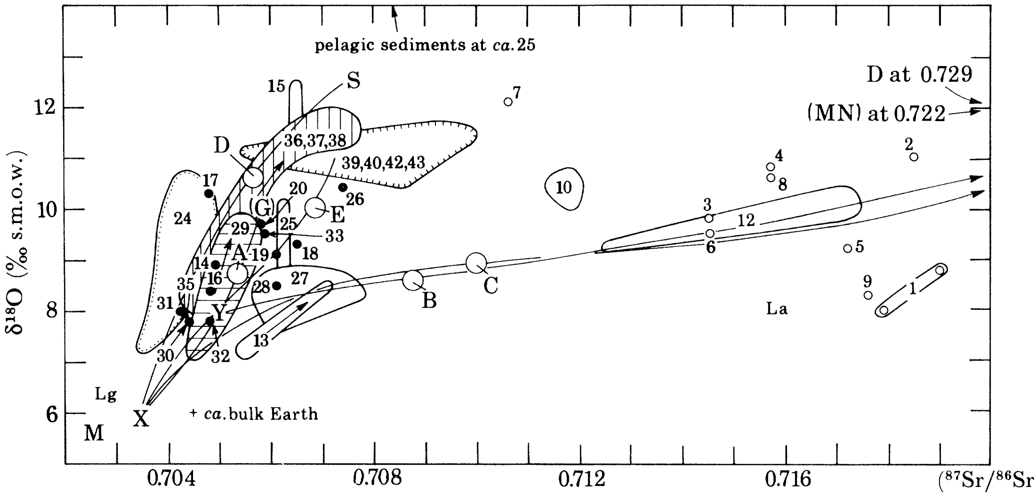


FIGURE 7. Plot of $\delta^{18}O$ against $(^{87}Sr/^{86}Sr)_i$ for the British Caledonian granitoids (as numbered in table 1). Also shown are the average isotopic compositions at 400 Ma of the mantle and the various crustal reservoirs (as designated in figure 5) which might have contributed to granitoid petrogenesis. The five curves shown illustrate a few of the possible evolutionary paths followed by a primary magma (×) which interacts with one or another of the crustal reservoirs. Curve A illustrates the contamination of × by bulk mixing with Middle Proterozoic (Grenvillian) lower crust (G) with $\delta^{18}O \approx 10‰$, $^{87}Sr/^{86}Sr \approx 0.7058$, and an $Sr_x$ to $Sr_G$ ratio of 1:2. Curve B shows the path followed a two-stage evolution where the bulk mixing of × and G produce a magma if intermediate composition Y, which is subsequently modified by combined fractional crystallization-assimilation of late Proterozoic (Dalradian) upper crust (D) with $\delta^{18}O \approx 12‰$, $^{87}Sr/^{86}Sr \approx 0.729$, and an $Sr_x$ to $Sr_D$ ratio of 2:1 for a weight proportion of assimilate to cumulate of 1:5. A slightly higher $\delta^{18}O$ value than the Dalradian average of 10‰ was chosen for the modelling because a partial melt derived from these very heterogeneous metasediments would likely be enriched in the $\delta^{18}O$-rich felsic component which would be the first to melt. The curve C illustrates the contamination by an a.f.c.-process of x with Dalradian upper crust for $Sr_x$ to $Sr_D$ ratio of 5:1 and a weight proportion assimilate of 1:5. The evolutionary path produced by a.f.c.-contamination with Mid-Proterozoic (Moinian) metasedimentary upper crust (MN) would be essentially the same as that of curve C because of their similar O-isotope compositions and Sr-contents despite the slight difference in their Sr-isotopic compositions. The curve D represents the array produced by the bulk contamination (i.e. magma mixing) of x with melts derived from the Southern Uplands Lower Paleozoic sediments (S) with $\delta^{18}O \approx 12.5‰$, $^{87}Sr/^{86}Sr \approx 0.7075$, and an $Sr_x$ to $Sr_D$ ratio of 2:1. Finally, the curve E illustrates the contamination of x by S through an a.f.c.-process with a $Sr_x$ to $Sr_S$ ratio of 2:1 and a weight proportion of assimilate to cumulate of 1:5. 'Older granites': ○, Scottish Highlands; 'younger granites': ●, Scottish Highlands; ▲, Southern Uplands and Midland Valley; ■, Northern England.

is a general trend for $\delta^{18}O$ values and $(^{87}Sr/^{86}Sr)_i$ ratios for the B.C.G. to be positively correlated, although the degree and slope of the correlation is not the same within individual intrusions or intrusive complexes, nor is the regional O–Sr correlation as well defined as it is for the Mesozoic Sierra Nevada and Peninsular Ranges batholiths in the western United States (Taylor & Silver 1978; Masi *et al.* 1981).

Figure 7 displays O–Sr isotopic relations for individual intrusive centres or geographically related groups of intrusions. The arrows shown within the different arrays denote the O–Sr trends from most mafic to most felsic compositions within individual intrusive centres. Also shown are average values representing our best estimates, of the O–Sr isotopic composition at 400 Ma of bulk earth, m.o.r.b.-type depleted mantle, and the various crustal reservoirs that may possibly have participated in B.C.G. petrogenesis. The substantial O-isotope variations and correlated O–Sr isotopic behaviour observed for most of the 'younger' granitoids for which there are multiple analyses – e.g. Kilmelford (24), Etive (29), or the Southern Uplands intrusions Doon (36), Criffell (37), and Fleet (38) – effectively precludes a derivation solely by differential partial melting of a single homogeneous source or a derivation from the differentiation of an isotopically homogeneous magma prior to emplacement and cooling. Rather, multiple sources are implied.

Although the O- and Sr-isotope relations for the 'younger' granites of Northern England, such as Eskdale (40) and Shap (42), and the 'older' granites of the Scottish Highlands, suggest that these intrusions were derived from an isotopically heterogeneous crustal source, this certainly is not the case for the 'younger' granitoids of the Southern Uplands and Midland Valley or the Scottish Highlands. An origin solely by crustal anatexis is not likely to produce the well developed and compositionally related O–Sr isotope correlations that are a typical feature of the 'younger' intrusive complexes in these regions. In most instances, the O–Sr data define sub-linear arrays of positive slope in figure 7 which trend away from the field expected for contemporary mantle or young mafic lower crust towards the upper right portion of the diagram. The different slopes defined by the arrays indicate a different high-$^{18}O$, high-$^{87}Sr$ component in each case.

Theoretical modelling by James (1981) has demonstrated that source contamination, such as that produced by mantle metasomatism (Hawkesworth *et al.* 1979; Menzies *et al.* 1983) or magma mixing (Eichelberger 1978) are two-component mixing processes which produce linear or hyperbolic arrays on stable-radiogenic isotope diagrams such as figure 7. By contrast, the phenomenon of combined fractional crystallization-assimilation (a.f.c.) is a three component process which produces S-shaped mixing curves on such diagrams which, for much of their path, may not directly extrapolate to the source or contaminent composition (Taylor 1980; James 1981). Therefore stable-radiogenic isotope arrays resulting from a.f.c.-processes may be subvertical, inclined with a positive slope, or sub-horizontal depending on the extent to which a primary melt has been contaminated and the initial differences in isotopic and chemical composition between the two end-members. The five curves (A–E) shown in figure 7 illustrate a few of the evolutionary paths which might possibly be invoked to explain the one or another of the O–Sr arrays observed for the B.C.G. In each case the primary low-$^{18}O$, low-$^{87}Sr$ end-member (X) is considered to have an initial composition of $\delta^{18}O = 6‰$ and $(^{87}Sr/^{86}Sr)_i = 0.7035$. The compositions of the different crustal reservoirs are indicated by the bold letters in figure 7.

From figure 7 we can draw the following, tentative conclusions which will be examined in the sections which follow by consideration of the Nd- and Pb-isotope data as well.

(i) The Southern Uplands granitoids (36–38) were generated, as envisaged by Halliday *et al.* (1980), largely by the bulk mixing of crustal melts produced within the relatively non-radiogenic, immature geosynclinal-type sediments with a primary mafic magma derived from a mantle source region. Subduction processes alone, as suggested by Thirlwall (1982) for the temporally related Old Red Sandstone lavas of the Midland Valley, cannot produce the high $\delta^{18}O$ values observed in the more felsic members of these intrusions. Mantle enrichment by the melting of subducted lower Palaeozoic sediments (S) could possibly produce the slightly $^{18}O$- and $^{87}Sr$-enriched character of the Doon (36) diorites and Distinkhorn (35) tonalite, with the more felsic granodiorites and granites of the Southern Uplands produced by the subsequent bulk upper crustal contamination of this hybrid mantle-derived magma by metasedimentary partial melts.

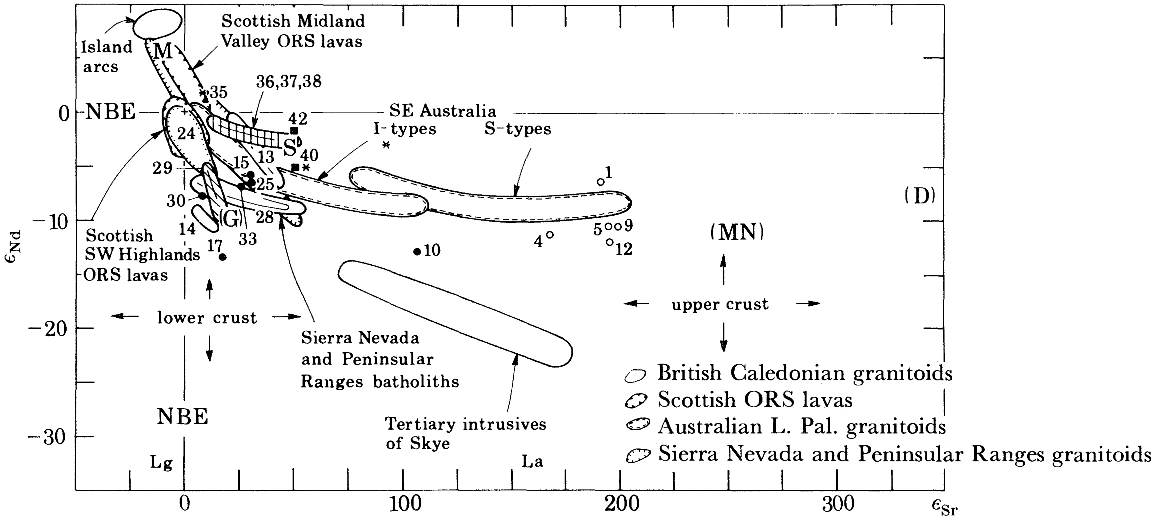


FIGURE 8. Initial Sr- and Nd-isotopic compositions of British Caledonian granitoids expressed in the $\epsilon$ notation of DePaolo & Wasserburg (1976). The notation is the same as in figure 5 and the symbols are the same as in figure 7. Also shown are the $\epsilon_{Sr}$–$\epsilon_{Nd}$ fields of the Scottish 'Old Red Sandstone' lavas of the southwestern Grampian Highlands and Midland Valley (Thirlwall 1982), the Tertiary intrusives of Skye (Carter *et al.* 1978); the I- and S-type granites of the Berridale and Kosciusko Batholiths in southwestern Australia (McCulloch & Chappell 1982), the Peninsular Ranges and Sierra Nevada Batholiths of the western United States (DePaolo 1981), modern island-arc volcanics (DePaolo & Wasserburg 1977), and the 'bulk Earth' reference point which is representative of undifferentiated mantle. The positions of depleted mantle and various crustal reservoirs at 400 Ma shown are estimated from Krogh & Hurley (1968), DePaolo & Wasserburg (1978), O'Nions *et al.* (1977), McCulloch & Wasserburg (1978), Hamilton *et al.* (1979), Halliday *et al.* (1980), Clayburn (1981) and references therein, McCulloch & Chappell (1982), and Halliday & Stephens (1983). The $\epsilon$ values were calculated from the initial Sr- and Nd- isotope ratios according to the definition of DePaolo & Wasserburg (1976) assuming bulk Earth at 400 Ma had $^{143}Nd/^{144}Nd = 0.51212$ and $^{87}Sr/^{86}Sr = 0.70402$.

(ii) The granitoids of Northern England (39–43), which are similar in isotopic character to the more granitic intrusions of the Southern Uplands, have an upper crustal origin involving the partial melting of compositionally heterogeneous sedimentary crust.

(iii) The 'older' granites of the Scottish Highlands were derived by local anatexis of the Late Proterozoic (D) crust in which they presently reside.

(iv) The 'younger' granitoids of the Scottish Highlands have a complex origin which, in individual cases, likely involved a juvenile mantle-derived component, the hypothesized

Middle Proterozoic (G) lower crust, and Middle and Late Proterozoic (MN and D) upper crust. For example, the Etive Complex (29) is best explained by the contamination of a mantle-derived magma by bulk mixing with melts derived from the partial melting of Middle Proterozoic (G) lower crust, followed by differentiation after emplacement into Late Proterozoic (D) upper crust which did not affect its isotopic composition (Clayburn *et al.* 1983). A similar origin, with differing proportions of the two components in individual cases, is envisaged for many of the other 'younger' granitoids of the Scottish Highlands such as the Corrieyairack vein complex (19), the Hill of Fare complex (20), the Ben Nevis complex (30), Ballachulish (31), Rannoch Moor (32), and Bonar Bridge (33) from the sparse data available. The mafic to intermediate xenoliths present in varying stages of digestion in some of the 'younger' intrusions may represent a restite component that was not melted during the partial melting of the lower crustal protolith. In the case of Strathspey (12) and Strath Ossian (23) a two-stage evolution involving the contamination of a hybrid magma, similar in composition to the Rannoch Moor tonalite (32), by an a.f.c.-process involving Late Proterozoic (D) upper crust appears most appropriate.

In figure 8 $\epsilon_{\mathrm{Nd}}$ is plotted against $\epsilon_{\mathrm{Sr}}$. Also shown are our best estimates of the Nd- and Sr-isotopic compositions at 400 Ma for the various crustal and subcrustal environments which may have contributed to B.C.G. petrogenesis.

In an $\epsilon_{\mathrm{Nd}}$–$\epsilon_{\mathrm{Sr}}$ diagram modern mantle-derived basalts define an anticorrelated trend (the 'mantle array') which extends from the upper left quadrant (above the depleted mantle (M) point in figure 8) passing through the 'bulk earth' reference point ($\epsilon_{\mathrm{Nd}} = 0$, $\epsilon_{\mathrm{Sr}} = 0$), and into the near margin of the lower right quadrant (DePaolo & Wasserburg 1976; O'Nions *et al.* 1977; Hoffman & White, 1982). Arc volcanics sometimes display a relative $^{87}$Sr-enrichment for a given value of $\epsilon_{\mathrm{Nd}}$, and thus are offset to the right of the mantle array (DePaolo & Wasserburg 1977). This feature is thought to reflect the effect of fluid transfer of l.i.l. elements from the downgoing oceanic slab to the overlying lithospheric mantle during subduction (Hawkesworth *et al.* 1979). Most crustal rocks and sediments have negative $\epsilon_{\mathrm{Nd}}$ and positive $\epsilon_{\mathrm{Sr}}$ values and, therefore, lie in the lower right quadrant in figure 8; the exact position determined by the degree to which their Rb/Sr and Sm/Nd ratios have been modified by crust-forming and weathering processes and their age. However, granulite facies metamorphic rocks may be Rb-depleted and hence, may with time, develop negative $\epsilon_{\mathrm{Sr}}$ values (Hamilton *et al.* 1979). Granitic rocks produced by simple mixing of mantle-derived melts with crustal materials will define a curved array on an $\epsilon_{\mathrm{Nd}}$–$\epsilon_{\mathrm{Sr}}$ diagram. The extent and degree of curvature of the array will depend on the mass ratio, the difference in $\epsilon_{\mathrm{Nd}}$ and $\epsilon_{\mathrm{Sr}}$, and the Sr and Nd contents of the two end-member components. Because the Sr/Nd ratio in sediments is less than that in most mantle-derived igneous rocks (McCulloch & Wasserburg 1978), $\epsilon_{\mathrm{Nd}}$–$\epsilon_{\mathrm{Sr}}$ mixing trends are characterized by convex-downward curvature. An excellent example of such a convex-downward trend has been documented by McCulloch & Chappell (1982). As illustrated in figure 8, the $\epsilon_{\mathrm{Nd}}$–$\epsilon_{\mathrm{Sr}}$ data for both I and S-type granites in southeastern Australia define curvilinear arrays which tend away from the depleted portion of the mantle array and extend far into the lower right quadrant, consistent with the idea of a derivation involving variable mixtures of young igneous and older metasedimentary sources.

The Sr- and Nd-isotope data shown in figure 8 for the B.C.G. are widely scattered in comparison to data for either the related Old Red Sandstone volcanics (Thirlwall 1982) or plutonic suites in other granite provinces such as the Lower Palaeozoic of southeastern Australia

(McCulloch & Chappell 1982) or the Mesozoic of the Sierra Nevada and Peninsular Ranges batholiths in the western United States (DePaolo 1981). The B.C.G. do, however, define reasonably distinct groups in figure 8 on the basis of age and tectonic setting.

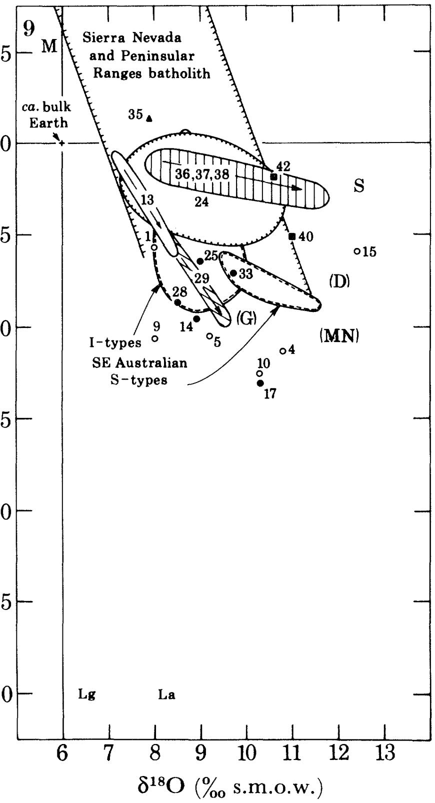
The 'older' granitoids (1–10) are characterized by initial $\epsilon_{Nd}$ values in the $-5$ to $-12$ range and initial $\epsilon_{Sr}$ values of greater than $+100$. These intrusions cluster around the most radiogenic portion of the Australian S-type array, reinforcing the idea that they were produced by upper crustal anatexis, the most likely source being the Late Proterozoic (D) metasediments which had a substantial crustal residence time before melting (O'Nions *et al.* 1983),

The 'younger' granitoids (11–34) of the Scottish Highlands, with the exception of Strathspey (12) which has an affinity to the 'older' granites and like them is a crustal melt, lie in the upper left hand portion in the SE quadrant in figure 8 with initial $\epsilon_{Nd}$ values of $+0.4$ to $-13.3$ and initial $\epsilon_{Sr}$ values of $-7$ to $+58$. As a group, they overlap the upper portion of the Australian I-type array and the lower portion of the Mesozoic Cordilleran granitoids but, except for Strontian (13), tend to have lower initial $\epsilon_{Nd}$ values for a given initial $\epsilon_{Sr}$ value than is observed in these other provinces. The 'younger' B.C.G. also exhibit a substantial isotopic diversity both within and among individual intrusive complexes. Note that for Strontian (13) and Etive (29) the evolutionary progression from mafic to felsic compositions is accompanied by a trend towards more radiogenic Sr-isotopic composition, whereas in the case of Foyers (28), the trend changes and reverses to less radiogenic character. The Kilmelford complex (24) is the only one of the 'younger' granitoids of the Scottish Highlands which extends into the NW quadrant in figure 8. The upper portion of the Kilmelford array largely overlaps the field for the *ca.* 410 Ma Old Red Sandstone (O.R.S.) lavas of the Southwest Highlands. Thirlwall (1982) considers these O.R.S. lavas, many of which have high contents of Sr and Ba similar to the 'younger' granitoids, to have been derived from a l.r.e.e. enriched mantle source. The exact nature of the genetically related Kilmelford diorites (24) and Etive Complex (29) is not so clear because of the unequivocal effects of crustal contamination.

The possible existence of an incompatible element-enriched mantle beneath the Scottish Highlands is not unexpected. Menzies & Murthy (1980) and Menzies *et al.* (1983) have presented evidence from kimberlite nodules and mantle xenocrysts which indicates that portions of the subcontinental mantle may have an Nd–Sr isotopic character akin to the less evolved portions of the continental crust. DePaolo (1981) has argued that such anomalous mantle may be restricted to old continental cratons where it can remain isolated from mantle convection and destructive plate margin processes for substantial periods of geologic time. A process which might possibly have produced an l.r.e.e.-enriched mantle beneath the Scottish Highlands is subduction during the Grenvillian Orogeny. Incompatible-element metasomatism of the lithospheric mantle wedge is a common process inferred for destructive plate margin environments at present (Hawkesworth *et al.* 1979). The Grenvillian was a time of major crustal accretion in other areas such as Scandinavia and North America, and it might be expected that l.r.e.e. enrichment of the upper mantle near the Archaean continental margin may have resulted from subduction processes during this orogenic event.

The trend of the Etive complex (29) away from the field for the Southwest Highlands O.R.S. lavas and Kilmelford (24) array toward substantially less radiogenic Nd-isotopic compositions with the change from dioritic to granitic compositions within the intrusive centre is indicative of contamination by a low $^{87}$Sr continental crust. Clayburn *et al.* (1983) have argued, on the basis of combined O–Sr–Pb isotope relations that the crustal contaminant was Middle Proterozoic (G) lower crust introduced into a mantle-derived melt by bulk mixing before emplacement within the upper crust. They also considered that the Etive magmas were unaffected by interaction with the Late Proterozoic (D) upper crust through which they passed. The trend of the Etive array in figure 8 is consistent with this view. The Sr–Nd isotope relations for the Foyers intrusion (28) present a striking contrast to those for the Etive complex. From figure 8 it is clear that the Foyers magmas may have interacted extensively with both Middle Proterozoic lower (G) and upper (MN) crust. However, it is the Foyers granodiorites which are the most contaminated by upper crustal assimilation and not the granites, which contain less radiogenic Sr and more radiogenic Nd than that in either the tonalite or granodiorite. The other 'younger' granitoid intrusions which lie near the Foyers tonalites and granites in figure 8, e.g. Cairngorm (25), Ben Nevis (30) and Bonar Bridge (33), are likewise dominated by a source region with moderate Sr-isotope ratio (initial $\epsilon_{\mathrm{Sr}} \approx +5$ to $+30$), but relatively low Nd-isotope ratio (initial $\epsilon_{\mathrm{Nd}} \approx -6$ to $-8$). The Strontian complex (13) is distinct in figure 8 from the other 'younger' granitoids of the Scottish Highlands: it appears to have been derived from a mantle source region whose isotopic composition may have been modified by l.i.l.-element enrichment before melting. The shift in Sr- and Nd- isotopic character from mafic to felsic compositions at Strontian can be explained by an a.f.c.-process involving a small degree of interaction with Middle Proterozoic (MN) metasediment during magma transit through the uppercrust. The Ratagain complex (17) has the lowest initial Nd-isotope ratio of any granitoid within the British Caledonides. Its position in figure 8 suggests that there was a component of Archaean granulite to the Ratagain magmas, a feature that is not surprising given the location of this intrusive complex only some 20 km away from the exposed Archaean terrain of the Lewisian Foreland in the Northwest Highlands (figure 1). The complete separation of the fields for the 'younger' B.C.G. of the Scottish Highlands and the Tertiary intrusives of Northwest Scotland, which Carter *et al.* (1978) have demonstrated contain a major component derived from Lewisian amphibolite facies lower crust, implies that this source did not play as significant a role in B.C.G. magmatism.

The 'younger' granitoids south of the Highland Border Fracture Zone in the paratectonic Caledonides are, in contrast to their counterparts to the north in the Scottish Highlands, quite restricted in their Nd- and Sr-isotopic compositions. The Distinkhorn tonalite (35) in the Midland Valley has the highest initial Nd-isotope ratio measured for any Caledonian granitoid and lies in the lower left hand portion of the NE quadrant in figure 8, just above the Southern Uplands array. Distinkhorn falls within the field for the Midland Valley O.R.S. lavas of equivalent age considered by Thirlwall (1982) to have originated in a l.r.e.e.-depleted mantle source region which had been modified during subduction by partial melts derived from altered and sediment-contaminated oceanic lithosphere. The three Southern Uplands intrusions – Doon (36), Criffell (37), and Fleet (38) – define a slightly convex downward array which emerges from the upper, least radiogenic portion of the Australian I-type field in the upper left hand portion of the SE quadrant in figure 8 and extends sub-horizontally from the right of the mantle array, towards the area of the diagram occupied by the Southern Uplands Lower Palaeozoic sediments (S). These sediments, whose range in isotopic composition is shown by the asterisks in figure 8, are a series of imbricated, thrust-bound units which individually exhibit upward transgressive sequences from spilitized basalts, through radiolarian cherts and pelagic clays, to compositionally diverse greywackes (Leggett *et al.* 1979). Because the sediments are composed of clastic sediments transported from the Precambrian upper crust of the orthotectonic Caledonides to the north as well as Lower Palaeozoic arc volcanics of the paratectonic Caledonides, they represent a mixture of contemporary mantle and average upper continental crust at *ca.* 400 Ma. Halliday *et al.* (1979) observed that the Sr-isotope ratios of the Southern Uplands plutons were too low for them to have been simple upper crustal partial melts. Subsequently, Halliday *et al.* (1980) argued on the basis of Sr–O isotope relations that these zoned intrusions were derived by the incomplete mixing of mantle or young lower crustal mafic melts with melts derived from the metasediments. The combined Nd–Sr data endorse this view. However, as noted previously, the high $\delta^{18}$O values (more than 10‰) for the Southern Uplands biotite and two-mica granites effectively preclude an origin solely by the differentiation of mantle-derived magmas which had been contaminated at source by melts of subducted sediment similar in composition to the Southern Uplands Lower Palaeozoic sediments.



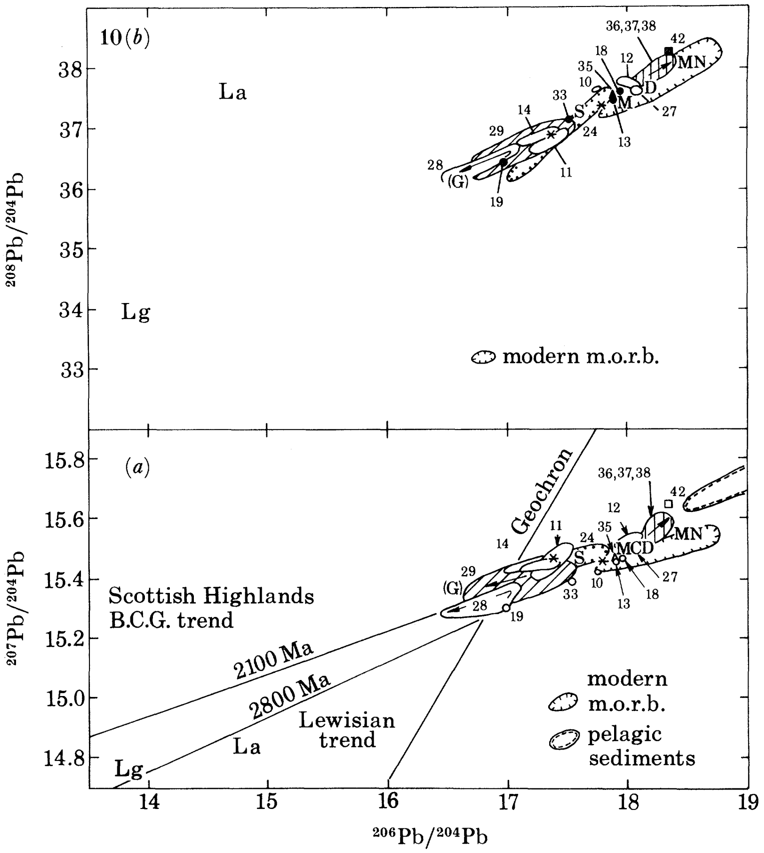


FIGURE 9. Plot of initial Nd-isotopic compositions against $\delta^{18}$O values for the British Caledonian granitoids. The notation and symbols are the same as in figure 8. Also shown are the $\epsilon_{\mathrm{Nd}}$–$\delta^{18}$O fields for the southeastern Australia granites (O'Neil & Chappell 1977; McCulloch & Chappell 1982) and Peninsular Ranges and Sierra Nevada Batholiths (Taylor & Silver 1978; DePaolo 1981; Masi *et al.* 1981). The positions of the various crustal reservoirs at 400 Ma shown are estimated from the references cited in figures 7 and 8.

FIGURE 10. Plot of Pb-isotope compositions of British Caledonian granitoids. The notation and symbols are the same as in figure 8. Also shown are the fields for m.o.r.b. (Cohen *et al.* 1980; Sun 1980) and pelagic sediments (Meijer 1976; Sun 1980). The position of the mantle and the various crustal reservoirs at 400 Ma are estimated from Moorbath *et al.* (1969), Chapman & Moorbath (1977), Clayburn (1981) and the references therein, Fletcher & Farquhar (1982), and Thirlwall (1983).

The Eskdale (40) and Shap (42) intrusions, south of the Iapetus suture in Northern England, have an isotopic composition similar to that of the Southern Uplands granites although the chemical character of the granites north and south of the Iapetus suture is distinctly different (figure 2). These two plutons lie at the radiogenic end of the Southern Uplands array in figure 8, implying an origin dominated by young, immature, metasedimentary upper crust.

In figure 9 initial $\epsilon_{Nd}$ values are plotted against $\delta^{18}O$ values. The isotopic diversity of the B.C.G. as a group is well illustrated. The full ranges of O- and Nd-isotope variations observed for the southeastern Australia granitoids, both I and S-types, are contained entirely within the field of the B.C.G. The B.C.G. exhibit a slightly larger range in O-isotope ratios than the Cordilleran batholiths of the western United States, but have $\epsilon_{Nd}$ values that only extend just above the 'bulk Earth' reference value ($\epsilon_{Nd} = 0$). DePaolo (1981) has argued that the magmas which formed the Sierra Nevada and Peninsular Ranges batholiths and are typical of subduction-related plutonism in continental-margin settings, originated in a depleted mantle source and were subsequently contaminated by continental crust through an a.f.c. process. This fundamental difference between the B.C.G. and the Cordilleran batholiths implies that the B.C.G. plutonism was not a direct manifestation of Iapetus subduction. The smaller range in initial $\epsilon_{Nd}$ values and shallow slope of the Nd–O array observed in figure 9 for the intrusions of the paratectonic Caledonides demonstrates that the component of old continental crust that dominates the plutons of the Scottish Highlands is unimportant, if present at all, south of the Highland Border Fracture Zone.

The extremely large Nd–O isotope variation observed for the Kilmelford complex (24) is likely indicative of both Proterozoic and Lower Palaeozoic crustal components to the Kilmelford diorites. The high Ni content of the Kilmelford diorites (Halliday *et al.* 1984), a feature also observed for diorites in other zoned intrusive complexes such as the Etive complex (Clayburn *et al.* 1983), requires a mantle source for these magmas.

Age corrected $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios are plotted against $^{206}Pb/^{204}Pb$ ratios in figure 10. Also shown are our estimates of the average Pb-isotopic composition of the mantle and various crustal reservoirs at 400 Ma which are relevant to B.C.G. petrogenesis. The data define two distinct trends in both plots.

South of the Highland Border Fracture Zone in the paratectonic Caledonides the Pb-isotope data for Distinkhorn (35), the Southern Uplands intrusive complexes (36, 37, 38), and Shap (42) define an array which is displaced upwards in figure 10*a* from the least radiogenic portion of the m.o.r.b. trend toward the field of pelagic sediments (Meijer 1976). Modern island-arc volcanics are characterized by high $^{207}Pb/^{204}Pb$ ratios relative to m.o.r.b. and steep $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ correlations, similar to that observed in figure 10*a* for the granitoids of the paratectonic Caledonides. Such behaviour has been attributed by Sun (1980) to a mixing of Pb between m.o.r.b. and subducted sediments. Halliday *et al.* (1980) have proposed that the zoned intrusive complexes of the Southern Uplands were a product of the mixing of mafic and felsic magmas at depths in the crust below the level of final emplacement. They also hypothesized that the mantle or lower crust was the likely source of the mafic magmas, whereas the Lower Palaeozoic sediments, which constitute the upper 8–12 km of the continental crust in this region, were a likely source for the felsic magmas. However, the Pb in these sediments, which lies in figure 10 to the lower left of the Pb-isotope trend for the granitoids, does not have the appropriate isotopic character to be the radiogenic end-member required in such a mixing process. It is possible that the sediments are very heterogeneous with respect to Pb, that they are contaminated by U–Pb hydrothermal alteration, or that the few surface samples analyzed are not representative of the sediments at depth. It should be noted that the 'type-II' western

U.S. ore leads of Zartman (1974), which are characterized by their high $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios (19.1–19.7 and 15.63–15.81, respectively), have the characteristics expected of detrital sediments derived from low metamorphic grade continental crust, and thus may be more representative of the sedimentary upper crustal Pb south of the Highland Border Fracture Zone.

North of the Highland Border Fracture Zone in the Scottish Highlands, the Pb-isotope data define a sub-horizontal array in figure 10*a* extending from near the 400 Ma mantle point to much less radiogenic compositions. It is not possible, from the Pb data above, to distinguish whether the Pb–Pb array for the Scottish Highlands was produced by contamination of mantle-derived magmas by less radiogenic lower crust or by the contamination of lower crustal melts with radiogenic upper crust, because the upper crustal rocks have Pb-isotope compositions which lie near the predicted mantle Pb average at 400 Ma. Strikingly clear from figure 10, however, is the fact that relatively unradiogenic lower crust has played a dominant role in determining the Pb-isotope composition of the 'younger' granitoids of the Scottish Highlands.

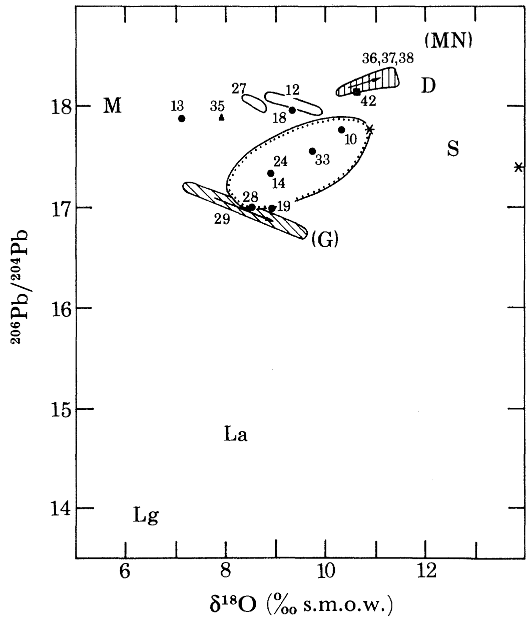


FIGURE 11. Plot of $^{206}Pb/^{204}Pb$ ratios against $\delta^{18}O$ values for the British Caledonian granitoids. The notation and the symbols are the same as in figure 8. The position of the mantle and various crustal reservoirs at 400 Ma are estimated from the references in figures 7 and 10.

The similarity in the position of the mantle and upper crustal reservoirs in figure 10 means that the slope of the Scottish Highlands array is determined by the position of the lower crustal component because mixing curves on Pb–Pb diagrams are straight lines. It is evident from figure 10*b* that the old, unradiogenic lower crustal component must have a low Th/U ratio because its $^{208}Pb/^{204}Pb$ ratio is low compared with its $^{206}Pb/^{204}Pb$ ratio. Blaxland *et al.* (1979) noted that the trend for the Pb–Pb array for 11 of the 53 analyses shown in figure 10 had a lower intercept of *ca.* 2700 Ma on a conventional Pb growth curve. This was cited as evidence for a Lewisian component to the Pb in the B.C.G. Subsequently, Halliday (1981) demonstrated that there was a general increase in initial $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios from feldspars with the

U content of cogenetic zircons within the B.C.G., and argued that this feature could not be produced by the mixing of Lewisian Pb with mantle Pb at 400 Ma. The fact that the B.C.G. Pb was predominantly of crustal origin suggested that it was in fact derived from Proterozoic crust which itself contained a component of Lewisian Pb. The Scottish Highlands array shown in figure 10*a*, based upon the larger data set under consideration here, supports that view. The slope of a 'best-fit' regression line through the B.C.G. data intersects the 400 Ma isochron at a $\mu_r$ value of 7.88, and the lower intersection of the regression line with the $\mu_1 = 7.88$ growth curve occurs at *ca.* 2100 Ma and is much shallower than either the 2800 Ma regression line through the Lewisian data of Moorbath *et al.* (1969) and Chapman & Moorbath (1977) or a mixing line between the average Lewisian and Dalradian or Moinian upper crust. Figure 10*b* demonstrates that Lewisian amphibolite-facies rocks cannot have contributed Pb to the B.C.G. magmas because of their high Th/U ratios, and therefore also $^{208}$Pb/$^{207}$Pb ratios, produced when U becomes mobile at this metamorphic grade (Chapman 1978). Clayburn *et al.* (1983) have argued that the Pb in the Etive complex (29) is a mixture of contemporary mantle Pb and relatively unradiogenic Middle Proterozoic (Grenvillian) lower crustal Pb. It would seem reasonable that the lower crustal Pb would itself be a mixture of Pb extracted from the mantle at 1200 Ma during Grenvillian plutonic activity and Pb contributed from the anatexis of Lewisian-derived sediments or the partial melting of Lewisian granulitic lower crust.

Figure 11 is a plot of $^{206}$Pb/$^{204}$Pb ratios against $\delta^{18}$O values for the B.C.G. The Pb–O relations shown in this figure largely reinforce the conclusions previously discussed regarding B.C.G. petrogenesis. It is clear from figure 11 that the three reservoirs that were important in determining the isotopic character of the B.C.G. magma were contemporary mantle, Middle Proterozoic lower crust, and Proterozoic–Lower Palaeozoic upper crust. The subordinate role of Archaean crust in B.C.G. petrogenesis is clearly illustrated.

## Summary and synthesis

Chemical and isotopic relations for the B.C.G. documentclearly the participation of at least four isotopically distinct reservoirs in their petrogenesis. North of the Highland Border Fracture Zone in the Scottish Highlands the major components to the 'younger' granitoids were: sub-continental mantle ($\delta^{18}$O ≈ 6 to 6.5‰, $^{87}$Sr/$^{86}$Sr ≈ 0.7035–0.7040, $^{206}$Pb/$^{204}$Pb ≈ 17.9–18.1); mafic to intermediate granulitic lower crust of the craton ($\delta^{18}$O ≈ 8 to 10‰, $^{87}$Sr/$^{86}$Sr ≈ 0.705–0.707, $^{206}$Pb/$^{204}$Pb ≈ 16.5–17.0), which is strongly enriched in Sr and Ba across the region; and metasedimentary upper crust ($\delta^{18}$O ≈ 8 to 14‰, $^{87}$Sr/$^{86}$Sr > 0.710, $^{206}$Pb/$^{204}$Pb ≈ 18.1–19.2). The 'older' granites of the Scottish Highlands were derived from the latter source. To the south in the Midland Valley and Southern Uplands the 'younger' granitoids were largely derived from: the upper mantle or subducted oceanic lithosphere ($\delta^{18}$O ≈ 5.7 to 7.0‰, $^{87}$Sr/$^{86}$Sr ≈ 0.7035–0.7040, $^{206}$Pb/$^{204}$Pb ≈ 17.9–18.1), and geosynclinal sediments ($\delta^{18}$O ≈ 11 to 14‰, $^{87}$Sr/$^{86}$Sr ≈ 0.705–0.711, $^{206}$Pb/$^{204}$Pb > 18.4). The granitoids of Northern England were derived largely from the latter source. The trends observed in figures 7–11 suggest that different mixing processes between those geologically reasonable end-members can explain the isotopic variations observed in the B.C.G.

South of the Highland Border Fault Zone where Precambrian metasedimentary upper crust is absent, the 'younger' granitoids define an I-type to S-type trend which is attributed to mixing in variable proportions between basalt or basaltic andesite magmas and siliceous partial melts produced within the sedimentary accretionary prism by the hot mafic magmas. The Distinkhorn tonalite in the Midland Valley and Doon diorite in the Southern Uplands are representative of the least evolved mafic melts, which were most likely produced from an incompatible element depleted upper mantle source. The displacement of these mafic rocks to the right of the mantle array in figure 8 suggests that this source was also enriched in $^{87}$Sr, a feature characteristic of both the subducted oceanic lithosphere and island-arcs where the lithospheric mantle overlying the subducted slab has been metasomatized before melting by fluids released during dehydration (DePaolo & Wasserburg 1977; Hawkesworth *et al.* 1979; Hoffman & White 1983). The two-mica granites of the Lake District in Northern England (e.g. Eskdale) and the Scottish Southern Uplands (e.g. Fleet) are the most peraluminous of the S-type intrusions in the paratectonic Caledonides, and are similar in isotopic composition to the postulated crustal end-member. The Lower Palaeozoic geosynclinal sediments which form the top 8–12 km of the upper crust in this region have the necessary high $\delta^{18}$O and initial $\epsilon_{\mathrm{Nd}}$ and moderate initial $\epsilon_{\mathrm{Sr}}$ values required of the crustal component.

North of the Highland Border Fracture Zone in the Scottish Highlands, the 'older' granitoids (e.g. Ben Vuirich, Strichen, Aberdeen) are S-type intrusions which have a chemical and isotopic character comparable with that of the Late Proterozoic metasedimentary upper crust of the Grampian Highlands; thus, an origin by local anatectic melting of this isotopically heterogeneous crust is implied. By contrast, the 'younger' granitoid intrusions of the Scottish Highlands have a highly varied origin and evolution which, in individual cases, likely involved (i) incompatible-element-enriched, sub-continental mantle; (ii) Middle Proterozoic mafic to intermediate granulitic lower crust, and (iii) Proterozoic metasedimentary upper crust. In the case of the Etive complex, for example, the predominant pre-emplacement history involved the bulk contamination of a mantle-derived magma by bulk melting of Middle Proterozoic lower crust. It is likely, therefore, that the other intrusions of the Southwestern Grampian Highlands, similarly characterized by low initial Sr-isotope ratios and low–intermediate $\delta^{18}$O values (e.g. Ballachulish, Rannoch Moor, and Ben Nevis), have a similar origin. The Strontian Complex in the Northwest Highlands also originated from a mantle source region. However, the higher $\delta^{18}$O and $\epsilon_{\mathrm{Sr}}$ values and low $\epsilon_{\mathrm{Nd}}$ values of its more felsic portions are likely the result of contamination by Moinian metasedimentary upper crust through a process of low pressure fractional crystallization-assimilation. Other of the large 'younger' granitoids of the Scottish Highlands, e.g. Bonar Bridge, Lochnagar, Cairngorm, and Hill of Fare, probably have an origin entirely within the lower crust. The Foyers intrusion is unusual because the early granodiorite phase of the intrusion has higher $\epsilon_{\mathrm{Sr}}$ values and Pb-isotope ratios and lower $\epsilon_{\mathrm{Nd}}$ values than the later granite phase. This atypical behaviour is consistent with an origin by partial melting near the base of the upper crust with the magma chamber becoming progressively dominated by lower crustal melts with time. The magmatic history of the Kilmelford intrusion is not well understood at present, but it is clear that this intrusive complex comes from a mantle source and likely that both Proterozoic granulitic lower crust and low-grade metasedimentary upper crust have played an important role in its subsequent evolution.

The ultimate cause of the B.C.G. magmatism remains a matter of conjecture. Our present understanding of chemical variations and isotopic systematics do, however, provide insight into the source region(s) from which the B.C.G. magmas were derived and place important constraints on the subsequent evolution of these magmas before final emplacement and cooling.

There is evidence that Iapetus subduction occurred in both northward and southward directions in the early Palaeozoic. The pre-tectonic, 'older' granites of the Grampian Highlands (e.g. Ben Vuirich at *ca.* 514 Ma) were formed before the oldest sediments in the Southern Uplands accretionary prism which are Early Ordovician in age (Leggett *et al.* 1979), and before the main regional metamorphism and deformation ($F_2$) in the orthotectonic Caledonides (Bradbury *et al.* 1976). They also predate the development of ophiolite and marginal basin assemblages (Bluck *et al.* 1980). As such there is no direct evidence which requires the earliest Caledonian plutonic activity to be subduction related. The association of alkaline magmas with the Carn Chuinneag intrusion (Pidgeon & Johnson 1979), a *ca.* 550 Ma granite in the Northwest Highlands, which is similar in many respects to the pre-tectonic intrusions of the Grampian Highlands, suggests that these granites may have been produced as the result of the introduction of anorogenic, mantle-derived magmas into the crust.

By *ca.* 480 Ma there was syn-tectonic, mantle-derived basaltic magmatism in the Scottish and Irish Dalradian which produced local crustal melting (Pankhurst 1970) as well as the formation and obduction of ophiolitic crust in the Midland Valley (Bluck *et al.* 1980). Following the climax of Grampian metamorphism and deformation at this time, magmatism occurred episodically from Middle Ordovician to Early Devonian time. Granitoid magmatism began in the northeastern Grampian Highlands at *ca.* 475 Ma with the development of S-type crustal melts (Halliday *et al.* 1979; Pankhurst & Sutherland 1982; Harmon 1983). The origin of these intrusions is best explained in terms of high heat production within the thickened continental crust of the orthotectonic Caledonides at that time (Richardson & Powell 1976) and the decompression, uplift, and rapid erosion of the Dalradian metamorphic pile in Middle-Late Ordovician to Early Silurian time. The later commencement of this magmatism in the central Grampian Highlands at *ca.* 445 Ma (van Breemen & Bluck 1981), compared with its initiation in the northeastern Grampian Highlands at *ca.* 475 Ma (Pidgeon & Aftalion 1978), may have been the result of slower uplift rates in the Central Highlands. At the same time, however, granite magmas with low initial Sr-isotope ratios and no inherited zircons were being produced near the northern edge of the Iapetus Ocean, and these are thought to represent high-level arc plutons (Longman *et al.* 1979; van Breemen & Bluck 1981). This is the first magmatism in the Caledonides that can be reasonably related to Iapetus subduction.

By Middle Silurian time closure of the Iapetus Ocean appears to have been complete, although Thirlwall (1981) argues for further subduction along a continuation of the Iapetus suture in the vicinity of the North Sea. The great majority of post-tectonic granitoid intrusions were emplaced during Late Silurian to Early Devonian time across the entire breadth of the Caledonian Orogenic Belt in the British Isles as well as the geosynclinal accretionary prism of the paratectonic Caledonides to the southeast. Much, if not all, of its magmatism is difficult to relate to subduction processes, such as those considered responsible for generation of the Mesozoic–Tertiary circum-Pacific batholiths. It is also striking that available radiogenic isotopic data for the Sierra Nevada and Peninsular Ranges batholites of the Cordillera of western North America indicate a derivation from a depleted mantle source region (see, for example, figures 7, 9 and 10), endorsing the view that m.o.r.b. material or a m.o.r.b. source is intimately involved in the generation of magmas generated by subduction processes (see, for example, DePaolo 1981). There is no compelling evidence for the involvement of a m.o.r.b. source in the generation of the granitoid magmas in the Scottish Highlands despite the fact that subduction of oceanic lithosphere did occur at the continental margin in the Southeast during Lower Palaeozoic time.

The fact that basalts and andesites with high Mg and Ni contents, as well as fine-grained (chilled) diorites also enriched in Mg and Ni were included in B.C.G. magmatism from the Southern Uplands through the Grampian Highlands is a clear indication that mantle-derived magmas were intimately involved in the generation of the 'younger' granitoids. Because geothermal gradients were not anomalously high by Silurian time, it is reasonable to preclude extensive lower crustal melting as the primary mechanism responsible for the initiation of post-tectonic magmatism. Also, it is most difficult to envisage melts much more mafic than granite in composition being produced by simple crustal anatexis. We therefore conclude that most of the B.C.G. dioritic, tonalitic, and granodioritic intrusions developed from mantle-derived magmas which were affected to varying degrees by crustal contamination before emplacement and crystallization.

The chemical and isotopic data discussed here illustrate that both contemporary mantle and older continental crust were important components of the 'younger' B.C.G. magmas. In the Scottish Highlands the mantle-derived component was generally enriched in Sr and Ba and derived from a source with 'enriched' isotopic characteristics. The fact that the Southern Uplands and Midland Valley intrusions have Sr- and Nd-isotopic compositions displaced to the right of the mantle array indicates either an important source component of sediment or oceanic lithosphere modified by hydrothermal interaction with sea water (Halliday 1983; Thirlwall 1983) to the B.C.G. magmas of the paratectonic Caledonides. Among the 'younger' B.C.G., S-types predominate south of the Iapetus suture and I-types predominate to the north (Halliday & Stephens 1983). The close matching of this feature with the distribution of Lower Palaeozoic geosynclinal sediments makes the genesis of the S-type granites of Northern England by crustal thickening associated with final Iapetus closure an attractive hypothesis. Despite this, the fact that some I-type magmatism occurred in the south suggests to us that mantle-derived magmas were important in the genesis of all the 'younger' granitoids.

The heat necessary to produce the crustal melts required in the petrogenesis of the 'younger' B.C.G. may have been provided directly by the mantle-derived magmas, as advocated by Halliday *et al.* (1980) and Halliday & Stephens (1983) for the Southern Uplands. Alternatively, to the north, in the Scottish Highlands, both mantle and crustal melting may have been a primary feature of B.C.G. magmatism in this region because of the thick crustal section produced by Iapetus closure. DePaolo (1981) has pointed out that a relatively steep geotherm could intersect a crustal solidus and produce localized melting near the base of the lower crust, but not reach the mantle solidus until deeper levels because restitic crustal material of mafic-intermediate composition will have a lower melting point than peridotitic upper mantle. Mafic magmas rising from the mantle could thus mix with the restite melts in lower crustal magma chambers, with fracture-assisted emplacement occurring in discrete pulses after some degree of hybridization and differentiation. Alternatively, emplacement of largely unmodified melts could occur if the mantle-derived magmas were not contaminated during their passage through the crust. The lack of widespread upper crustal contamination of the B.C.G. can be explained by the fact that assimilation will become more difficult as low-temperature, crystal-rich intermediate to felsic magmas become very viscous and rise into cooler, upper crustal country rocks (Shaw 1965; Taylor 1980). Also, frictional heat may have contributed significantly to melting. Although the B.C.G. are largely late- or post-closure, it is to be expected that major structural dislocations and movements in the lower crust and adjacent lithospheric mantle will have accompanied final welding of the two continents, and we suggest that this process may have produced sufficient fractional heat to significantly aid in the generation of the 'younger' Caledonian granitoids.

The continental crust has developed throughout Earth history by incremental accretion during episodic orogeny. In post-Archaean times this crustal augmentation has taken place at destructive plate margins in conjunction with subduction processes. Recent Nd-isotope evidence illustrates clearly that Archaean crust formed as a primary addition from the mantle (Hamilton *et al.* 1977, 1979). There is, however, continuing controversy and debate concerning the extent to which Proterozoic and Phanerozoic continental crust records a net input of juvenile material from the mantle against a recycling of previously accreted continental crust. Current interpretations of geochemical and isotopic evidence are equivocal. Moorbath (1978) has argued that major periods of continental growth in *ca.* 3800–3500, *ca.* 2900–2600, *ca.* 1900–1600, and *ca.* 600–0 Ma have similarities which require a primary mantle component to continental crust of all ages. More recently, DePaolo (1981) has recognized an Nd-isotopic component of mantle origin in the Mesozoic batholiths of California in the western United States and Déruelle *et al.* (1983) have cited O- and Sr-isotopic evidence for a primary mantle origin of the Recent calc-alkaline lavas of the southern Andes. However, Armstrong (1968), Fyfe (1976) and Shaw (1976) believe that the continental crust has been continually recycled since separation of the Earth into core, mantle, and crust early in its history. The Sr- and Nd-isotope studies of Allègre & Ben Othman (1980), Hamilton *et al.* (1980) and McCulloch & Chappell (1982) have documented that many Phanerozoic granitoids contain large components of continental crust, a characteristic which supports the idea of crustal recycling. The chemical and isotopic evidence discussed here strongly suggests that there was a significant mantle component to Caledonian magmatism of the Scottish Highlands. The proportion of this juvenile mantle component varies from as much as 60–70 % for the mafic intrusions, to virtually nil in most felsic ones. However, only a few of the B.C.G. are dominated by a mantle-derived component. The extensive Caledonian migmatitic complexes of the Scottish Highlands, not discussed here, are upper crustal partial melts (Clayburn 1981) and some of the large post-tectonic granitic plutons may have a lower crustal origin. A liberal estimate would therefore limit the mantle component to the B.C.G. as a whole to less than 20 %. Therefore, although Caledonian magmatism in Britain resulted in the addition of large amounts of igneous material to the upper crust, the Caledonian Orogeny cannot be considered a major crust-forming event because most of the Caledonian granitoids in Scotland and northern England are dominated by recycled continental crust. Davies (1983) has drawn a similar conclusion from the Sr–Nd-isotope systematics of the granites of southern England and southeastern Ireland.

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