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Models for granites and their mineralizing systems in the British and Irish Caledonides.

Jane A. Plant

British Geological Survey,
154 Clerkenwell Rd.
London EC1R 5DU

Abstract

The geochemistry and geological setting of metalliferous and mineralized granites are discussed with reference to the Caledonides of Britain and Ireland. The geochemistry of Cu and Mo porphyries and Sn-U granites, which is described using trace element plots normalized to primordial mantle, is related to models of crustal evolution at destructive plate margins. Cu porphyries ('T' type granites) have the most primitive geochemistry and characterize the early stages of subduction under conditions of high pH_2O in the mantle and lower crust, while Mo porphyries are emplaced later, away from the trench, as the crust thickens and the mantle becomes drier. Sn-granites, which generally have high heat production, are generated in tensional regimes following orogenesis or in cratonic rift zones over dry mantle previously metasomatized by F or Cl. Transfer of high heat production granites to the upper crust has been an essential part of cratonization since at least the early Proterozoic. The evolution of metalliferous granites from Cu and Mo porphyries to Sn-U granites can be modelled in terms of decreasing hornblende separation and increasing plagioclase and potassium feldspar separation, and does not require the involvement of upper crustal melt components as proposed in the 'S' type (sedimentary protolith) model for Sn-U granites.

The association between the magma genesis of metalliferous granites and block movement on deep faults, which is particularly important for Mo porphyries and Sn-U granites, is emphasized. The emplacement of granites in seismically active zones also provides a mechanism for initiating and maintaining the conditions of high heat flow and permeability necessary to sustain hydrothermal circulation systems to form economic mineral deposits.

The redistribution of elements from primary minerals into secondary sites as a result of interaction of rock with aqueous solutions is considered. Most of the elements of the porphyry suite (Hg, Pb, Cu, Ba) tend to be more mobile in aqueous solutions at lower temperatures than elements such as Sn and W which require the involvement of a hot ($\geq 500^\circ\text{C}$) acid reducing aqueous phase to form mineral deposits. Other differences between porphyry and Sn-U systems include the relative importance of sulphide and oxide species respectively in their metalliferous mineral assemblages.

The geological models developed and the primary trace element signatures of metalliferous and mineralized granites are evaluated for the British Caledonides, for which comprehensive geochemical and isotopic data are available, and possible extensions of suites of metalliferous intrusions into Ireland are suggested. Models of granite genesis require modification for the Caledonides since, in contrast to Andean-type continental margin or oceanic island-arc systems, metalliferous granites were emplaced almost contemporaneously (410-390Ma) post-dating the main tectonothermal events by as much as 90Ma in the orthotectonic Caledonides. Nevertheless the main types of metalliferous granite suites ranging from Cu and Mo porphyries to Sn-U granites can be identified, the most widespread metal association indicated by regional geochemical maps being U-Mo.

In the Irish Caledonides, available trace element and other geochemical and geological information suggest that the Donegal, Galway and Leinster granite suites may include evolved calc-alkaline intrusions of Mo porphyry association containing elevated levels of U and other incompatible elements. Metalliferous mineralization associated with the granites is considered to be favoured by the contemporaneous age of the intrusions with the metalliferous suite of Scotland, by the emplacement of granites in major fault zones, and, outside Connemara, by the low metamorphic grade of the country rocks which would promote water-rock interaction.

Introduction

Metallogenic models are increasingly important in mineral exploration for which they provide a framework linking geological, geophysical and geochemical information (Barton, 1983; Hart et al., 1978). They can be applied at a regional scale for the recognition of terrains which are prospective for mineral deposits and at more detailed stages of investigations to identify drilling targets. Robust genetic models are available for a wide range of mineral deposits ranging from magmatic segregations (e.g. chromite depo-

sits) to calc-alkaline volcanic exhalative massive sulphides. From these models exploration criteria for the automated screening of computer-readable data sets can be derived. There is however no generally accepted model for granite-associated mineralization despite the early development of simple single stage models based on crystal fractionation and the separation of residual magmatic fluids enriched in incompatible elements*. Part of the difficulty in developing

*Trace-element patterns are normalized to primordial mantle (Wood, 1979) throughout the paper except for REE which are normalized to chondritic values (Nakamura, 1974).

a modern conceptual model for this type of mineralization is in understanding the genesis of granites — especially of mineralized intrusions affected by pervasive water-rock interaction. It is particularly appropriate therefore to relate modern information on the petrogenesis of granites and their hydrothermal systems to the granites of Britain and Ireland since it was around them that much of the “granite controversy” centred between those favouring a magmatic (e.g. Bailey, 1936) and others a metasomatic origin for the intrusions (e.g. Reynolds, 1943 and 1944).

A considerable amount of detailed information is now available on the Irish granites including, for example, the classical studies of Pitcher's group in Donegal (Pitcher and Berger, 1972) and of Leake's group in Connemara (Leake, 1978). Information obtained from exploration programmes conducted by the Geological Survey of Ireland for uranium and other metals is also available (e.g. O'Connor, 1981). It is difficult to add to these detailed studies, and instead the approach adopted here is to consider Irish granites and their potential for metalliferous mineralization in a regional context.

Metallogenic models for granites from modern and ancient mountain belts and arc systems are reviewed first, together with information on the geochemistry, petrogenesis and geological setting of the different types of granite associated with metalliferous mineralization, ranging from Cu and Mo porphyries to Sn-U granites. Information on water-rock interaction systems associated with granites is considered as a basis for identifying geochemical, isotopic, mineralogical and petrographic changes indicative of mineralization. The metallogenic models are then evaluated with reference to the Caledonides of Britain and Ireland. The greatest range in age and type of Caledonian granites is found in the orthotectonic Caledonides of Scotland for which a large amount of new trace element and isotopic data is available. This information is used to prepare a classification of Caledonian granites as a basis for distinguishing barren and metalliferous granites, and for characterizing the different types of granite suites in Britain and Ireland.

Models for mineralization associated with granites and porphyries

Exploration for metalliferous minerals associated with granites is frequently based on the 'S' and 'I' type models of granite genesis (Chappel and White, 1974) or the ilmenite and magnetite series granites in the terminology of Ishihara (1977). Cu and Mo porphyries which are associated with active subduction at destructive plate margins are generally attributed to partial melting of an igneous 'I' type protolith. The mineralization which mainly comprises a metal sulphide assemblage is related to formational/meteoric water — magma interaction. In contrast, the genesis of 'two-mica' Sn and U granites is ascribed to crustal anatexis in areas of thickened sial, in 'geosynclines', or in collision orogenic belts; the origin of Sn and U mineralization is attributed to palingenesis of wet sediments (Moreau, 1976; Tischendorf, 1973). These are the sedimentary protolith 'S' type granites of Chappel and White (1974), characterized by relatively low Na₂O with high K₂O and Al₂O₃, a predominance of high SiO₂ lithologies, irregular element variation diagrams, high initial ⁸⁷Sr/⁸⁶Sr isotope ratios, the absence of hornblende and the presence of biotite and muscovite with accessory monazite and garnet rather than sphene — properties that are attributed to the

sedimentary pile from which the granites formed by partial melting. Beckinsale (1979) in a discussion of the Sn granites of SE Asia has added the criteria of ¹⁸O enrichment and low ferric : ferrous iron ratios and suggested that where 'S' and 'I' type granites are found together, the former should occur on the 'oceanic' side of the latter. The granite cusp model, whereby an aqueous phase enriched in incompatible elements is thought to collect beneath granite roof zones following magmatic fractionation according to the scheme of Bowen (1956), is used to account for the high level evolution of such granites and their mineralization. There are several difficulties with these models for Sn-U mineralization associated with granite which include:

1. **Geochemical considerations.** Sn-U granites have similar distinctive primordial mantle-normalized trace element patterns* requiring upper crustal sediments in widely separated Sn provinces such as SW England, NE Scotland, Nigeria and parts of the USSR to have similar trace and major element compositions (see below). The similarity of the patterns for High Field Strength (HFS) elements are particularly difficult to reconcile with crustal melting models since almost identical proportions of resistate heavy minerals would be required in the protolith. Gravity modelling of Sn-U granites precludes intracrustal fractionation of basic minerals such as hornblende or pyroxene, so that it is difficult to derive large-volume Sn-U granites which have exceptionally low contents of Cr, Cu, Co, Mg, Ni, V, Zn and Fe from shales which are enriched in these elements (Taylor, 1964 and 1966). Moreover, pre-concentration of Sn and W in the crust is required by such models (Mitchell and Garson, 1981).

2. **Experimental petrology and oxygen isotope data.** A major control on the depth of emplacement of granite magmas is their water content such that only dry magmas can rise to high levels in the crust (Brown and Fyfe, 1970). Sn-U mineralization is generally formed within, at the most, a few kilometres of contemporary erosion surfaces in apparently "wet" granites. Moreover there is no correlation between pH₂O, other evidence of water-rock interaction and the degree of magmatic evolution (Plant et al., 1980). Oxygen isotope data show that the aqueous fluids associated with mineralization at and below temperatures of greisenization (c.500°C) are predominantly metamorphic, formational or meteoric rather than juvenile (Sheppard, 1977).

3. **Tectonic setting.** Sn-U granites such as those of the European Hercynian province or of SE Asia are found in settings characterized by rapid changes in subduction patterns and collision between thin microplates as well as in regions of large scale crustal thickening. Moreover 'S' type granites frequently post-date melting/ductile deformation events by tens of millions of years and show no spatial relation to metamorphic zones, migmatization or other indications of high crustal temperatures which could give rise to anatexis (Johnstone et al., 1979). Instead they are frequently discordant and occur in tensional settings characterized by deep faulting and block movement on major fault systems (Taylor, 1979; Watson et al., 1984).

Much of the evidence concerning the genesis of Sn-U granites has been derived from isotope geochemistry, but frequently without due recognition that such intrusions

*Elements which have bulk solid-liquid distribution coefficients, *D*, significantly less than 1 and which become enriched during basic to acid fractionation in non-orogenic tholeiitic and alkali basalt suites.

(with their content of heat-producing elements) often represent the long-lived centres of geothermal fields or hot spring activity (Fehn et al., 1978; Simpson et al., 1979; Moore, 1982) and contain considerable textural evidence of metasomatism. The extent to which isotopic or chemical determinations have been made on granite samples that have undergone hydration and isotopic exchange in the crust is difficult to assess from the literature, since petrographical information is frequently inadequate (see also Taylor, 1979).

A different model for Sn-W-U mineralization associated with granites has recently been developed (Simpson et al., 1979; Plant et al., 1980) which relates the formation of metalliferous granites generally to sub-crustal processes at destructive plate margins with emplacement through deep faults at the end of orogenesis. As the water-deficient granite magma rises to high levels in the crust, hydration of the granite occurs initially by host-rock fluids at high metamorphic temperature. Reduction of silicate and primary accessory minerals is thought to commence at this stage, evolving into deuteric alteration of the granite magma and, finally, as the granite cools and cracks, hydrothermal convection with flow of formational and subsequently meteoric water through fracture systems. Such 'S' type characteristics as the high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, ^{18}O enrichment and low ferric : ferrous ratios are attributed to reaction between the granite and its host rock through a fluid phase.

Sn (cassiterite) deposition occurs as the hydrothermal system begins to be established at temperatures of the order of 500°C (Rankin and Alderton, 1982), U mineralization occurring later at lower temperatures ($\leq 150^\circ\text{C}$). It may also be remobilized to form pitchblende veins which post-date magmatism by up to hundreds of millions of years. This has been related to the High Heat Production (HHP) of some granite batholiths which are enriched in U, K, Th and which at times of increased tectonism/heat flow are capable of regenerating hydrothermal circulation systems (Fehn et al., 1978; Simpson et al., 1979).

This model, which distinguishes barren, metalliferous (containing high primary concentrations of metals predominantly in silicate minerals) and mineralized granites (in which metals are in secondary concentrations in ore minerals) is further developed here. It is not only consistent with modern geochemical research on granites and their hydrothermal systems, but it also enables clear exploration criteria to be developed which are applicable to metalliferous mineral exploration in the Caledonides where the 'S' type model is particularly misleading.

Tectonic setting and primary geochemistry of metalliferous granites

Cu and Mo Porphyries

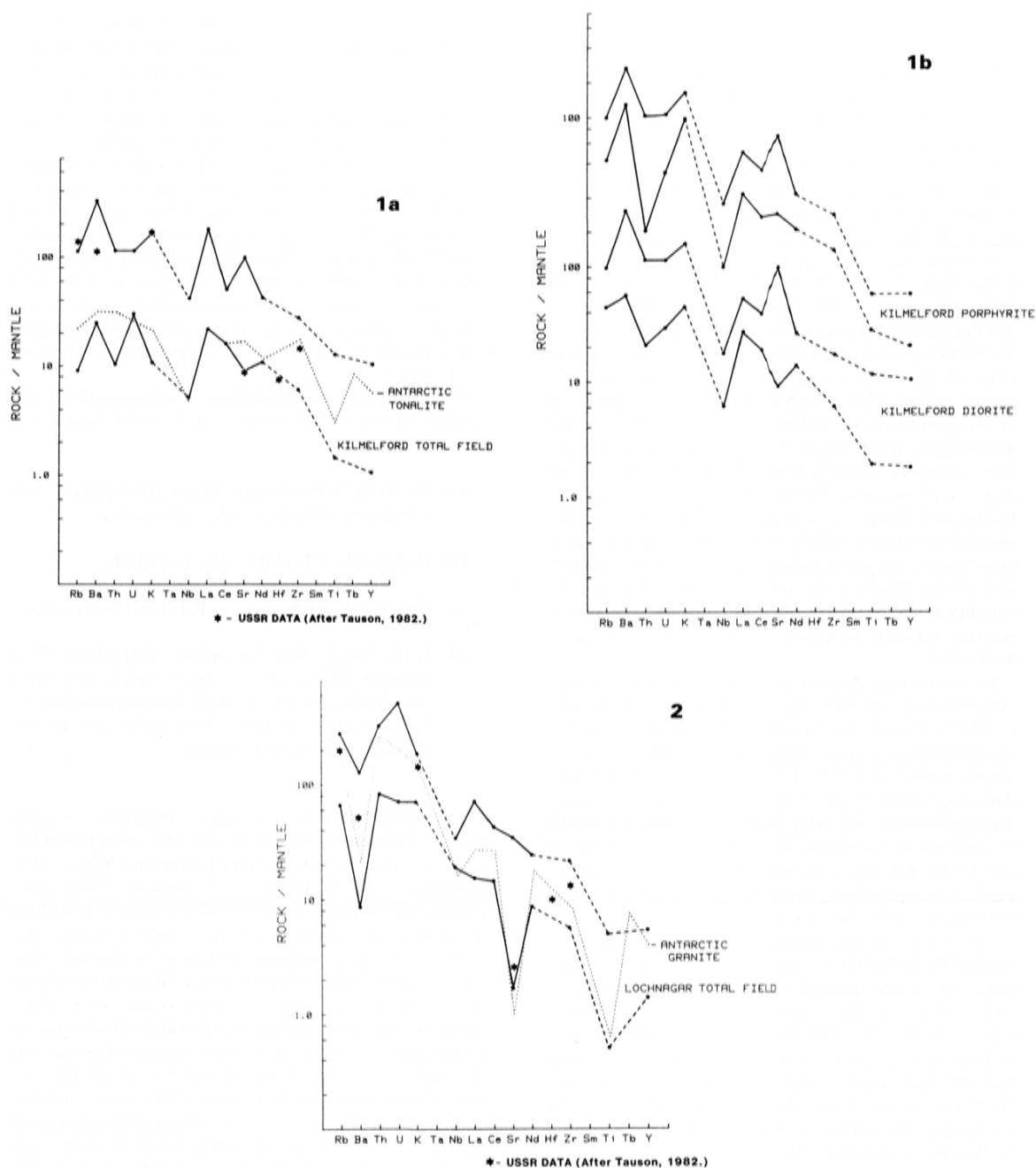
Considerable information on the geochemistry of calc-alkaline granites with which porphyry Cu and porphyry Mo deposits are associated and of alkaline/sub-alkaline granites which host Sn-U mineralization is available. This can be used to prepare general models for metalliferous granites. Calc-alkaline granites are temporally and spatially associated with subduction of oceanic lithosphere (Sillitoe, 1974; Sawkins, 1976; Mitchell and Garson, 1981). Major Cu-porphyry deposits are found mostly at a high elevation in young (Mesozoic-early Tertiary) mountain belts or Tertiary island arcs; the Bougainville Cu-porphyry in the Solomon

Islands, for example, is approximately 100km NE of a trench down which the Solomon Sea oceanic lithosphere is being subducted. In island arcs, Cu-porphyries are associated with calc-alkaline stocks of mainly intermediate composition and, in mountain belts such as those of western North America and the Andes, with calc-alkaline stocks of intermediate to acid composition. Few high level porphyry Cu deposits are found in ancient mountain or island arc belts because they tend to be uplifted and eroded, although calc-alkaline diorite to granodiorite plutons are thought to represent their eroded centres (Mitchell and Garson, 1981). Mo porphyries which tend to be emplaced at a later stage of crustal evolution away from the trench can be divided into granodiorite and granite systems containing high levels of Cu, Ba and Sr and of F, Rb and U respectively (Mutschler et al., 1981).

The primary geochemical characteristics of calc-alkaline granites (Tarney, 1976; Weaver et al., 1979; Saunders et al., 1980) include:

- (a) Moderate to low Fe enrichment accompanying SiO_2 enrichment with increasing fractionation.
- (b) High levels of K_2O , Rb, Ba, Sr and Th.
- (c) High Ba/Sr, Rb/Sr and low K/Rb and Na/K ratios.
- (d) High Large Ion Lithophile (LIL)/High Field Strength (HFS) element ratios which show more complex enrichment and depletion patterns than tholeiitic magmas in which both suites of elements generally behave incompatibly.

Systematic variations in magma compositions, such as the K-h trend (increased K_2O , Rb and decreased K/Rb ratios at constant SiO_2 content) (Jakes and White, 1972; Miyashiro, 1974; Dickinson, 1975; Beswick, 1986) across continental margins or intra-oceanic arc systems away from the trench, are consistent with the change from primitive granites associated with Cu-porphyries to evolved intrusions associated with Mo-porphyries. Magmatic evolution in calc-alkaline and plutonic (and volcanic) rock associations is also accompanied by increased proportions of intermediate and silicic rock types, increased contents of Th (and to a lesser extent Ce and La) at similar silica contents and increasing K/Na and Ce/Yb ratios (Tarney et al., 1977; Saunders et al., 1980). Other characteristics of intermediate to acid calc-alkaline granites are their exceptionally low Nb, Ta and low Ba levels with a tendency for high Nb/Ta ratios to change to high Ta/Nb ratios with magmatic evolution and high Hf/Zr ratios to increase to high Zr/Hf. Decreases in Sr, Eu, P, Ti and Ba also occur in more evolved melts. Zr, Y and Nb show only a slight increase in abundance with increasing evolution of the melt, and tend to show no spatial variations across arc systems or continental margins. Rare earth elements (REE) generally behave compatibly in the series with light REE enrichment increasing with magmatic evolution. Trace element patterns for primitive and evolved calc-alkaline granites are shown in Figures 1a, 1b and 2. A model for the generation of calc-alkaline magmas at destructive plate margins (Ringwood, 1974; Tarney, 1976; Hawkesworth et al., 1979; Wyllie, 1983) can be used to account for the geochemistry of calc-alkaline granites. Depending on the thermal structure of the subduction zone, dehydration of the descending slab during greenschist to amphibolite to eclogite meta-



Figures 1a, 1b and 2. Examples of primordial mantle normalized trace element diagrams for primitive calc-alkaline granites from destructive plate margins. (Kilmelford and Lochnagar data, O'Brien et al., 1985; Antarctic data, Saunders et al., 1980; USSR data, Tauson, 1982.)

morphism is thought to release supercritical water carrying silica, alkalis and other volatiles into the overlying mantle wedge, thereby promoting melting in the mantle or lower crust either directly or indirectly. Tarney et al. (1977) and Saunders et al. (1980) suggest that it is this process which enriches the LIL elements which readily form hydrated complexes in calc-alkaline magmas, whereas Ti, Zr, Nb, Y and the heavy REEs and to a lesser extent P are immobile during alteration of rocks up to amphibolite grade so that they sink with the eclogite slab or are retained as minor

phases in the upper mantle under conditions of high pH_2O . The HFS element contents may also be lowered during subcrustal or crustal fractionation. The relative importance of recycling old (in mountain belts) or new (in island arcs) continental crust and of fractional crystallization is not known. The importance of a crustal component might be expected to increase in extremely thickened, highly evolved crustal segments such as those of the Andes. Geochemical and isotopic studies combined with field and petrographic examination in samples unaffected by mineralization in

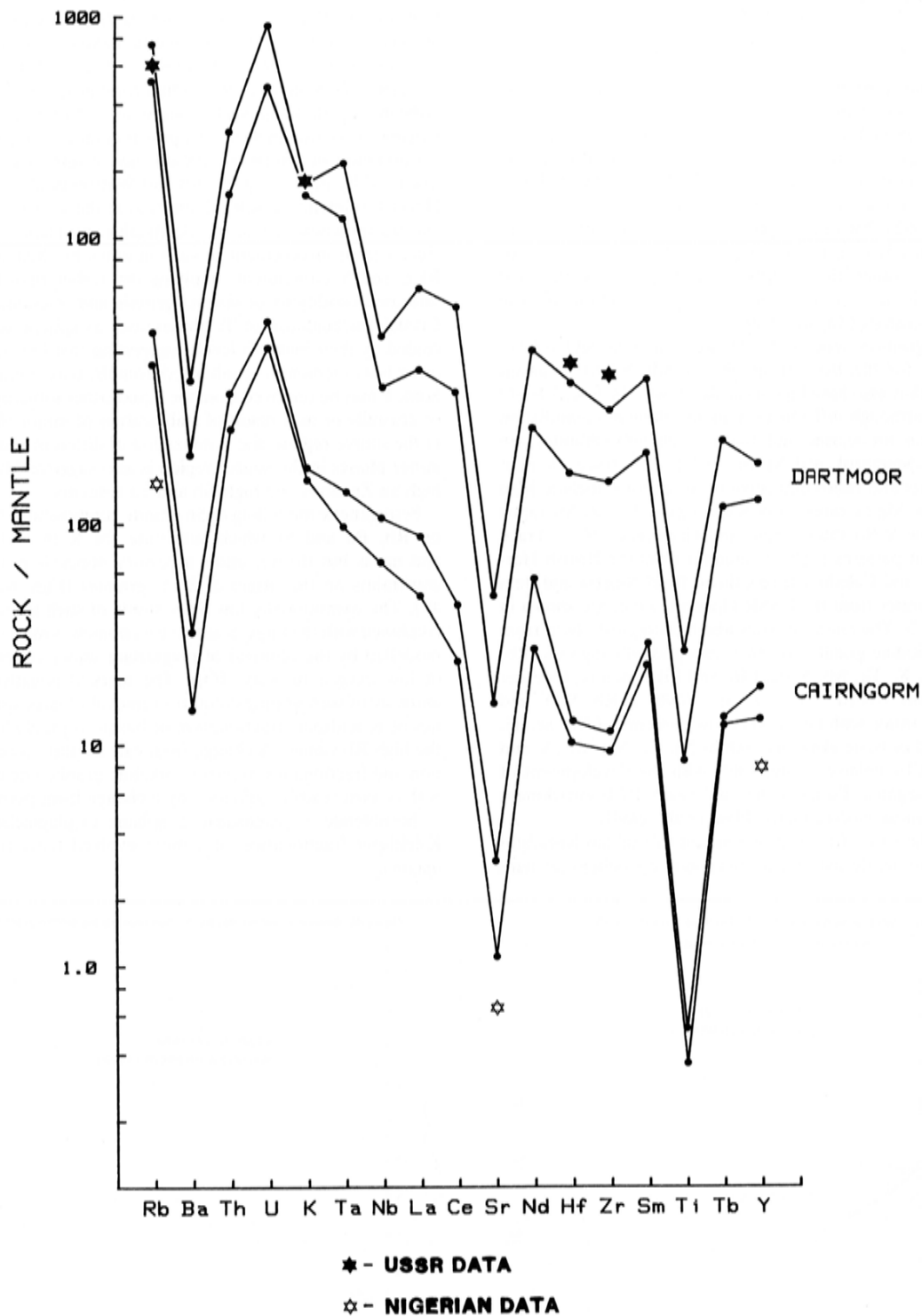


Figure 3. Primordial mantle normalized trace element diagram for tin-bearing granites. (Cairngorm and Dartmoor data, Simpson and Plant, 1984, Watson et al., 1984; USSR data, Tauson, 1982; Nigerian data, Bowden, 1982.)

Peru indicate however that the most evolved intrusions of the Andean batholith complex have juvenile isotopic compositions (Harman and Barreiro, 1984) and that there is no evidence of an increasing component of crustal material with decreasing age as previously suggested by Pitcher and Busset (1977). Instead a model of separate equilibrium

fusion events in an isotopically juvenile source area (mantle or underplated igneous rocks) followed by high level fractionation has been developed for each super unit (Atherton et al., 1979). Fractionation of the calc-alkaline series generally can be modelled in terms of plagioclase \pm pyroxene \pm hornblende \pm sphene.

Sn-U Granites

Unlike porphyry Cu deposits, relatively uneroded Sn granites occur in the Precambrian (Taylor, 1979). Alkali-rich, high SiO₂ granites of the type which host Sn deposits first became important in the late Archaean to Proterozoic following the development of stable shield-mobile belt tectonics after about 2500Ma (Croner, 1976; Brown and Mussett, 1981). Two main types of tectonic environment are recognised for Sn-U granites. Firstly, they occur in orogenic belts in which their emplacement is post-orogenic, and secondly they are associated with major fracture zones in stable cratons (Taylor, 1979).

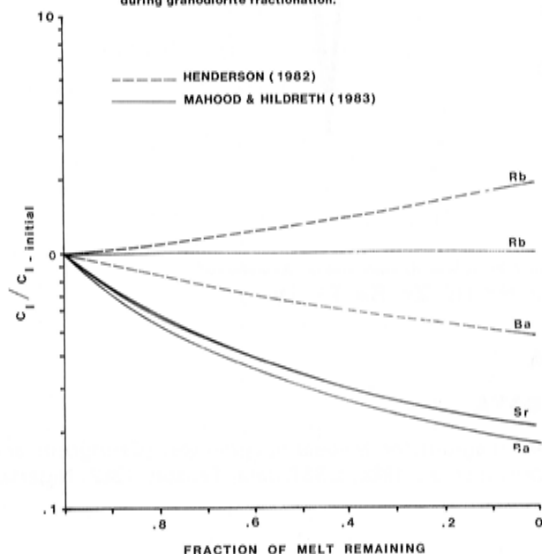
Sn granites tend to be highly acid with SiO₂>70%, except for the Bolivian granites in which SiO₂ is about 66%; they also have high total alkalis with high K₂O/Na₂O ratios although differences in major element composition between tin-bearing and barren high SiO₂ granites are small (Stemprok and Skvor, 1974). The trace element contents and ratios indicative of Sn granites include high Li, low Mg/Li ratios, low K/Rb ratios, low Zr/Sn ratios and low V/Nb ratios (Beus and Grigorian, 1977). Trace element patterns for Sn-U granites from the British Hercynian and Caledonian provinces, from Nigeria and data for granites from the USSR (Tauson, 1982) are shown in Figure 3. The characteristics which distinguish them from calc-alkaline granites are their exceptionally high Cs, Rb, Th, U, K, Ta, Nb, Y (and Be and Li) contents, together with low Nb/Ta, Th/U, Zr/Sn, V/Nb, K/Rb, Sr/Y and Mg/Li ratios with low to very low contents of Ba, Sr, Ti, Zr and of basic elements such as Ni, Cr, Mg, Co, V and Ni. REEs behave incompatibly with the development of large negative Eu anomalies and heavy REE enrichment in the most evolved melts (Plant et al., 1980).

In the case of the Cairngorm and Cornubian batholiths they are clearly distinguished on regional geochemical maps

from the crustal sequences into which they are emplaced, and gravity modelling indicates that they extend as voluminous, low density, felsic intrusions for at least 10-15km in the crust (Bott et al., 1972; Dimitropoulos, 1981). The difficulty of deriving such voluminous, highly evolved magmas by crustal melting in a post-orogenic setting or by fractionation of "normal" calc-alkaline magma has been discussed by Plant et al. (1980) and Watson et al. (1984). Hence hornblende which is important in the source region and fractionation history of calc-alkaline intrusions is precluded from involvement in such granites by their heavy REE and Y enrichment, implying dry rather than H₂O-saturated conditions of magma genesis and fractionation. Crystal fractionation of Ti phases such as sphene is precluded by their high Nb levels, suggesting that low Ti and other basic elements are inherited from the parent magma. Some P may be removed from the liquid either sub-crustally or crustally or as a result of stabilization of minor phases in the source region; the stabilization of different suites of minor phases in the source region is also suggested by the high Sn/Zr ratios and high Nb and Ta contents.

Petrogenetic modelling of Sn granite compositions based on Rb, Ba and Sr which substitute for K in feldspars and micas but do not enter accessory minerals provides constraints on the origin of Sn-U granites (Figs. 4a and 4b). The exceptionally low Sr contents of such intrusions combined with the large negative Eu anomaly is most easily modelled by the removal of plagioclase under conditions of low oxygen fugacity (fO₂). The marked negative Ba anomaly of such granites requires removal of large quantities of K feldspar; fractionation of biotite is precluded by the high Rb values. A change from calc-alkaline composition and fractionation trends to alkaline granite chemistry is thus most readily explained by a change from pyroxene ± hornblende ± plagioclase ± sphene to plagioclase ± K-feldspar fractionation of a more evolved felsic parent magma.

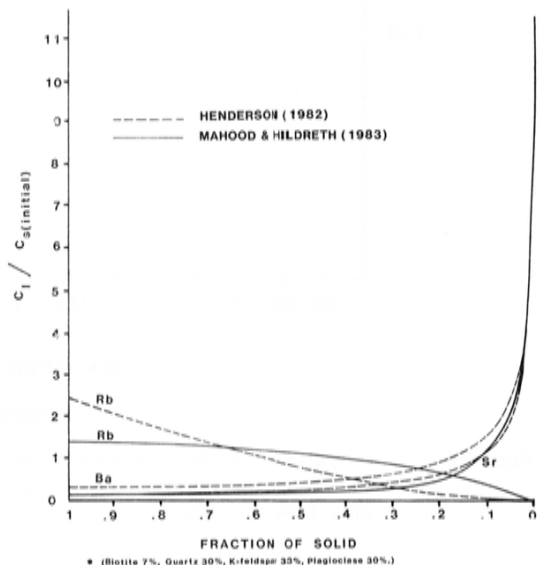
Figure 4a General model for Rb, Ba, Sr, levels in a residual melt, during granodiorite fractionation.



* (Amphibole 11%, Plagioclase 56%, K-feldspar 17%, Biotite 11%, Quartz 6%.)

Figure 4a. General model for Rb, Ba and Sr, levels in a residual melt, during granodiorite* fractionation. *(Amphibole 11%, Plagioclase 56%, K Feldspar 17%, Biotite 11%, Quartz 6%.)

Figure 4b General model for Rb, Ba, Sr, behavior during biotite granite fusion.



* (Biotite 7%, Quartz 30%, K-feldspar 33%, Plagioclase 30%.)

Figure 4b. General model for Rb, Ba and Sr behaviour during biotite granite* fusion. *(Biotite 7%, Quartz 30%, K Feldspar 33%, Plagioclase 30%.)

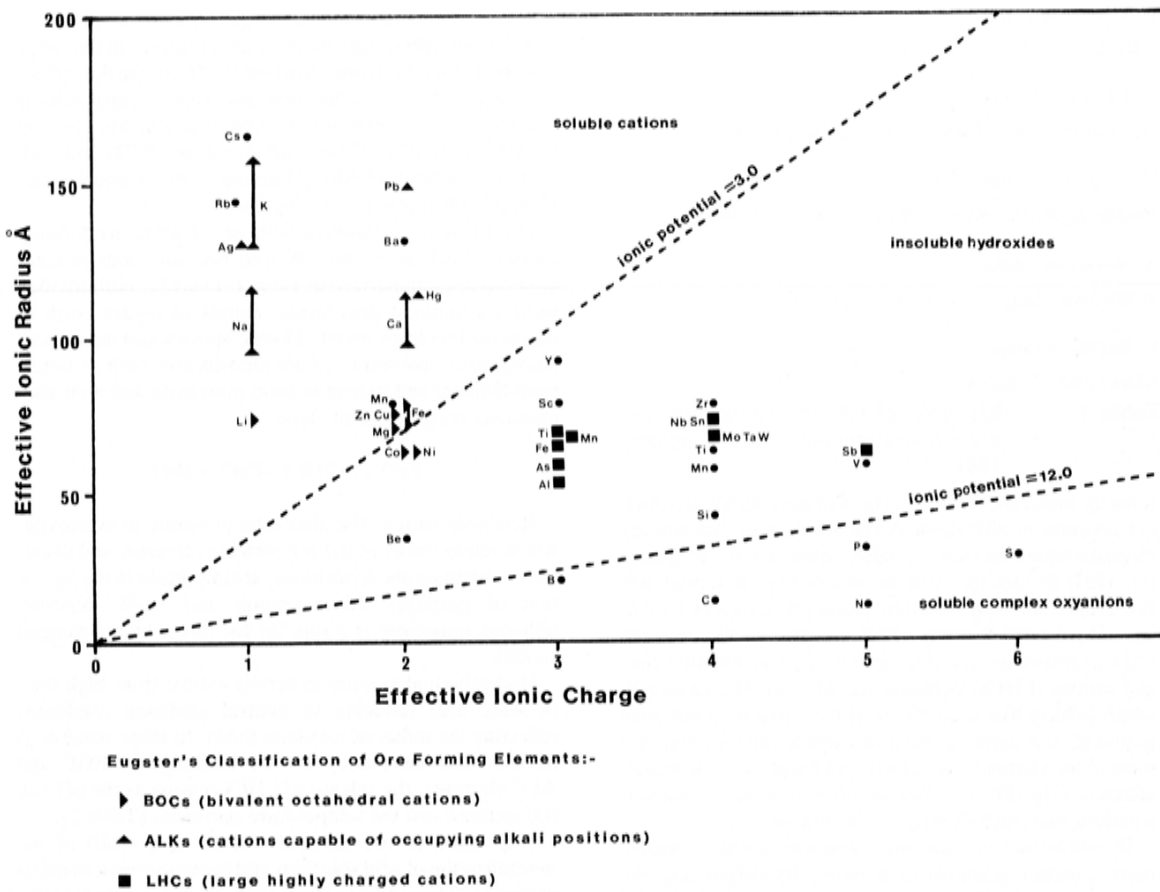


Figure 5. Effective ionic charge plotted against ionic radius for some common ions (after Gordon et al., 1958).

The generation of Sn-U granites in Britain and Bolivia has been related to F metasomatism of anhydrous mantle over subduction zones (Pearce and Gayle, 1977; Simpson et al., 1979; Plant et al., 1980). The fluids derived from the breakdown of phlogopite in the down-going slab are thought to be stabilized in the overlying mantle wedge. A mantle phase such as phlogopite could accommodate large amounts of elements such as Sn, F, K, Rb, Li, Cs, U. Partial melting during subsequent deep fracturing of the crust and upper mantle generates evolved magma at low temperature under a high partial pressure of F, such conditions favouring the generation of large volume, low temperature magmas of evolved composition.

A general model for metalliferous granites is thus suggested whereby porphyry Cu deposits form in the early stages of subduction in conditions of high pH₂O in the mantle with the generation of primitive 'I' type magmas in which hornblende plays an important role in magma genesis and subsequent fractionation. Later, away from the trench, over drier regions of the sub-continental lithosphere and as the crust thickens, Mo porphyries are generated, the later ones being of relatively high heat production and large volume. Finally, Sn-U granites are emplaced in the tensional regimes following orogenesis. They have large volumes, low densities and high contents of heat-producing elements, and their transfer to high levels of the crust has been important in its stabilization since the late Archaean to early Proterozoic (c.f. Darnley, 1981). This general model also explains the restriction of Cu porphyries to young arc or mountain belt systems since they are associated with the early phases of crustal evolution, while Sn-U

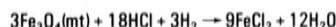
granites are associated with cratonization following orogenesis so that they are found relatively uneroded in Precambrian rocks.

Redistribution of chemical elements in aqueous ore forming solutions

During ore formation, primary minerals which formed at high temperature (and pressure) in silicate systems are changed into phases that are stable in aqueous conditions at low pressure and progressively lower temperature. The redistribution of elements involves interactions between rock and solutions which contain varying proportions of acid ligands (F⁻, Cl⁻, CO₃²⁻, S²⁻), strong bases (Na⁺, K⁺, Ca²⁺) and complexes of amphoteric elements (Si, Al, Zr, Sn, W) resulting in the replacement of the primary silicate and accessory mineral assemblages by secondary silicate, gangue and ore minerals.

The general behaviour of elements in water can be deduced from their ionic potential (Fig 5). Those of low ionic potential (<3), for example Li, Ba, Ca and Mg, tend to form hydrated cations, while those of high ionic potential (>12), for example B and S, form soluble complex oxyanions. The former group includes the important LIL elements which are commonly used as petrogenetic indicators, isotopes of Rb, Sr, K and Pb also being important in radiometric age dating. The elements of intermediate ionic potential are relatively immobile in water and are precipitated as hydroxides. This group includes the HFS elements which also have low solubility in silicate systems, and which, because of their incompatibility with sites in major rock

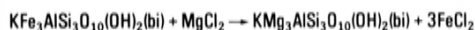
I. Congruent dissolution.



II. Incongruent dissolution.



III. Congruent exchange.



IV. Incongruent exchange.



V. Melt-fluid exchange.

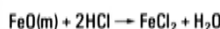


Table 1. Examples of release mechanisms for ore-forming elements (after Eugster, 1984).

forming minerals, tend to form accessory minerals which are resistant to alteration. A classification of ore-forming elements based on their crystallographic behaviour (Eugster, 1984) divides the elements of low ionic potential into two groups showing behaviour similar to ferrous Fe Bivalent Octohedral Cations (BOCs) and Alkali elements (ALCs) respectively; a third group of Large Highly Charged cations (LHCs) including As, Mo, Sn, Sb, Ta and W which behave like ferric Fe or Ti have intermediate ionic potential. It is apparent from this simple classification that most of the elements associated with porphyry-style mineralization (Hg, Pb, Cu, Ba) are more mobile in aqueous solutions than such elements as W and Sn.

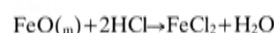
Hydrothermal systems associated with granites involve more complex reactions than simple hydrolysis and the neutral to acid pH range of such systems preclude OH complexes. Experimental studies (e.g. Eugster, 1984) and fluid inclusion studies of Sn-W deposits (Haapala and Kinnunen, 1979; Kelly and Rye, 1979; Patterson et al., 1981; Collins, 1981; So et al., 1983) indicate that Cl⁻ is the main anion in ore-forming solutions with deposition temperatures ranging from 500-200°C. The dissolution and transport of Zr, Sn, W, Be, Al and Mo has also been attributed to their ability to form acid complexes with Cl⁻ or F⁻ which contain alkaline elements (Beus and Grigorian, 1977). Solubility data on Sn-W minerals in F-bearing solutions are not available, however. In the case of W, tungstic acid has been proposed as the representative carrier (Krauskopf, 1970).

Table 2. Efficiency of ore-forming elements release mechanisms (after Eugster, 1984).

Reaction type and condition	LHC	BOC	ALC
1. Congruent dissolution at low pH and fO ₂	XXX	XXX	XXX
2. Incongruent dissolution, no oxidation	X	XXX	XX
3. Incongruent dissolution with oxidation		XXX	XX
4. Congruent exchange, neutral pH, no oxidation	X	X	—
5. Incongruent exchange, with oxidation	—	XXX	XX
6. Melt-fluid exchange with HCl production	XX	XX	X

Studies of reactions between supercritical fluid phases in equilibrium with silicate melts at temperatures in the range 850-600°C suggest strong enrichment of Cl in the fluid phase and repeated water saturation and vapour separation is considered to be effective in extracting Zn, Mn, Fe and Cu (Holland, 1972; Kilinc and Burnham, 1972) and such elements as Sn and Mo (Manning, 1981; Candella and Holland, 1984) into circulating fluids.

The types of reactions capable of releasing ore-forming elements such as Sn and W into solution from primary minerals are summarized in Table 1. In acid conditions they include congruent dissolution, mainly of oxides (such as magnetite) to form metal chloride species and water, and incongruent dissolution of aluminosilicates such as potassium feldspar and biotite to form muscovite and melt fluid exchange reactions of the type:



Reactions such as the alteration of biotite to muscovite, which release most of the ore-forming elements and decrease or eliminate alkali positions, are important in the formation of porphyry mineralization and Sn-W deposits, although muscovite is a sink for the large, highly charged cations.

Hydrothermal systems generally evolve from high temperature acid reducing to neutral oxidizing conditions reflecting the influx of meteoric fluids. In these conditions release reactions mainly involve exchange of BOC and ALC elements, the release of LHCs ceasing as the pH and fO₂ increase and the temperature decreases (Table 2).

Deposition of ore minerals occurs as a result of the neutralization of acid solutions and the conversion of metal chlorides (?fluorides) to oxides (Sn, W, U), sulphides (Cu, Fe, Pb, Zn) or sulphates (Ba). In granites and schists deposition involves the conversion of feldspar and biotite to muscovite (Hemley and Jones, 1964). Rocks which contain Ca, for example limestones and basic or ultrabasic rocks, also neutralize acid (Kwak and Askins, 1981) particularly F-bearing solutions.

Deposition of cassiterite from SnCl₂ solutions involves oxidation while wolframite may be precipitated by mixing H₂WO₄ from granite-derived hydrothermal solutions with FeCl₂ produced by acid alteration of the country rock (Eugster, 1984); in the presence of carbonate, scheelite is the main tungsten ore mineral. Sulphide deposition is also related to neutralization of acid ore-forming solutions dominated by chloride species, but conditions differ from those for oxide precipitation by a requirement for a source of H₂S. If magmatic H₂S is invoked, a decrease of salinity as a result of mixing with meteoric waters is a likely precipitating mechanism. Sulphur derived from oxidation of disseminated sulphides or organic S or reduction of evaporitic sulphates in country rocks, for example shales, have also been suggested as sources of H₂S by Eugster (1984).

Experimental studies of hydrothermal systems are consistent with those of geothermal areas where high to low pressure steam contains high chloride and fluoride levels, e.g. Ellis and Mahon (1967); with decreasing temperature such systems evolve into acid sulphate waters. Post-magmatic circulation involves neutral chloride waters containing Na, K, As, boric acid, SO₄²⁻, bicarbonate, ammonia, bromide, F, Li, Rb and Cs. Studies of the Na/K and H⁺ ion activities in deep waters from hydrothermal areas (Brown and Ellis, 1970) in relation to experimental data (Ellis and Mahon, 1967) indicate that the high temperature (200-359°C) water compositions in many rock

Table 3.

Principal host minerals for trace elements in mineralized and non-mineralized acid — intermediate igneous rocks.
(After Beus and Grigorian, 1977.)

Element	Mineralized Rocks	Non-mineralized Rocks	
		Intermediate Rocks	Acid Rocks
Lithium	lithium micas (pegmatites), spodumene, amblygonite.	hornblende, biotite, feldspar.	biotite, feldspar.
Rubidium	secondary micas and clays, low temp. potassium feldspar (adularia).	biotite and other micas, feldspars.	micas, K feldspar.
Beryllium	beryl, bertrandite, phenacite, chrysoberyl.	plagioclase, muscovite.	plagioclase, muscovite.
Fluorine	fluorite, topaz, villiaumite, apatite.	amphiboles, micas.	micas.
Copper	sulphides.	pyroxenes, amphiboles, biotite, magnetite.	biotite in Cu-Mo porphyries.
Zinc	sulphides.	amphiboles, biotite, magnetite.	biotite.
Lead	sulphides.	feldspars, biotite, U/Th rich accessory phases.	feldspars, U/Th rich accessory phases.
Niobium	columbite, pyrochlore, loparite, niobo-tantalates.	ilmenite, zircon, sphene, biotite.	ilmenite, zircon, sphene, biotite.
Tantalum	tantalite, microlite, niobo-tantalates.	ilmenite, zircon, sphene, biotite.	ilmenite, zircon, sphene, biotite.
Molybdenum	molybdenite, wolfenite.	magnetite, ilmenite, sphene, plagioclase.	sphene, K feldspar, plagioclase.
Tin	cassiterite, tourmaline.	biotite, muscovite, ilmenite.	biotite, muscovite, ilmenite.
Caesium		biotite, muscovite.	biotite, muscovite.
Tungsten	tungstates.	biotite.	biotite.
Thorium	monazite, thorite.	zircon, sphene, biotite, monazite, apatite, xenotime, allanite.	zircon, sphene, monazite, apatite, biotite, xenotime, allanite.
Uranium	uraninite, pitchblende, phosphates, haematite, martite, niobo-tantalates.	zircon, sphene, biotite, monazite, apatite, xenotime, allanite.	zircon, sphene, monazite, biotite, apatite, xenotime, allanite, grain boundaries.
Rare-Earths	complex (REE) silicates, monazite, xenotime, allanite, niobo-tantalates.	biotite, plagioclase (Eu), monazite, allanite, sphene.	apatite, zircon, micas (LREE).
Barium	barite, celsian, cymrite.	micas, plagioclase.	micas, K-feldspar.

types correspond to an equilibrium assemblage of quartz-K feldspar-albite-muscovite (Ellis, 1973) with kaolinite becoming the stable aluminosilicate at lower temperature as the $H^+/(Na^+ + K^+)$ ratio increases. Mineralized granites are thus distinguished from metalliferous or barren granites by evidence of extensive reaction of primary silicate or accessory minerals with aqueous fluids.

Changes associated with water-rock interaction in mineralized granites

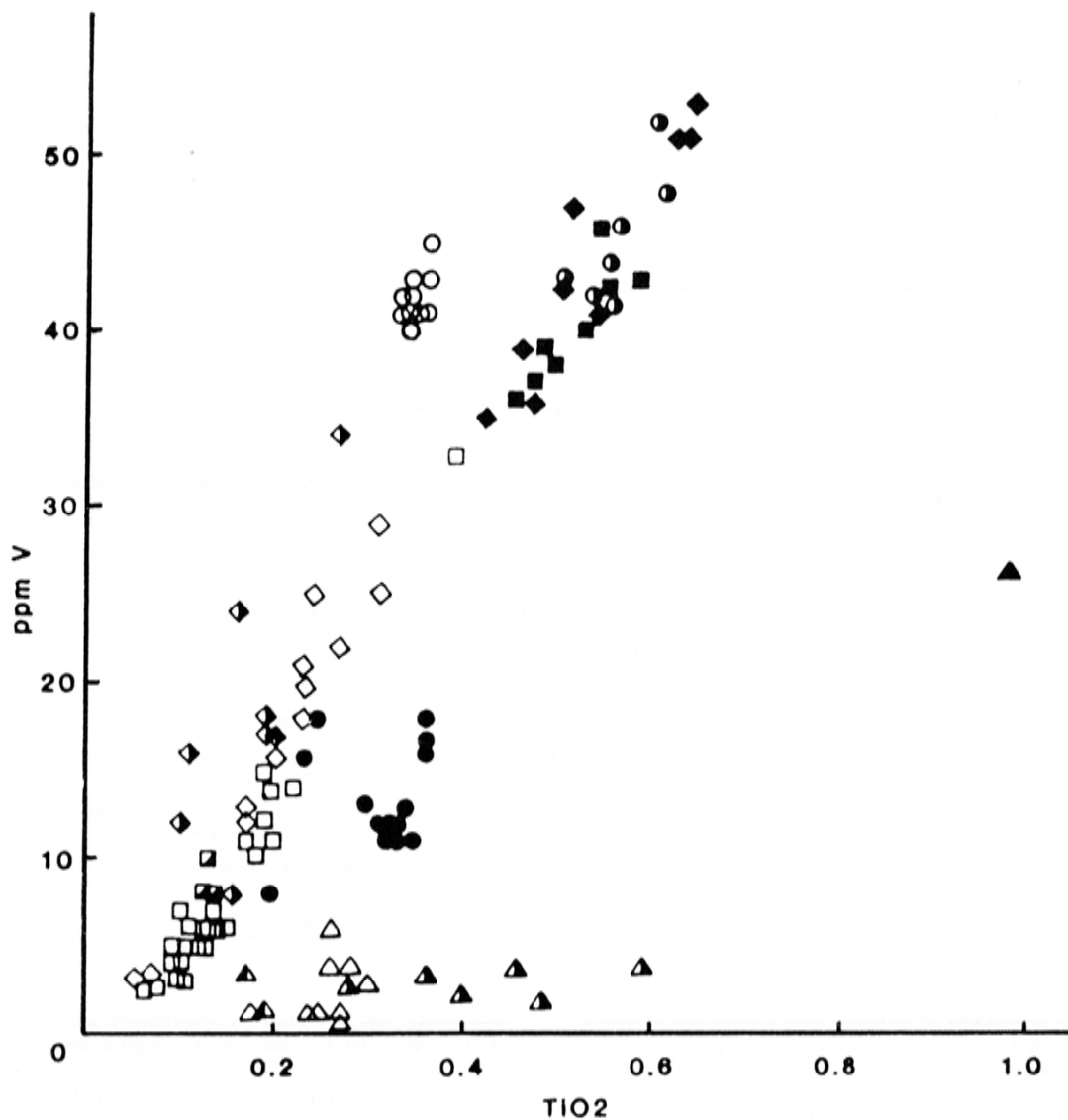
Hydrothermal alteration associated with porphyry deposits can be described in relation to four main concentric zones, an innermost potassic zone which generally coincides with the low grade core of the deposit, a phyllic zone approximately coincident with a pyrite zone of mineralization, a poorly developed argillite zone, and a wide outer propylitic zone. In Sn-U mineralized granites such as those of SW England, major features indicative of prolonged high to low temperature water-rock interaction are apparent in the field (Simpson et al., 1979; Taylor, 1979). They include greisenization (high temperature acid leaching), the growth of sub-solidus K feldspar to give megacrystic and "feather textured" granite (high temperature K metasomatism) and the occurrence of veined or metasomatized breccia pipes which contain fragments of granite or country rock in tourmaline or quartz-rich matrices. Large areas of sericitization, chloritization, kaolinization and haematization are related to lower temperature water-rock interaction. The

mineralogy and petrology of mineralized granites also reflects water-rock interaction with the replacement of biotite by muscovite or tourmaline and the destruction of primary accessory minerals such as zircon and sphene in areas of intense greisenization. The minerals in which ore-

Table 4.

Effects of secondary alteration of granites. (After Stemprok and Skvor, 1974).

Process	Change in modal composition	Change in petrochemical composition
albitization	-K feldspar -Ca plagioclase +albite	+Na ₂ O -K ₂ O
muscovitization	-K feldspar -plagioclase -biotite +muscovite	-K ₂ O
greisenization	-K feldspar -plagioclase -biotite +quartz +mica	-Na ₂ O +SiO ₂ +Al ₂ O ₃
silicification	-K feldspar -biotite	+SiO ₂
sericitization	-K feldspar -plagioclase	+K ₂ O -CaO
kaolinization	-K feldspar -plagioclase	-K ₂ O -Na ₂ O



KEY TO FIGURE 6

- | | |
|---------------------------------|-----------------------------------|
| ◆ SKIDDAW CUMULATE RICH GRANITE | ▲ CARROCK FELL LEACHED GRANOPHYRE |
| ◇ SKIDDAW LIQUID RICH GRANITE | △ CARROCK FELL GRANOPHYRE |
| ◐ SKIDDAW GREISEN | ▲ CARROCK FELL HYBRID SUITE |
| ■ ESKDALE GRANODIORITE | ▲ CARROCK FELL GABBRO |
| □ ESKDALE GRANITE | ● SHAP |
| ◑ ESKDALE GREISEN | ● ENNERDALE |
| ○ THRELKELD | |

Figure 6a. Plot of HFS elements, V vs. TiO_2 for the Lake District showing primary magmatic trends. (After O'Brien et al., 1985).

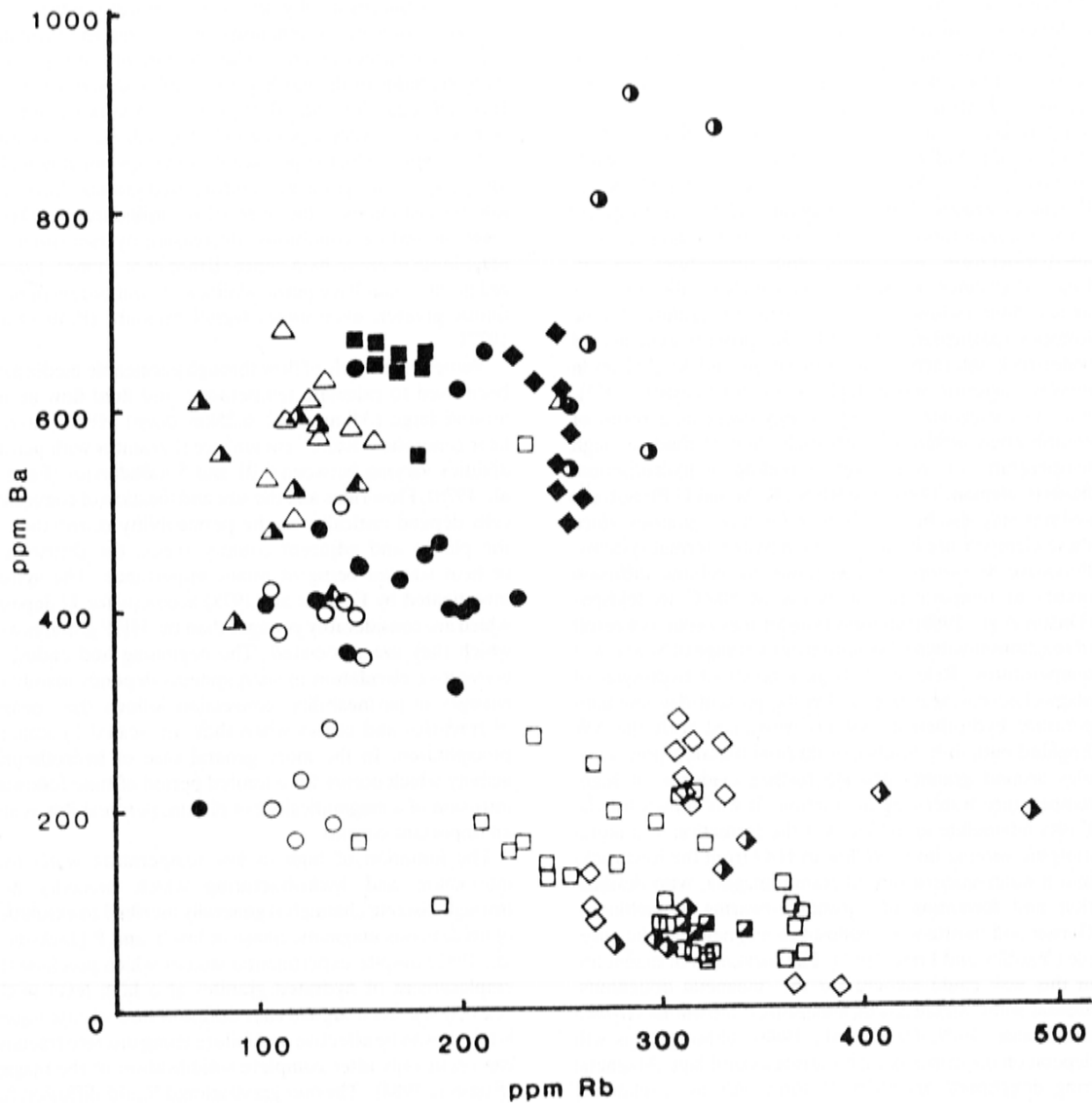


Figure 6b. Plot of LIL elements, Ba vs. Rb for the Lake District showing dispersion of magmatic trends as a result of hydrothermal alteration. (After O'Brien et al., 1985).

forming elements occur in mineralized granites are compared with those of unmineralized granites, in which the primary assemblage reflects magmatic history of the intrusion, in Table 3. Changes in major element chemistry as a result of secondary alteration is shown in Table 4 (Stemprok and Skvor, 1974).

Geochemically one of the simplest criteria indicative of mineralization associated with granites is the increased standard deviation of trace (and major) element contents (Beus and Grigorian, 1977; Simpson et al., 1979) although their mean content may remain unchanged. Hydrothermal activity also affects trace and major element variation diagrams for LIL elements such as Rb/Sr, Rb/Ba, K/Rb, Sr/Ba and U/Th and Mg/Li. These plots show relatively simple trends in rocks formed mainly by magmatic processes reflecting diadochic substitution, but they are dispersed and scattered in mineralized intrusions (Fig. 6b) while HFS element plots such as V/TiO₂ retain simple magmatic trends (Fig. 6a).

Evidence of hydrothermal alteration can also be obtained by plotting LIL elements or their ratios against the HFS elements or their ratios, for example Ti to V (Fig. 6a), Zr to Sn, V to Nb, since they show igneous fractionation trends and are resistant to alteration. Increased B/Ga and B/SiO₂ ratios have been shown to be indicators of B metasomatism as a result of high temperature interaction of granites with shale-derived fluids (Lister, 1979; Simpson et al., 1979). Chondrite normalized REE patterns generally reflect the magmatic history of intrusions, but around areas affected by acid reducing fluids REE patterns (Alderton et al., 1980), Zr/Sn and other HFS element ratios may be affected. Dispersion of the Ga/Al ratio which is normally constant in igneous rocks (Nockolds and Allen, 1958) may also occur with the deposition of high Al/Ga minerals such as topaz from highly acid solutions. It is at this stage (when resistant primary accessory minerals such as zircon and monazite break down) that U is initially released into solution, although it is subsequently readily remobilized from easily

leachable sites because of the number and stability of its complexes (Langmuir, 1978).

The quantity and number of generations of fluid inclusions of different compositions increase in mineralized granites reflecting the extent and duration of high to low temperature water-rock interaction (Roedder, 1977; Rankin and Alderton, 1982). Hence early saline fluids containing B, S, Sn, Cu, Pb and W are found in the Dartmoor granite, low- to moderate-salinity fluids in the Sn-W-Cu mineralized Carnmenellis granite, and pervasive low-temperature, low-salinity fluids throughout the SW England granites. Preliminary data indicate the presence of few fluid inclusions in the Cairngorm granite. Stable isotopes (particularly ^{18}O , ^{16}O) also provide evidence of water-rock interaction. Greisenization and kaolinization involve meteoric water depleted in ^{18}O (Taylor, 1977), but ^{18}O enrichment of granites may occur as a result of equilibration of magma with shale-derived fluids at high temperature, or as a result of boiling of hydrothermal fluids (Coleman, 1979). The Rb/Sr, K/Ar and U/Pb isotopic systems may also be affected in mineralized granites, since these elements are highly mobile in hydrothermal systems. Pervasive Sr isotope contamination by volume diffusion occurs at temperatures in excess of 500°C in feldspar (Dickin et al., 1980) but mass transfer may occur as a result of reactions involving dissolution or exchange of Sr at lower temperatures. Release of Sr as a result of hydrolysis of plagioclase has been reported in the present-day low-temperature hydrothermal systems associated with the SW England batholith. Studies of thermal metamorphic aureoles around granites provide further evidence of high-temperature water-rock interaction. It was shown for the Easky adamellite in Ireland that the formation of a metamorphic aureole involved flow of H_2O from the host rocks into a water-undersaturated granite magma, with desilication and formation of corundum-bearing assemblages. Garnet and biotite were oxidized to magnetite in the aureole (Yardley and Long, 1981). The formation of magnetite in this way could account for the 'magnetic doughnuts' around some metalliferous/mineralized intrusions (Brown and Locke, 1979; Plant et al., 1980), although this will depend on the iron mineral buffering assemblage. Magnetic 'ring doughnuts' are likely to form only in a relatively anhydrous crustal setting. The iron ore mineral suite of the Ardara granite, Donegal, was shown by Atkin (1979) to be a function of host rock lithology as a result of oxidation-reduction reactions. Such reactions may explain the presence of reduced Fe-ore phases (e.g. ilmenite) in mineralized Sn-U granites.

Conditions for hydrothermal circulation

There is a relation locally and regionally between granite magmatism, tectonic lineaments and metalliferous mineralization. In the case of the Andean batholith for example, magma intrusion was focussed up a linear structure throughout the life of the batholith (70Ma) (Pitcher, 1978). The super units of the batholith were undersaturated with water for most, if not all, of their crystallization history, and are thought to have frozen at a sub-volcanic level, as a result of absorption of meteoric water (Pitcher, 1979). The pervasive hydrothermal activity and mineralization in the Arequipa segment of the batholith compared to the barren Lima segment has been attributed to its higher crustal setting and quenching of the magmas as they hit epizonal water (Atherton et al., 1979).

The emplacement of granites in seismically active zones provides a powerful mechanism for initiating and maintaining hydrothermal centres. The amount of convection of aqueous fluids in the earth's crust can be described by the Rayleigh equation (see Bott, 1982) and varies mainly in response to changes in permeability (which vary by an order of 10^{12} between highly permeable and impermeable rocks) and temperature gradients. Unfractured granites have very low permeabilities of the order of 10^{-3} millidarcies* (Davis, 1969) in surface conditions, decreasing by two orders of magnitude in about 6km depth (Brace et al., 1968). Fractured granites can have permeabilities several orders of magnitude greater, even under higher pressure (Pratt et al., 1977).

Numerical models of flow through permeable media have been used to calculate temperature and fluid flow in and around large (34km wide, 6.25km deep) HHP (internal heat generation 10×10^{13} cal/cm³/sec⁻¹) granites with permeabilities varying between 0.01 and 5 millidarcies (Fehn et al., 1978). Flow rates and the size and location of convective cells depend critically on the permeability distribution in the pluton and adjacent country rocks, the distribution of heat sources being of minor importance. The system investigated by Fehn et al. (1978) accounts for U deposits which are considerably younger than the HHP granites with which they are associated. The beginning and ending of convective circulation in such systems depends mainly on changes in permeability; convection follows the opening of fractures and ceases when they are sealed by mineral precipitation. In the more general case of hydrothermal activity which occurs for a limited period of time following intrusion of a magmatically hot pluton, permeability is also an important control.

The initiation of high to low temperature water-rock interaction and hydrofracturing which precedes flow through discrete channels is generally ascribed to exsolution of an aqueous magmatic phase at low T and P (Jackson et al., 1982) despite experimental studies which preclude the emplacement of hydrated granites at a high level in the crust. It has been argued that diffusion into silicate liquids is too slow to be effective and failure along discrete fractures can occur only after complete solidification of the magma (Eugster, 1984). Thermo-gravitational liquid diffusion has been demonstrated to be effective in high level acid magma chambers however (Hildreth, 1979). Moreover, hydration of granites in the crust could involve mass transfer whereby lower density hydrous phases which formed by interaction between the granite and its host rocks at contacts and in xenolith swarms are carried convectively in the advancing magma. Bartlett (1969) claims that convection occurs in plutons even if the viscosity is $>10^8$ poise and evidence of current activity in the Ardara pluton, Donegal, has been presented by Holder (1979).

The tectonic setting of Caledonian granites in Britain and Ireland

Most of the granites of Ireland, Scotland and Northern England which are potential sources of metals are of Caledonian age. Granite magmas were emplaced into the crust of Britain and Ireland in the late stages of the Caledonian orogeny in broadly contemporaneous phases of igneous activity at about 500-460Ma (orogenic granites), between 440-410Ma (late orogenic granites) and in a major phase

*1md = 10^{-11} cm²

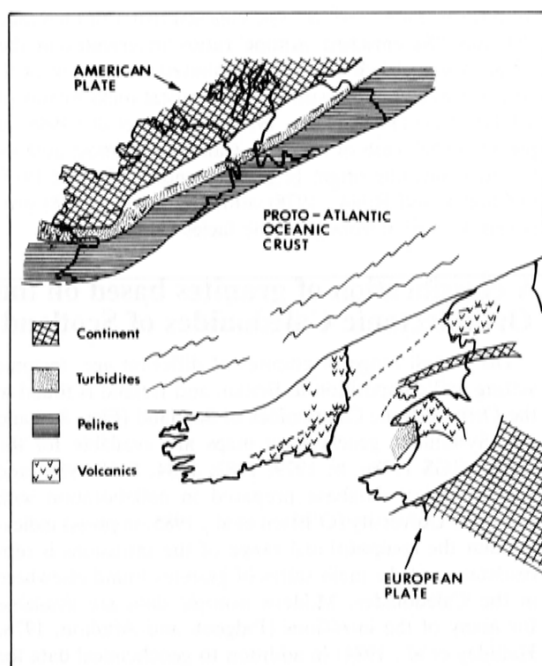


Figure 7. Palaeogeographical reconstruction for upper Ordovician times (after Phillips, Stillman and Murphy, 1976).

of newer granite emplacement at about 410-390Ma which extended throughout the Caledonides into Appalachia. Most recent models for the evolution of the British and Irish Caledonides postulate a collision orogeny related to the closing of the Proto-Atlantic ocean, Iapetus. This ocean existed for much of the Cambrian and Ordovician until closure and suturing at the end of the Silurian, to form the Devonian ORS continent (Phillips et al., 1976). The last events in the cycle may have involved oblique subduction and sinistral strike-slip movements (McKerrow, 1984) which juxtaposed the American continental plate of which NW Ireland and northern Scotland formed a part, and a younger European plate which now comprises much of south and southeast Ireland, England and Wales (Fig. 7). The postulated end-Silurian Caledonian suture follows the Solway Line in southern Scotland and possibly continues along the Navan-Shannon Line in Ireland.

The Lewisian complex of Archaean to early Proterozoic gneisses and granulites, which is exposed in the foreland of NW Scotland and in isolated inliers in the Scottish Caledonides and the gneisses of Inishtrahull in Ireland, are fragments of the American plate. Seismic evidence (Bamford et al., 1977) indicates the presence of a Lewisian-type granulite basement in the lower crust beneath most of Scotland north of the Solway Line which is not present to the south and which may represent the southern edge of the ancient American Plate. The significance and distribution of Grenville basement is controversial; gneisses of the Rockall Bank and Annagh in NW Ireland, although generally of Lewisian aspect (Dunning, pers. comm.), give Grenville ages (Van Breeman et al., 1978; Max and Sonet, 1979) but the Rb-Sr whole-rock isochron of 1000Ma obtained on the Ardour gneiss in Scotland was not confirmed by U-Pb isotope studies of granulites which record separate events at 1550Ma and 570Ma (Pankhurst and Sutherland, 1982). The existence of Grenville basement in Scotland has also been questioned on isotopic (O'Nions et

al., 1983; Halliday, 1984), geochemical (Plant et al., 1984b) and geological grounds (Stewart, 1982), although Harmon et al. (1984) conclude that there is reasonable evidence of a significant Grenville component to the basement beneath the British Caledonides. The difficulty in identifying a Grenville event may be the extent to which it represents isochemical reworking of the basement rather than additions of juvenile material to the crust. In the southern European plate, studies of isolated inliers indicate that the pre-Caledonian basement was younger and relatively thin, consisting of calc-alkaline volcanics and sediments ranging in age from ca.700-500Ma (Thorpe et al., 1984) which, it has been suggested, were formed in a series of island arcs and marginal basins (Le Bas, 1980).

For the purpose of this discussion the Caledonides are considered in relation to three tectonostratigraphic zones which are broadly continuous across Britain and Ireland (Fig. 7). Firstly the Orthotectonic Caledonides which represent tectonic and igneous activity in an Andean-type continental margin over a northward-dipping subduction zone. In this zone high grade metamorphism and complex deformation accompanying tectonic shortening and thickening of the crust (the Grampian Orogeny) occurred in late Cambrian to Middle Ordovician times; Lewisian basement where it occurs in inliers is reworked. The unconformable cover sequence of middle to late Proterozoic Moine psammites and pelites, and late Proterozoic to Lower Palaeozoic Dalradian sequence are affected by major thrusting and recumbent folding respectively. The Old Moines, in which there is evidence of a >750Ma tectonothermal event, have been suggested (Plant et al., 1984b) to represent a pre-Caledonian crystalline block against which the Dalradian sequence was deposited in an extensional orogenic marginal basin, and against which it was subsequently deformed. The second zone is that of the Longford Down — Southern Upland belt of Ordovician and Silurian greywacke-shale sediments which are thought to have been accreted against the northern plate during northward subduction of the Iapetus oceanic lithosphere, probably when it lay far to the SW of northern Scotland, offshore the Grenville province of Canada (Leggett et al., 1979; McKerrow, 1984). Deformation within this zone is attributed mainly to active subduction events during the Ordovician and Silurian rather than to collision. Thirdly, to the south of the Caledonian suture is the late Palaeozoic succession of predominantly greywacke-shales with Ordovician volcanics which extends from SE Ireland to the English Lake District and which is thought to have formed over a southeasterly dipping subduction zone. Zones 2 and 3 are the Paratectonic Caledonides in which low-grade metamorphism from zeolite to greenschist facies is related to such local processes as sediment burial in volcanic arcs (Oliver et al., 1984), and in which closure of Iapetus late in the Silurian is reflected by only weak deformation, the basement being unreworked.

There are several differences between the British and Irish Caledonides which have a bearing on granite genesis. These include the convergence of the Caledonian orogenic front and suture, and the narrowing of the Moine block westwards towards North America so that the cover succession in the Orthotectonic Caledonides of Ireland is mainly Dalradian. The most significant difference in relation to granite genesis, however, is probably the convergence towards Ireland of the major fault zones of the Moine Thrust, Great Glen, Highland Boundary and Southern Uplands Faults (Fig. 8).

The relation of granite magmatism and calc-alkaline volcanism to the main tectonothermal events in the Caledon-

ides differs in several important respects from modern Andean-type plate margins or island arc systems. There is, for example, little evidence of early subduction-related plutonism in the northern province of the Caledonides, although this may be a feature of the present level of erosion (Watson, 1984). Moreover, the main influx of granite magmas (the post-orogenic granites) were emplaced in the American and European plates and in the accretionary prism at approximately the same time, following the end-Silurian suturing, and post-dating the Grampian collision event in the Orthotectonic Caledonides by as much as 75–80Ma.

In Britain metalliferous mineralization is associated mainly with the post-orogenic granites together with a few of the late-orogenic intrusions, the main areas of mineralization being those of the Lake District and Northern Pennines, which formed above large buried batholiths (Fig. 9) (Simpson et al., 1979; Brown et al., 1980; Moore, 1982).

The genesis of the late- and post-orogenic granites is controversial. Hence one school of thought (Halliday, 1984; Halliday and Stephens, 1984; Harmon and Barreiro, 1984), largely on the basis of isotope and trace element studies, emphasise differences in the genesis of granites to the north and south of the Southern Uplands Fault. The late- and post-orogenic granites in the Orthotectonic province are considered to be mainly 'I' type intrusions and predominantly of a single granite type (Stephens and Halliday, 1984), while in the Paratectonic Caledonides, the Criffell, Fleet, Eskdale, Shap and Skiddaw granites which contain increased ^{18}O and relatively high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are attributed to high level *in situ* partial melting and are classified as 'S' type. Geochemically the post-tectonic granites are said by Harmon et al. (1984) to fall within a narrow band of composition, the most notable variation being in their contents of Sr, Ba, Rb, La, Ce and Th with marked enrichment in Sr, Ba and light REE and depletion in Rb and Th in granites of the Orthotectonic Caledonides. All post-tectonic granites in Scotland and in the Orthotectonic and Paratectonic Caledonides are said to exhibit very similar patterns for the HFS elements Nb, Zr, P and Ti with similar contents of Y in granites north of the Solway-Shannon Line, but with Y enrichment in those of Northern England; the latter are severely depleted in Sr and enriched in Rb relative to their counterparts in Scotland. The high Sr and Ba contents of the 400Ma granites of Scotland are attributed to a mantle or lower crustal source by Halliday and Stephens (1984).

A second group of workers, using a variety of regional geochemical, lithochemical, geophysical and isotopic data in relation to the tectonic evolution of Scotland, emphasise changes between the late- and post-orogenic granite suites which they attribute partly to a decrease in the crustal component of the intrusions with time. They also consider that most of the post-orogenic granites north and south of the Caledonian suture are predominantly 'I' type (Simpson et al., 1979; Watson and Plant, 1979; Plant et al., 1980; Plant et al., 1984b). These granites which comprise several geochemical suites are thought to be derived from trace element-enriched, perhaps compositionally zoned, subcontinental lithosphere by a process comparable to that used to account for changes in the composition of contemporaneous Lower Old Red Sandstone volcanics across Scotland (Thirlwall, 1982), although a lower crustal component is present in the Etive complex. Plant et al. (1983) and Watson et al. (1984) relate changes in magma composition to deep faulting of previously metasomatized mantle/lower crust rather than to magmatism over an active

subduction zone. The 'S' type characteristics of increased ^{18}O and ^{87}Sr enriched isotope ratios in granites in the Paratectonic Caledonides are attributed to reaction of 'I' type juvenile granites with hydrous crustal rocks by way of a fluid phase (Plant et al., 1983; O'Brien et al., 1985, in press). In the case of the Irish Caledonides most authors favour a juvenile origin (e.g. O'Connor, 1974 and 1975; O'Connor and Brück, 1978) although Leake (1978) proposed derivation from granulite facies lower crust.

A classification of granites based on the Orthotectonic Caledonides of Scotland

The largest range of granites of different age, tectonic setting and composition in Britain and Ireland is found in the Orthotectonic Caledonides of Scotland (Figs. 8, 9 and 10). Systematic geochemical maps are available for the region (IGS 1978a, b; 1979; 1982; 1984; BGS 1985) and a geochemical database prepared in collaboration with Leicester University (O'Brien et al., 1985, in press) indicates that the compositional range of the intrusions is representative of the main suites of granites found elsewhere in the Caledonides. Modern isotopic data are available for many of the intrusions (Pidgeon and Aftalion, 1978; Halliday et al., 1984) in addition to geochemical data for the basement and cover sequences which show that it is characterized by depletion in U, Th, Rb and K, but light REE-enriched with high Sr, Ba and Zr contents (Figs. 11a and 11b). The presence of ancient Lewisian-like granulite facies basement (Bamford et al., 1977) with a distinctive isotopic and trace element geochemistry (Sheraton et al., 1973) is of value in distinguishing between lower crustal and juvenile magmas. The granites of northern Scotland are therefore used as a basis for classifying Caledonian granites generally.

The relation of the different suites of granites to the tectonic regime in which they were emplaced is summarized in Figures 10 and 12. The isotopic characteristics of the different suites are summarized in Table 5a, emphasis in this discussion being placed on data for U-Pb systematics in zircons and Sm-Nd systematics which are less affected by water-rock interaction. Although the age of emplacement and the geochemical and other characteristics of the granites overlap, several broad groups of intrusions may be distinguished. The suites include orogenic granites, many of them small biotite granites in which K feldspar predominates over plagioclase, which were emplaced during or closely following (mainly within 10–25Ma of) the metamorphic climax (Figs. 10 and 12). They are concentrated in areas of high-grade metamorphism (Johnstone et al., 1979) and studies of the metamorphic environment (Richardson and Powell, 1976) and of the isotopic compositions of the intrusions (Table 5b) indicate that they are the products of regional anatexis of the upper-middle crustal Moine or Dalradian assemblages. They are thus 'S' type granites in the sense of Chappell and White (1974). These granites have no known association with metalliferous mineralization (although placer gold occurs over the Strath Halladale and Monadhliath migmatite complexes) and they are indistinguishable from their host rocks, both geochemically and geophysically.

The emplacement of granites with 'S' type isotopic and geochemical characteristics appears, on the basis of available radiometric age dates, to have persisted longer in the East Grampians (until about 440Ma in the case of the Glen Kylachy intrusion; Pankhurst, 1974). The region is also distinguished by the presence of basic rocks emplaced

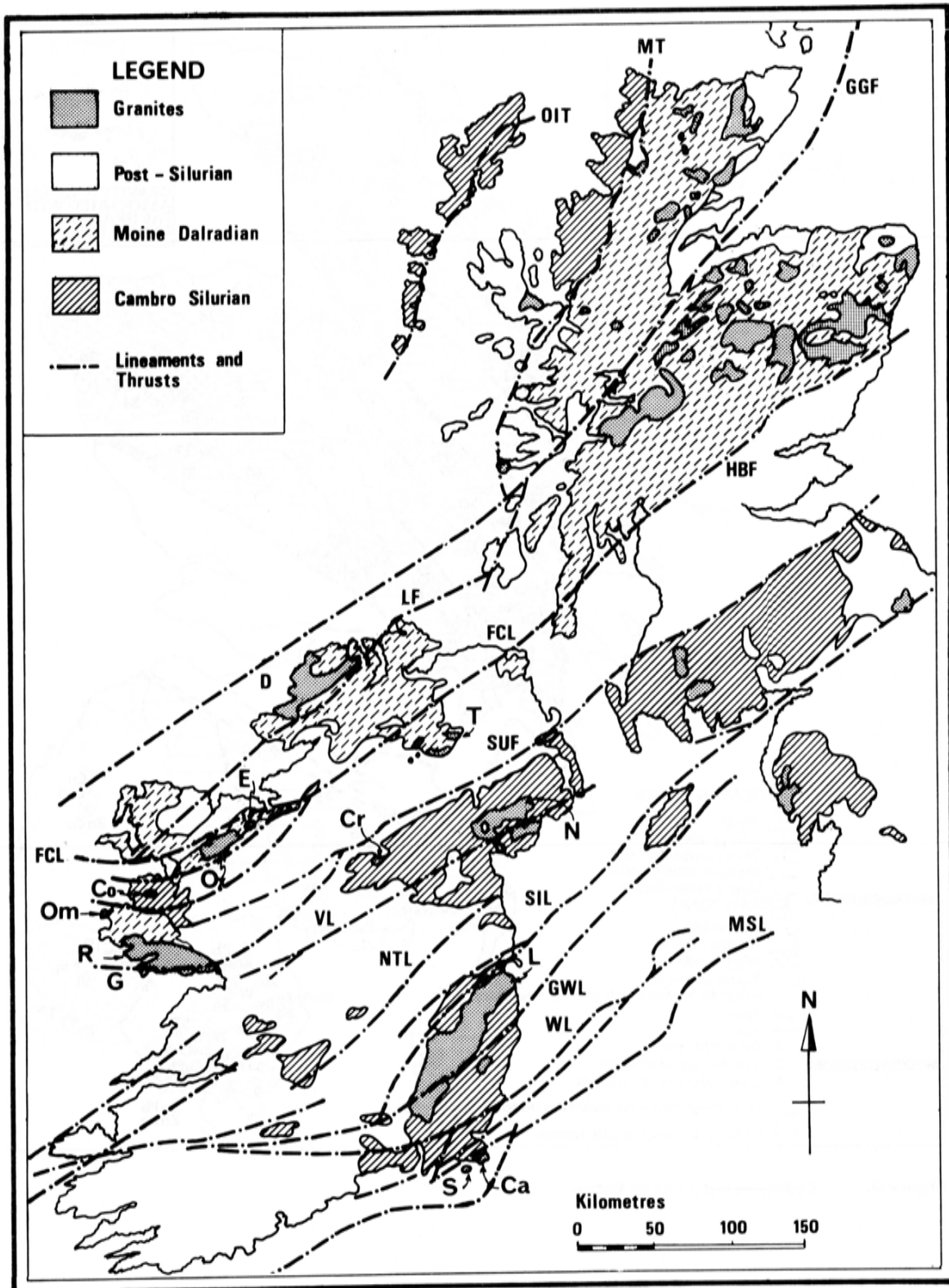


Figure 8. Distribution of major exposed and hidden NE lineaments and granites in Britain and Ireland. OIT, Outer Isles Thrust; MT, Moine Thrust; GGF, Great Glen Fault; HBF, Highland Boundary Fault; LF, Leannan Fault; FCL, Fair Head — Clew Bay Linear; SUL, Southern Uplands Fault; VL, Virginia Linear; NTL, Navan — Tipperary Linear; SIL, South Ireland Lineament; GWL, Graignamanagh — Wicklow Linear; WL, Wexford Linear; MSL, Meanai Strait Line. (After Gardiner, 1975; Leake, 1978; Max et al., 1983).

The Caledonian granites of Ireland are indicated as follows: Ca, Carnsore; Co, Corvock; Cr, Crossdoney; D, Donegal; G, Galway; L, Leinster; N, Newry; O, Oughterard; Om, Omey; Ox, Ox Mountains (Slieve Gamph); R, Roundstone; S, Saltees; T, Tyrone.

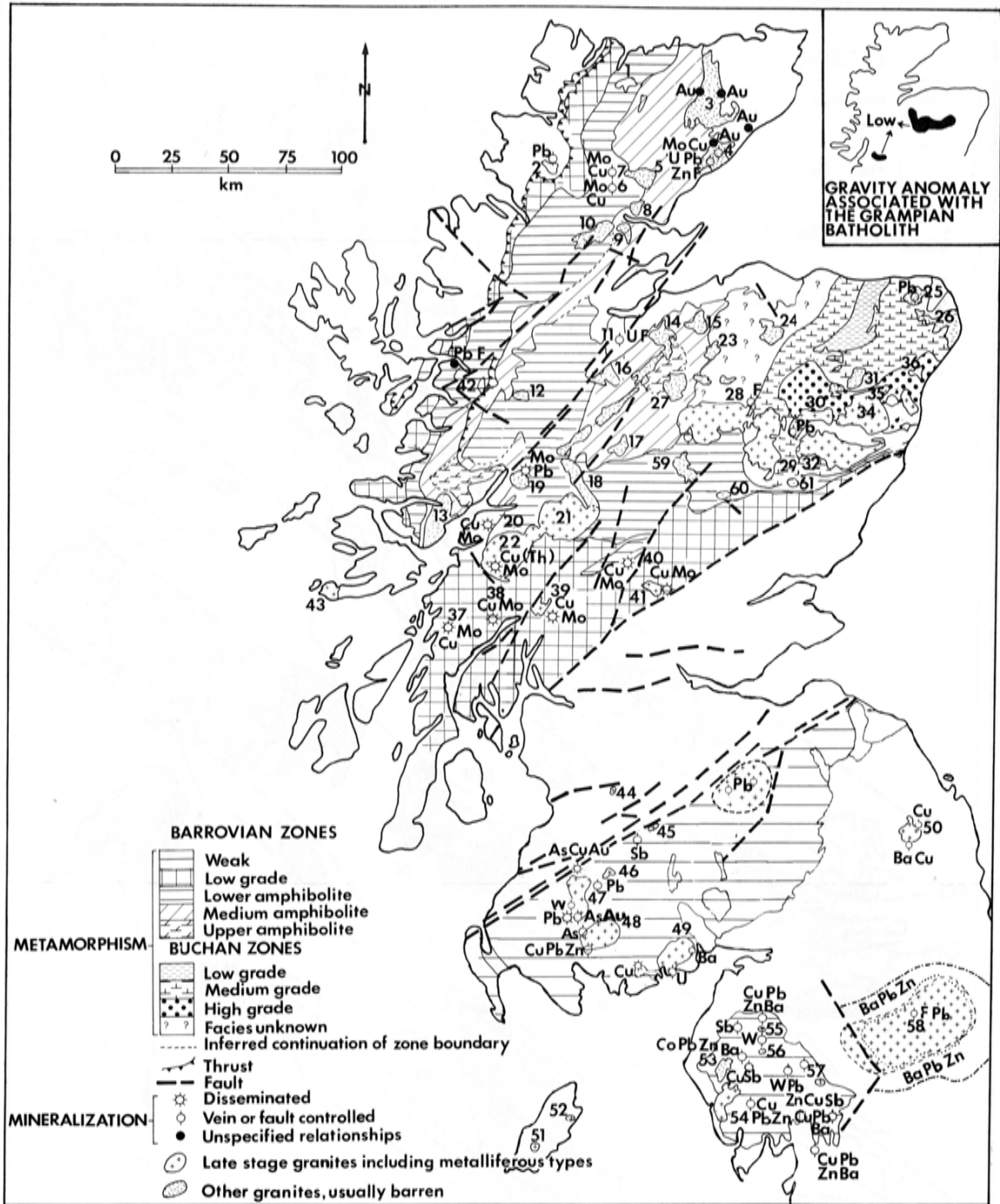


Figure 9. Caledonian granites of Britain.

*References:

- | | | |
|-----------------------------------|-------------------------------|------------------------------|
| 1 Van Breemen et al., 1979. | 2 Pidgeon and Aftalion, 1978. | 3 Pankhurst, 1982. |
| 4 Pankhurst, 1979. | 5 Clayburn, 1981. | 6 Hamilton et al., 1980. |
| 7 Harmon et al., 1984. | 8 Clayburn et al., 1983. | 9 Halliday et al., 1979. |
| 10 Bell, 1968. | 11 Halliday, 1984. | 12 Halliday et al., in prep. |
| 13 Summerhayes, 1966. | 14 Halliday et al., 1980. | 15 Rundle, 1979. |
| 16 Shepherd and Darbyshire, 1981. | 17 Wadge et al., 1974. | |

Figure 9. Key to granite types and locations

No.	Name	Age	Ref*	Type
1	Ben Loyal	—	—	I
2	Loch Borrolan	430±4 U:Pb Z	1	A
3	Strath Halladale	—	—	Mig
4	Helmsdale	420 U:Pb Z	2	A
5	Lairg-Rogart	—	—	A
6	Grudie	405±15 Rb:Sr	3	I
7	Loch Shin	—	—	—
8	Migdale	400 U:Pb Z	2	A
9	Fearn	—	—	U
10	Carn Chuinneag	560±10 U:Pb Z	2	S
11	Abriachan	—	—	A
12	Cluanie	417 U:Pb Z	2	A
13	Strontian	435±10 U:Pb Z	2	A
14	Moy	—	—	S
15	Ardclach	—	—	U
16	Foyers	415 Rb:Sr	4	A
17	Strathspey	439±9 Rb:Sr	5	U
18	Strath Ossian	405±9 Rb:Sr	5	A
19	Ben Nevis	400 Rb:Sr	6	I
20	Ballachulish	400 (Est) Rb:Sr	7	I
21	Moor of Rannoch	400 (Est) Rb:Sr	7	I
22	Etive	400±5 Rb:Sr	8	I
23	Grantown	—	—	U
24	Ben Rinnes	—	—	I
25	Strichen	475±5 U:Pb Monaz	2	S
26	Peterhead	—	—	S
27	Monadliath	—	—	I
28	Cairngorm	408±3 Rb:Sr	3	I
29	Glen Gairn/Lochnagar	415±5 Rb:Sr	9	I
30	Cromar	—	—	I
31	Bennachie	399±8 Rb:Sr	10	I
32	Mount Battock	—	—	I
33	Aberdeen	440 Rb:Sr	11	S
34	Hill of Fare/Skene complex	413±3 Rb:Sr	9	I
35	Kenmay	—	10	S
36	Pitmedden	411±7 Rb: Sr Mins	—	U
37	Kilmelford	—	12	I
38	Garbah Achadh	—	—	—
39	Garabal Hill	410	13	I
40	Tomnadaschan	—	—	—
41	Comrie	406 Rb:Sr	—	I
42	Glanelg-Ratagain	—	9	A
43	Ross of Mull	426 Rb:Sr	9	A
44	Distinkhorn	414±3 Rb:Sr	5	I
45	Spango	390±6 Rb:Sr	—	U
46	Cairnsmore of Carsphairn	—	—	U
47	Loch Doon	408±2 Rb:Sr	14	I
48	Cairnsmore of Fleet	392±2 Rb:Sr	14	I
49	Criffel-Dalbeattie	397±2 Rb:Sr	14	I
50	Cheviot	—	—	I
51	Foxdale	—	—	U
52	Dhooon	—	—	U
53	Ennerdale-Buttermere	420±4 Rb:Sr	15	I
54	Eskdale	429±4 Rb:Sr	15	I
55	Skiddaw	392±5 Rb:Sr	16	I
56	Threlkeld	461±15 Rb:Sr	17	U
57	Shap	392±2 Rb:Sr	—	I
58	Weardale	—	—	I
59	Glen Tilt	—	—	I
60	Glen Shee	—	—	I
61	Glen Doll	—	—	I

Rb: Sr refers to whole rock analyses unless otherwise stated.

Z — represents Zircon; Bio — Biotite; Monaz — Monazite; Mig — Migmatite; Hbl — Hornblende; Mins — Minerals.

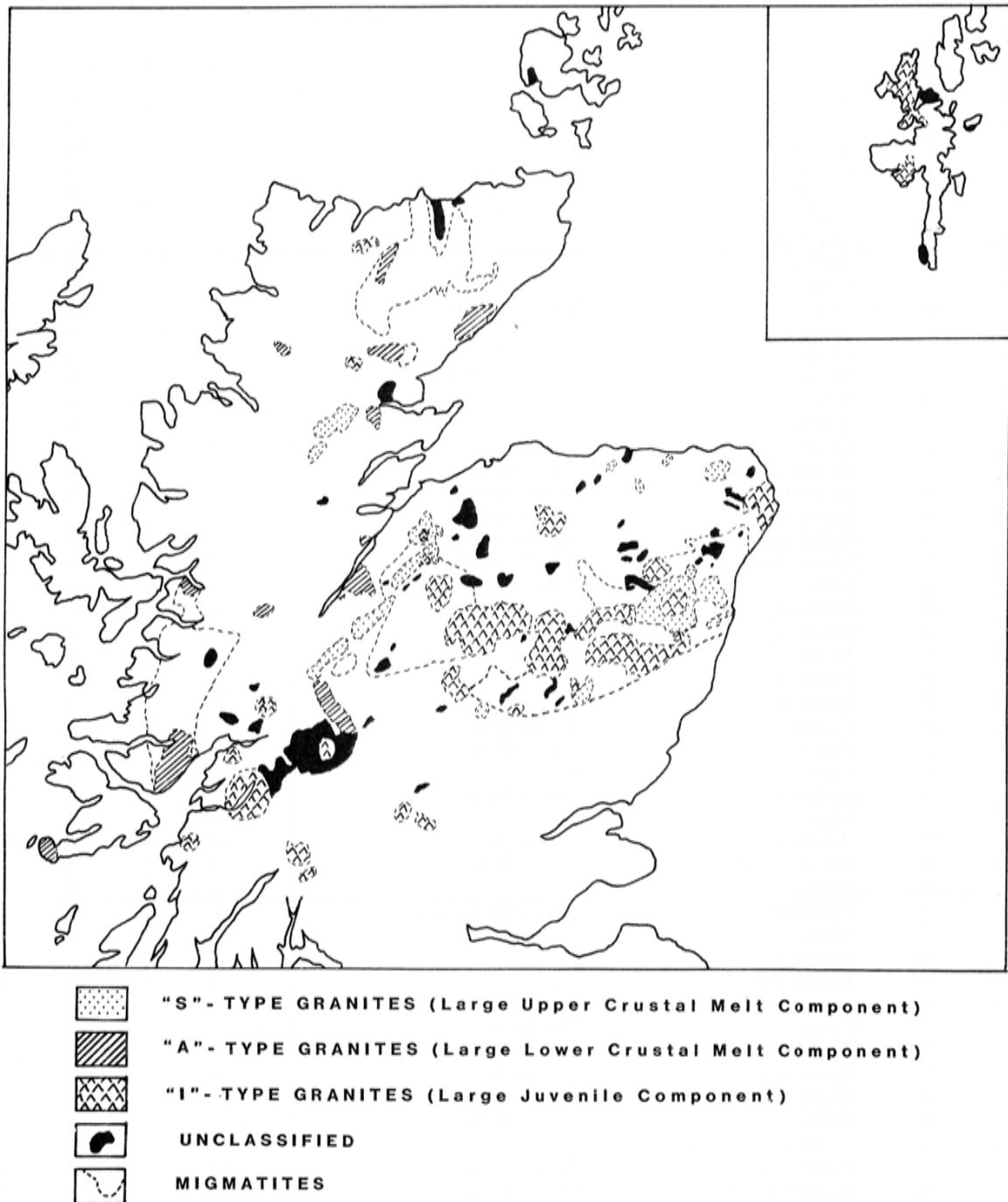


Figure 10. Distribution of granite types in northern Scotland.

during the peak of metamorphism and by the high temperature, low pressure Buchan metamorphism. Over much of the Northern Highlands 'S' type granite emplacement ceased considerably earlier; the Strontian intrusion has been dated at 435Ma and the alkaline/shoshonitic intrusions of Loch Borrolan and Glendessary which have lower initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Table 5a, Fig. 9) were emplaced at about 430Ma near to the orogenic front.

The late orogenic granites were emplaced from about 440-410Ma (Dewey and Pankhurst, 1970) into rocks which were still at temperatures higher than the blocking temperature of K-Ar in micas as reflected by their lack of clear cut

thermal aureoles. They were emplaced mainly during a period of uplift and erosion, a decline in crustal temperatures (Fig. 12), and as ductile deformation gave way to brittle failure with the initiation of major transcurrent fault zones. Early shear faults came into existence at about 430Ma while major regional transcurrent fault sets, such as those of the Great Glen with which several of the late orogenic granites are associated, came into existence at or before 420Ma (Watson, 1984).

Several of the late orogenic granites and their associated minor intrusions show a complex interrelation with fault movements, for example intrusions emplaced in the Great

Glen Fault zone are affected by late movements of the Fault. Isotopically these granites show a shift to low initial Sr isotope ratios, although ϵ_{Nd} and the content of inherited zircons indicate a large crustal component (Table 5a).

The composition of this suite varies from alkaline complexes at the orogenic front such as Loch Borrolan and Ratagain, which probably contain a relatively high proportion of a juvenile component, to tonalite — granodiorite — adamellite complexes emplaced mainly in the Eastern Moines to the north of the Great Glen (Fig. 10 and 12). Some of the suite, for example the Helmsdale and Fearn intrusions, are adamellite. Many of the granites are indistinguishable geochemically and geophysically from their host rocks (Plant et al., 1980; Brown and Locke, 1979), although they generally have higher Ba, Sr and Zr contents and low radioelement levels. The isotopic and trace element chemistry of the intrusions, particularly of the older suites of intrusions emplaced up to 415Ma, is consistent with a lower crustal component possessing the trace element characteristics of the Lewisian complex (Fig. 11a). Many of the granites give upper intersection ages of 1600Ma (Pidgeon and Aftalion, 1978) which is too young for much of the Lewisian complex, and too old for Grenville basement (c.1100-1000Ma), although Halliday (pers. comm.) has suggested that the upper intersection may represent a Lewisian age which appears to be younger as a result of later events. The granites of this suite are thus classified as 'A' type granites (containing a large component of lower crustal granulite to upper amphibolite facies derived material) on the basis of trace-element and isotope chemistry.

Metalliferous mineralization and geochemical anomalies are associated only with the adamellite intrusions of Abriachan and Helmsdale granites which lie in the Great Glen Fault zone. These intrusions contain moderate enrichments of U, Mo, and Pb (Fig. 9).

The post-orogenic granites were emplaced from 415-400Ma into cool crust following regional uplift of the orogen in a regime of vertical block faults, some of which penetrated to mantle depth (Fig. 12) (Watson, 1984). They are found mainly in the SW and East Grampian Highlands (Fig. 10). In the Northern Highlands only the Grudie Granite (405Ma) is considered to represent the suite, although post-tectonic granites some of which cut Middle Old Red Sandstone rocks occur in Shetland. Almost all of the granites of this suite are metalliferous. They can be divided into three main groups on the basis of their petrology, trace-element geochemistry and geological setting as follows:

(1) Small diorite-granodiorite complexes of calc-alkaline affinity which lie mainly along two easterly trending lineaments in the west and southeast Grampians. The suite includes the Kilmelford, Garabal Hill, Arrochar, Comrie, Glen Tilt, Glen Shee and Glen Doll intrusions, the Glen Tilt and Glen Shee intrusions having invaded NE-trending faults (Watson, 1984). Nockolds, (1932) assigned a parental role to pyroxene-microdiorite for the intrusions, several of which are associated with mafic or ultramafic rocks occurring as the earliest intrusive phase. Trace-element patterns for the Kilmelford porphyrite and diorite (Fig. 1b) show that it is characterized by relatively smooth curves which either lack or have poorly developed negative Sr, Ba and Ti anomalies with low total Nb, Y and REE contents, the latter generally showing compatible behaviour. The trace-element patterns are consistent with limited hornblende-dominated fractionation of primitive calc-alkaline melt. Several intrusions are weakly mineralized, for example the

Glen Shee and Corrieyairack intrusions (Williamson, 1935 and 1936) and the Kilmelford complex which has Cu-porphyr style mineralization (Ellis et al., 1977). Isotopic systems based on K/Ar, Rb/Sr and U/Pb are likely to have been disturbed with increased or decreased ^{18}O contents, depending on the derivation and extent of boiling of ore-forming fluids. ϵ_{Nd} values are high at +5.8 to +0.4 and -3.7 for the Kilmelford and Garabal Hill complexes respectively (Halliday, 1984), indicating a predominantly juvenile composition.

(2) Large complexes of calc-alkaline affinity which contain higher proportions of granodiorite-adamellite and are frequently emplaced by ring faulting. One of the distinguishing features of this group is their association with apinites (although these also occur in the Ratagain complex, for example). The suite includes the Etive, Lochnagar, Ben Nevis and possibly the Ballachulish and Grudie intrusions. Adamellite intrusions of the suite such as the Starav intrusion are characterized by large negative gravity anomalies and by high Mo-U anomalies on geochemical maps. They occur mainly on WNW- or NNW-trending lineaments and form a particularly important group along the Cruachan line in the SW Highlands (Plant et al., 1984a). Trace element patterns for the Lochnagar complex (Fig. 2) show a considerably higher degree of fractionation than the intrusions of group (1), with clear negative Sr and Ba anomalies in addition to negative Ti and low Y and Nb values. REEs behave compatibly in these complexes which are strongly light REE-enriched. O, Sr and Pb isotopic data and trace-element studies of the Etive complex (Clayburn et al., 1983) suggest that it was formed in a lower crustal reservoir by interaction of melt derived from an enriched mantle source over the subducted Iapetus slab with melt derived from 'moderately unradioactive' lower crust. The trace-element chemistry is consistent with limited fractionation of individual intrusions following episodic mixing events in a deep magma chamber. Progressive depletion of successive intrusive phases in radiogenic Pb as well as enrichment in ^{87}Sr and ^{18}O in the later more evolved members of the complex is accompanied by increased Rb/Sr. Total U, Th, Mo and other incompatible trace-element contents show a similar trend. These trends could reflect a high degree of fractionation, but enrichment of the source shortly before magmatism is suggested by the lack of correlation between U and the radiogenic Pb isotopes. Moreover the Lochnagar intrusion which occurs near to the Sn-U granites of group (3) contains higher levels of Sn than granites of broadly similar composition such as the Etive complex to the west (O'Brien et al., 1985).

(3) Large high SiO_2 sub-alkaline granites which represent the high points of an easterly trending batholith more than 100km long occur in the East Grampian Highlands. These granites are not associated with contemporary basic magmatism or with tonalitic or granodioritic differentiates. The suite includes the Monadiath, Cairngorm, Glen Gairn, Mount Battock, Hill of Fare and Bennachie intrusions (diorites in the area are related to the Lochnagar centre). The granites are associated with a large negative gravity anomaly (Dimitripoulos, 1981) and throughout their outcrop they have significantly higher levels of trace elements than their host rocks which vary from the Central Highland Division (with an essentially Moine-like chemistry) in the west to Upper Dalradian greywacke-shales in the east. The most chemically evolved granites of the suite with the highest levels of Sn-U, Be, etc are the Cairngorm, Glen Gairn and Bennachie intrusions (Plant et al., 1980). The granites have particularly distinctive trace-element patterns

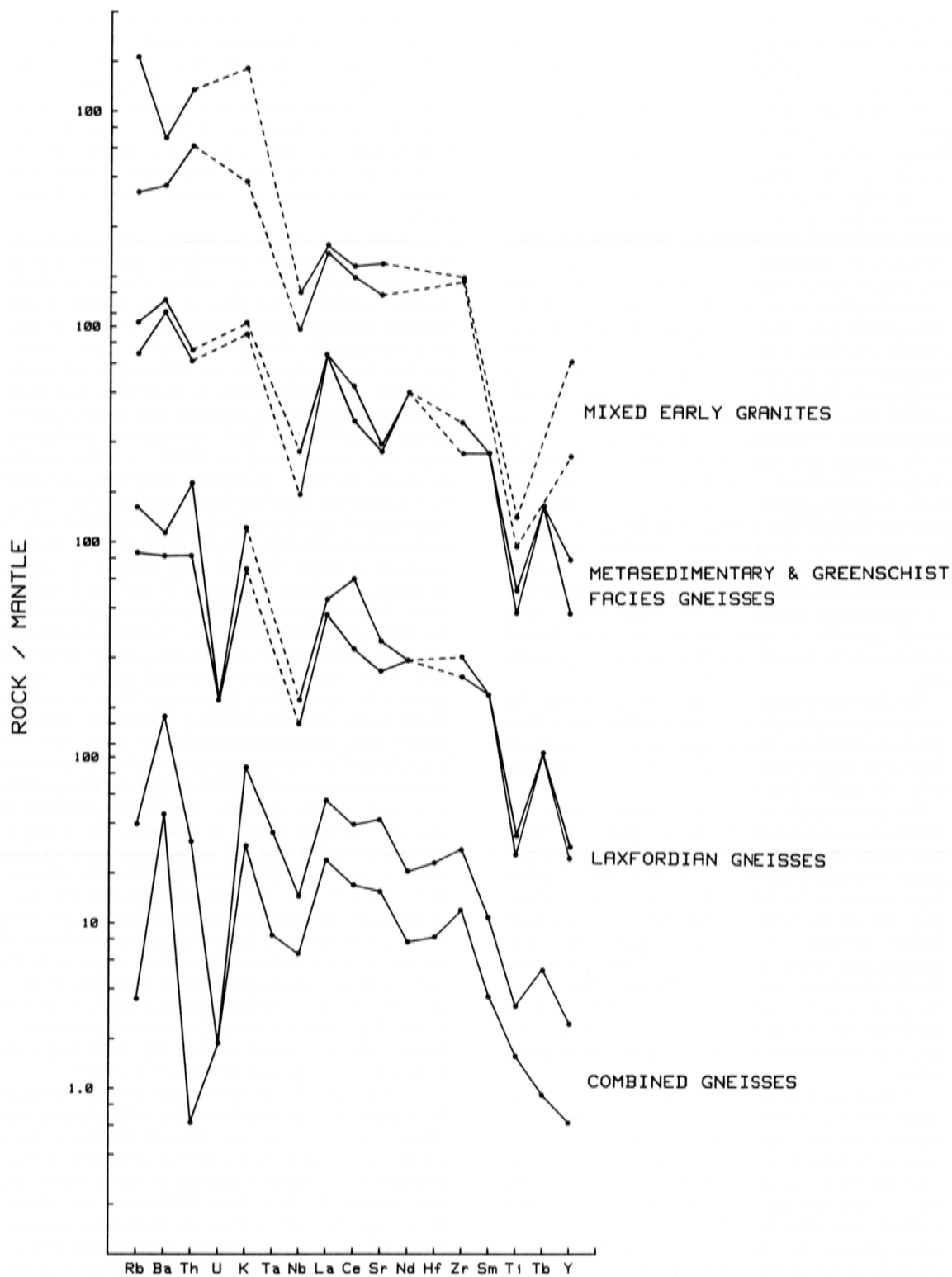


Figure 11a. Geochemistry of Lewisian Basement Complex. (Data from Tarney et al., 1972; Horsley, 1978; Drury, 1978 and 1980; Weaver and Tarney, 1980.)

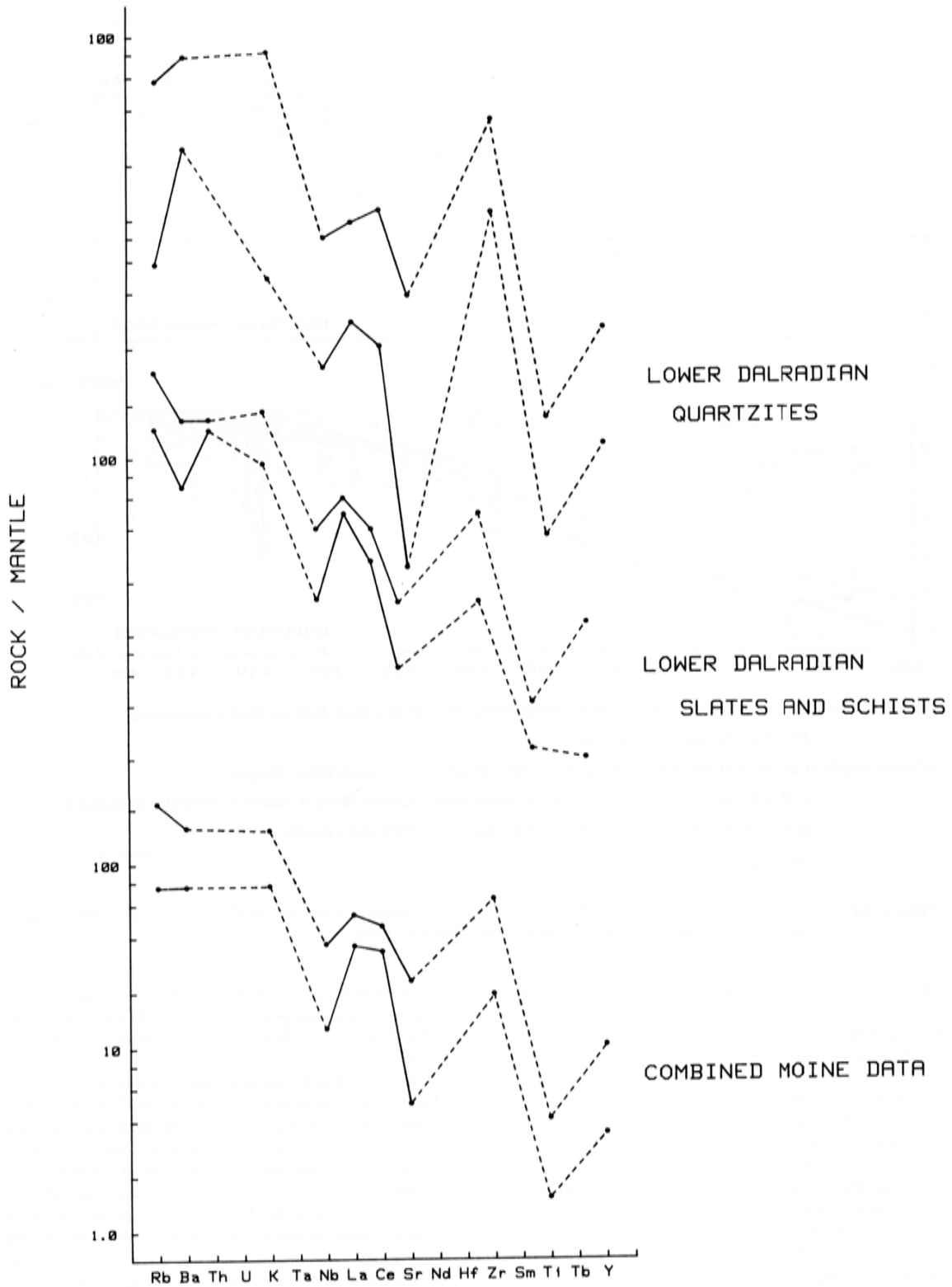


Figure 11b. Geochemistry of Moine-Dalradian cover sequence. (Data from Winchester et al., 1981; Lambert et al., 1981 and 1982; Hickman and Wright, 1982.)

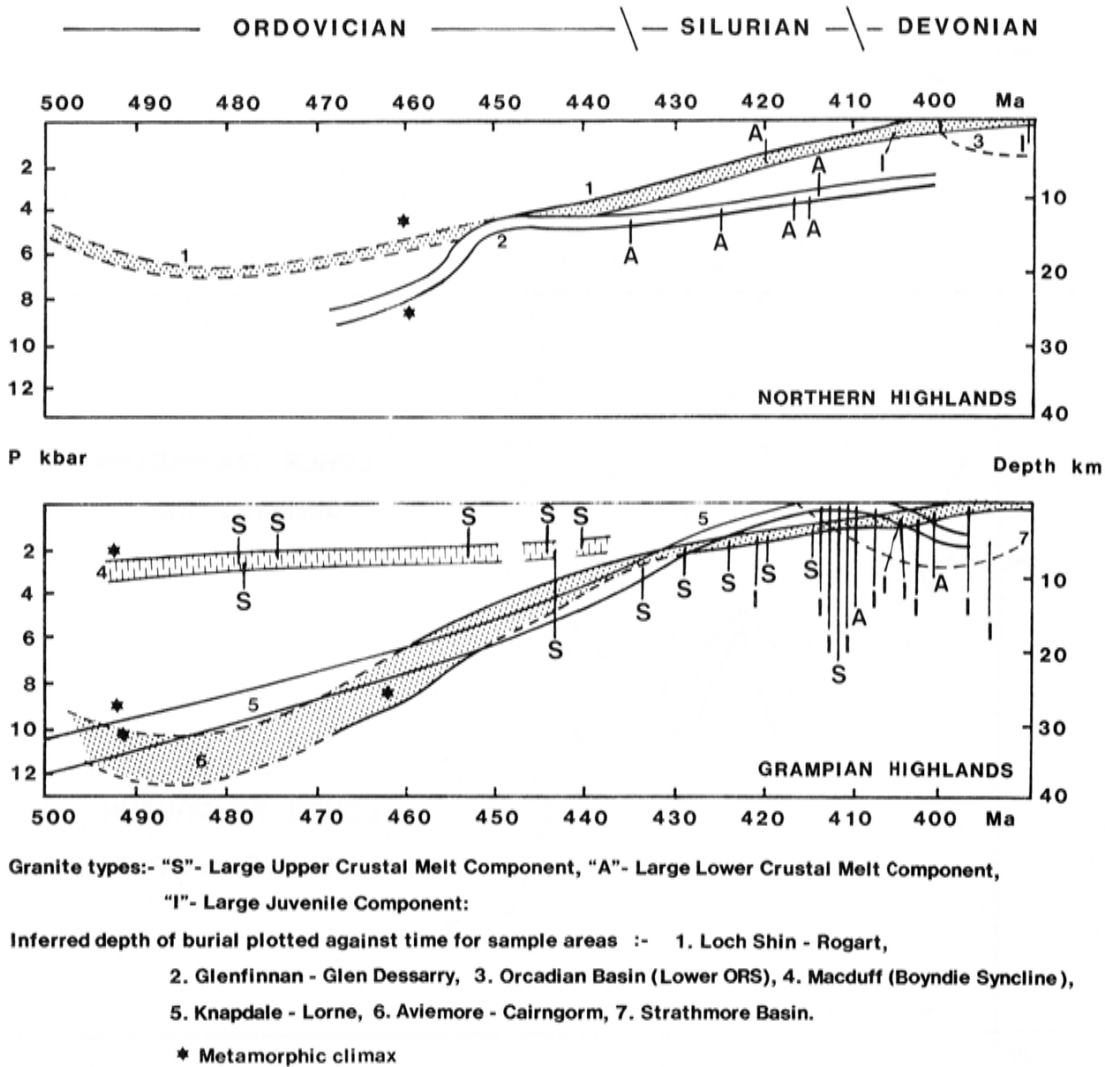


Figure 12. Inferred depth of burial plotted against time for sample areas of the Orthotectonic Caledonides of Northern Scotland. (Recovery paths after Watson, 1984)

and they are also characterised by heavy REE enrichment with well developed negative Eu anomalies and by the incompatible behaviour of REE (Plant et al., 1980). They can be modelled by the removal of a felsic melt containing mainly K-feldspar, plagioclase and biotite in which hornblende is unimportant. The very high levels of U, Th and Ta in the granites suggest that the melt was derived from sources lacking in stable minerals with an affinity for these elements. Deep crustal rocks contain accessories such as zircon, sphene, allanite and ilmenite which accommodate U, Th, and Ta, whereas such accessories are rare in mantle rocks. A juvenile source for the zircons in the East Grampian batholith is also suggested by the U-Pb systematics which identify only trace amounts in the Hill of Fare and Lochnagar intrusions. ^{18}O values for the granites are in the range 8.3-10.1% (Harmon and Barreiro, 1984) and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are <0.706 (Pankhurst and Sutherland, 1982). The Hill of Fare Granite has high ϵ_{Nd} values consistent with a predominantly juvenile origin although Halliday (1984) reports values for the Cairngorm intrusion of -6.3 . These granites, which on the basis of their trace-element patterns are identical to Sn-U granites, are considered to

represent post-orogenic intrusions of predominantly 'I' type juvenile origin (Simpson et al., 1979; Watson and Plant, 1979; Plant et al., 1980) (see also Halliday and Stephens, 1984a and b).

The post-orogenic metalliferous granites of Scotland are characterized generally by low initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios, moderately high ϵ_{Nd} ratios (the highest of the Highland granites) with only trace amounts of inherited zircons (Table 5a). ^{18}O isotope determinations of unmineralized intrusions are within the 'normal' range for granites (Taylor, 1977) with the highest values in the Cairngorm granite. These metalliferous granites, almost all of them enriched in incompatible elements such as Mo, are thus considered to be predominantly 'I' type granites.

Although many of the granites in Scotland are metalliferous they are associated with mineralization only (a) in zones that became sites of major fault systems when the granites were areas of high heat flow and fluid circulation, during the waning phase of the Caledonian orogeny (mineralization generally gave a low-temperature suite dominantly of U-Bi-F with subordinate Pb-Mo-Ba). Examples include the Helmsdale and Grudie Granites emplaced in

the Great Glen and Loch Shin Faults respectively. (b) Where the country rocks are at low grades of metamorphism, for example in the SW Highlands where metamorphism is at greenschist or epidote-amphibolite facies. These include the Mo-bearing Ballachulish intrusion, for which mineralization is also favoured by major fracture systems, and the Kilmelford — Garabal Hill (Arrochar) — Comrie Cu porphyry-style intrusions.

Metalliferous granites with high levels of Sn-U-Li-Be (the Monadhliath — Cairngorm — Mount Battock line of intrusions) are largely unmineralized, except where they cut pelitic or calcareous sediments at garnet grade. The potential for mineralization also exists where they cut hydrated Newer Basic Intrusions. The lack of mineralization is attributed to the anhydrous crustal setting in which the magmas were emplaced (Plant et al., 1983). A further factor may be the depth of erosion which has removed the volcanic and subvolcanic portions of complexes, except in a few cases (e.g. Kilmelford).

Granites of the Orthotectonic province in Ireland

The granites of the Orthotectonic Caledonides of Ireland can be related to the same episodes of magmatism identified in Northern Scotland (Fig. 8) (Leake, 1978). In both regions post-orogenic granites emplaced between 418-385Ma comprise the largest volumes of granite magmas and include most of the metalliferous and mineralized intrusions. In Ireland two main groups of such intrusions are important, the Donegal and the Galway Granites, both groups being emplaced in Dalradian rocks. The older granites such as the Oughterard (Galway) and Slieve Gamph complex in the Ox Mountains, which were contemporaneous with barren intrusions in Scotland, are not considered further.

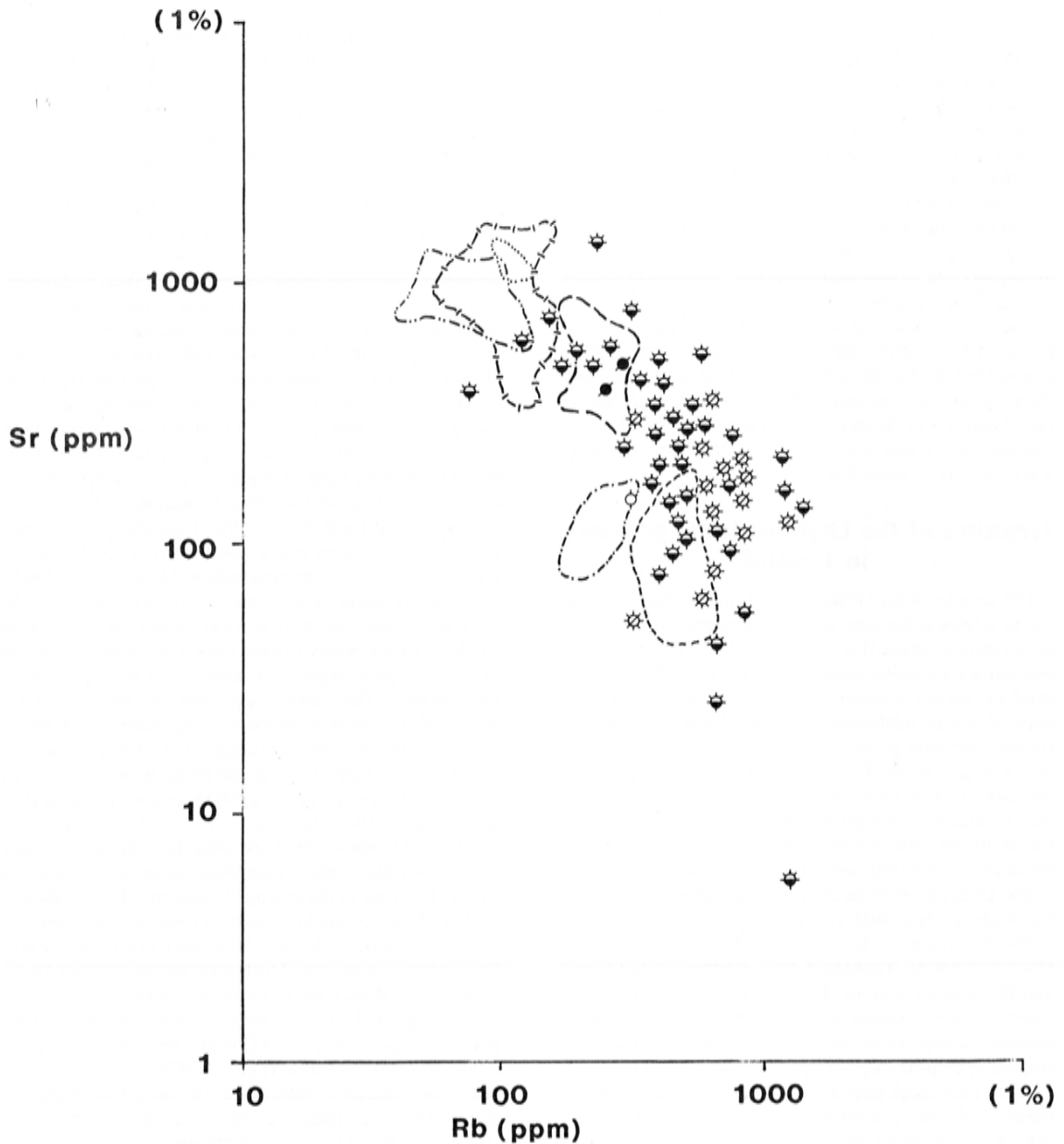
The Donegal Granites comprise eight plutons which, on the basis of their field relations, were emplaced in the following sequence: Thorr, Toories, Ardara, Rosses, Main Donegal Granite, Trawenagh Bay and the isolated Fanad and Barnesmore plutons (Pitcher and Berger, 1972). The Thorr, Toories, Ardara and Fanad plutons have the most primitive compositions and were variously emplaced by stopping or diapiric emplacement. The later Main Donegal, Rosses, Trawenagh Bay, and Barnesmore, which comprise mainly high silica calc-alkaline granites with low Fe_{total} and Mg, were emplaced by magmatic wedging or cauldron subsidence (Pitcher and Berger, 1972).

The major element composition of the Donegal Granites is comparable to that of the Helmsdale Granite or the calc-alkaline intrusions of porphyry Mo association. Few published trace-element data are available but U/Th and Rb/Sr (O'Connor, 1981; O'Connor et al., 1982) (Figs. 13a and 13b), suggest that the Donegal Granites fall into the field of evolved calc-alkaline intrusions. The crustal setting of the granites of the SW Highlands and those of Donegal are also broadly similar; both suites of intrusions were emplaced into the Lower Dalradian Ballachulish Group and show an association with old deep crustal discontinuities (Pitcher and Berger, 1972; Leake, 1978). Both groups are associated with apinites (which in Donegal occur mainly around the Ardara mass), and the Rosses intrusion and the Etive complex are also associated with dyke emplacement indicative of a tensional tectonic regime. Moreover, the age-relations of the two complexes (404Ma and 405Ma) are broadly similar, and the model developed for magma genesis of the Etive complex (Clayburn et al., 1983) seems appropriate for both regions. In the SW Highlands molyb-

denite mineralization has been identified in the Ballachulish intrusion (Evans et al., 1980), but with only minor Mo occurrences recorded in the Ben Nevis and Etive complexes, while U values in stream sediments and water samples are poorly correlated, suggesting that most U is in primary silicate minerals. There are indications however that mineralization may be favoured more in Donegal than the SW Highlands of Scotland. Hence, the Main Donegal Granite appears to have been emplaced in an active, major transcurrent fault zone which has moved intermittently during and following granite emplacement (Fig. 8) (Hutton, 1982), whereas in the SW Highlands only the relatively small, less evolved, Ballachulish intrusion shows such a relationship to the Great Glen Fault. The Main Donegal Granite has a wide synkinematic aureole and internal trains of xenoliths, which conform in their distribution to an original stratigraphy, penetrated and wedged apart by thick granite sheets, both the pluton and its aureole having been strongly deformed during the late stages of emplacement. An additional factor favouring hydration of the Granite during emplacement was the lithology and metamorphic grade of the country rocks which were at or below the greenschist facies of metamorphism (Long et al., 1983). High temperature water-rock interaction between the Donegal Granite and its host rocks during emplacement in the Knockateen Slide/Leannan Fault Zone may be reflected by the abundant pegmatites, aplites and microgranites in the complex. The various ages between 500 and 400Ma previously recorded by radiometric age dating methods for the Main Donegal Granite (Leggo et al., 1969; Halliday et al. 1980) also suggest re-equilibration of primary isotope systems, although an age of c.405Ma is now accepted. The large range of Th/U ratios (up to 10.3 for the Main Donegal Granite; O'Connor, 1981) are unlikely to be primary, and instead probably reflect mineralization associated with an overall decrease in the average U content of the batholith. U, Mo, Rb and Sr are likely to have been mobilized initially during this phase, although U may have been redistributed later at times of increased tectonism and/or increased magmatism. The Rosses and Barnesmore plutons are also tentatively suggested to be metalliferous and mineralized granites respectively (see O'Connor, this volume).

The Galway Granites (Leake, 1978) consist of small discordant cauldron subsidence or stock-like bodies of mainly biotite-granodiorite and adamellite, such as the Omev and Roundstone Granites and the large Galway batholith. The group includes some of the youngest granites in the Caledonian province of Britain and Ireland outside Shetland (Pidgeon, 1969).

The western end of the Galway batholith consists of a series of intrusions, the Carna, Errisbeg Townland and Murvey Granites, which range in composition from granodiorite to granite, the last phase being the Murvey muscovite-albite granite which is locally gametiferous. The main Galway Granite is a relatively voluminous composite batholith of >1000km² with a negative gravity anomaly (Murphy, 1981) indicating an extension of 4 to 8km depth in the crust (Leake, 1978). It intrudes migmatite gneisses of the Argyll Group Dalradian in the north and greenschist facies Ordovician of the South Connemara Group in the south. The sequence of events in the Dalradian host rocks is complex. Regional metamorphism to sillimanite grade (Buchan series after early Barrovian metamorphism) was followed by severe hornfelsing at the time of emplacement of basic and ultrabasic intrusions (Long et al., 1983). Subsequently migmatization and tectonism occurred in which the mafic rocks were incorporated into the gneiss. As in the case

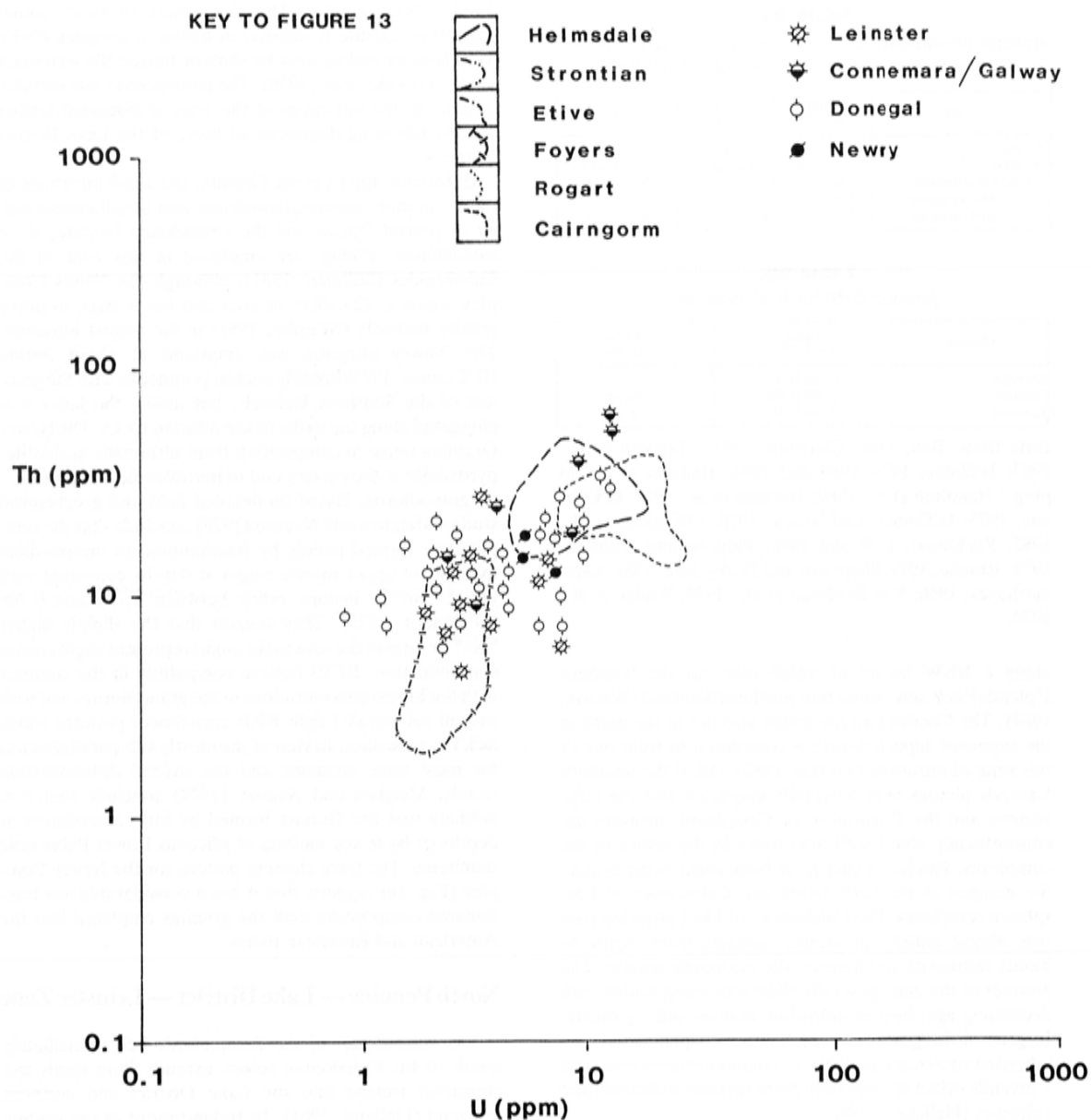


Figures 13a and 13b Examples of inter-element relations between Scottish and Irish granites (After Plant et al., 1980.) (Irish data from Wright, 1964; Leggo et al., 1966 and 1969; Brück and O'Connor, 1977; Meighan and Neeson, 1979; O'Connor et al., 1981.)

of the Main Donegal Granite, the Galway batholith is emplaced in a major fault zone which may represent the extension or a major splay of the Southern Uplands Fault of Scotland (Leake, 1978).

The crustal setting of the Galway granite, which is characterized by early Buchan metamorphism (although later obliterated) affecting Argyll Group Dalradian metasediments and associated with basic and ultrabasic intrusions, is reminiscent of the East Grampian region of Scotland in which Sn-U granites were emplaced. Moreover both the Connemara region of Ireland (Long et al., 1983) and the East Grampian region (Ashcroft, 1984) may represent separate blocks of different crustal histories to that of the main Dalradian terrain which is characterized by large scale recumbent nappes and Barrovian metamorphism. The Galway granites were emplaced somewhat later in the

Caledonian cycle however, and they show a greater range of composition than the Sn-U granites of Scotland. They were emplaced contemporaneously with the Mo porphyries of Scotland and the major and trace-element chemistry (Figs. 13a, 13b and 14) (Coats and Wilson, 1971) suggests an evolved calc-alkaline composition of Mo(U) association, comparable to that of the Starav intrusion of the Etive complex. Trace-element patterns (Fig. 14) and such geochemical criteria as the compatible behaviour of REE (Pankhurst and Sutherland, 1982) and high Sr/Y ratios also favour an evolved calc-alkaline rather than a Sn-U alkaline granite association. The emplacement of the Galway batholith in a major fault zone (depending on temporal relationships with fault movement) and the low metamorphic grade of the country rocks to the south of the batholith favour mineralization. Emplacement into Ordovician or Argyll



Group Dalradian rocks which are potential sources of S may also favour Mo or Cu sulphide mineralization, while emplacement of granites into basic rocks could have localized mineralization, had significant hydrothermal systems developed. Accounts of the petrography of some of the Galway Granites, such as the unusual Murvey intrusion, suggest the possibility that at least parts of the Granite complex have been affected by high temperature water-rock interaction, while tourmaline-muscovite-garnet lithologies which are reported to occur throughout the complex (Leake, 1978) are also tentatively suggested to be related to high temperature water-rock interaction.

Granites of the Paratectonic Caledonides

The granites of the Paratectonic Caledonides may be divided into those of the Southern Uplands — Longford

Down Zone which were emplaced into the accretionary prism together with those of the Midland Valley — Murrisk Zone emplaced over a northerly dipping subduction zone, and those of the North Pennine — Lake District — Leinster Zone emplaced into the southern (European) plate of the Caledonides over a southerly dipping subduction zone.

The Southern Uplands-Longford Down and Midland Valley-Murrisk Zones

Granites of the Southern Uplands together with those of the Midland Valley of Scotland are amongst the latest intrusions to be emplaced in the Caledonides (Fig. 8 and 9) (Pankhurst and Sutherland, 1982). The small intrusions of the Midland Valley, which are mainly dioritic, cut Old Red Sandstone rocks, while the three large plutons (all of which are associated with marked negative gravity anomalies) of Loch Doon, Cairnmore of Fleet and Criffel-Dalbeattie intrude Upper Ordovician, Lower Silurian and Upper Silurian sequences respectively. The intrusions lie

Table 5a.

Isotope characteristics of 'S', 'A' and 'I' type granites for the Orthotectonic Caledonides of Scotland.

Granite	Initial Sr ^{87/86}	Inherited Zircon	Nd
'S' type	0.710	Abundant	-10.6
'A' type	0.705-0.706	Abundant	+1.3 to -13.3
'I' type Cu porphyries	0.704-0.707	Trace	-5.8 to +0.4
Mo porphyries	0.706-0.707	Trace	-2.7
Sn-U granites	0.706-0.707	Trace	-1.8 to -6.3

Table 5b.

Isotope data for Irish granites.

Granite	Initial Sr ^{87/86}	Inherited Zircon
Donegal	0.705-0.706	n.d.
Galway	0.704-0.706	None
Leinster	0.704-0.710	n.d.

Data from: Bell, 1968; Clayburn, 1981; Clayburn et al., 1983; Halliday, 1979, 1980 and 1984; Halliday et al., in prep.; Hamilton et al., 1980; Harmon et al., 1984; O'Connor, 1975; O'Connor and Brück, 1976; O'Connor et al., 1982; Pankhurst, 1979 and 1982; Pidgeon and Aftalion, 1978; Rundle, 1979; Shepherd and Darbyshire, 1981; Summerhayes, 1966; Van Breemen et al., 1979; Wadge et al., 1974.

along a NNW lineament which may cut the Southern Uplands Fault and extend into northern Scotland (Watson, 1984). The Cheviot Granite which also lies to the north of the supposed Iapetus suture is considered to form one of this suite of intrusions (Le Bas, 1982). All of the Southern Uplands plutons were forcefully emplaced and the large plutons and the Cairnsmore of Carsphairn intrusion are concentrically zoned with acid rocks in the centre of the complexes. Patches of diorite or basic rocks occur around the margins of the Loch Doon and Cairnsmore of Carsphairn complexes. The Cairnsmore of Fleet intrusion consists almost entirely of granite, ranging from biotite to biotite-muscovite and megacrystic muscovite granite. The granites of this zone generally show increasing acidity with decreasing age, both in individual plutons and regionally. In general the granites of the Southern Uplands have no inherited zircons and positive ϵ_{Nd} values are consistent with a juvenile origin or derivation from juvenile sediments and volcanics (Halliday, 1984).

The Loch Doon intrusion has been successfully modelled petrogenetically (Tindle and Pearce, 1981) using *in situ* fractionation, while the Cairnsmore of Fleet intrusion has a trace element pattern which is closely similar to Etive or Lochnagar (O'Brien, 1985). A general model for the Southern Upland granites (Harmon, 1983; Halliday, 1983; Harmon et al., 1984; Halliday and Stephens, 1984) has been proposed, however, which involves mixing of an upper mantle/lower crustal magma of intermediate composition with partially melted country rock sediments to form felsic differentiates in the cores of the intrusions. The potential for mineralization in the first model depends on magma composition and the extent of water-rock interaction, whereas in the second model the composition of sediments is of importance. In the Southern Uplands, Cu and Au-As mineralization is associated mainly with minor intrusions emplaced before the granite plutons (Fig. 9), for example the Black Stockarton Moor subvolcanic diorite complex (Leake et al., 1981) which was emplaced ahead of the main Criffel-Dalbeattie mass and also the Glen Head diorite complex to the south of the Loch Doon pluton (R. C.

Leake, pers. comm.). The Cairnsmore of Fleet biotite-muscovite granite is unusual in having a complex Pb-Zn vein field extending over its shallow buried SW extension (Fig. 9) (Leake et al., 1978). The petrogenesis and metallogenesis of the intrusions of this zone is discussed further below, following discussion of those of the Lake District granites.

In Ireland, the Corvock Granite, the small intrusions of biotite-granite, biotite-granodiorite and hornblende-tonalite of central Tyrone and the Crossdoney Granite, all of calc-alkaline affinity, are emplaced in this zone of the Caledonides (Stillman, 1981), although the Newry Complex which is 42×10km in area and has a large negative gravity anomaly (Murphy, 1981) is the largest intrusion. The Newry intrusion was emplaced at about 399Ma (O'Connor, 1975) broadly contemporaneous with the granites of the Southern Uplands, but unlike the latter it is elongated along the strike of the Silurian rocks. The Newry Granites range in composition from ultramafic peridotite-pyroxenite at the eastern end to hornblende and porphyritic granodiorite. Based on detailed field and geochemical studies Meighen and Neeson (1979) conclude that the complex was formed mainly by fractionation of intermediate magmas of upper mantle origin at depths consistent with initial $^{87}Sr/^{86}Sr$ isotope ratios between 0.705 and 0.706 (O'Connor, 1975). They suggest that the slightly higher $^{87}Sr/^{86}Sr$ ratio in the acid rocks might represent slight crustal contamination. REEs behave compatibly in the complex with the lowest concentrations in the granodiorites and with overall sub-parallel light REE enrichment patterns which lack Eu anomalies. In view of the mostly sub-parallel trends for most trace elements and the overall differentiation trends, Meighen and Neeson (1979) conclude that it is unlikely that the Granite formed by bulk assimilation at depths or by *in situ* melting of siliceous Lower Palaeozoic sediments. The trace element pattern for the Newry Complex (Fig. 14) suggests that it has a considerably less fractionated composition than the granites emplaced into the American and European plates.

North Pennine — Lake District — Leinster Zone

The central part of the Paratectonic belt immediately south of the Caledonian suture extends from south and southeast Ireland into the Lake District and northern England (Holland, 1981). In Ireland more of the leading edge of the European plate, comprising marine argillaceous sediments and limestones associated with basalts and andesites (frequently pillow lavas) with very few acid rocks, is preserved (Fig. 7). Further to the SE, the rocks of the Leinster region are considered to represent an environment more distal from the subduction trench with many of the features of a thickened continental margin. It is this zone which is preserved in the Lake District and northern England, and into which post-orogenic granites were emplaced in Ireland and England. Considerably more mineralization is recorded for the Leinster Granite in Ireland and the intrusions in the Lake District and North Pennines than similar intrusions to the N of the Iapetus suture.

In England the post-orogenic granites include the Shap and Skiddaw intrusions of the Lake District (Firman, 1978) and the large buried batholiths shown by geophysical evidence to extend beneath the Lake District and the North Pennines (Weardale and Wensleydale) (Figure 9) (Bott and Masson-Smith, 1957). The Eskdale intrusion may also belong to this suite. The exposed granites of Shap, Skiddaw

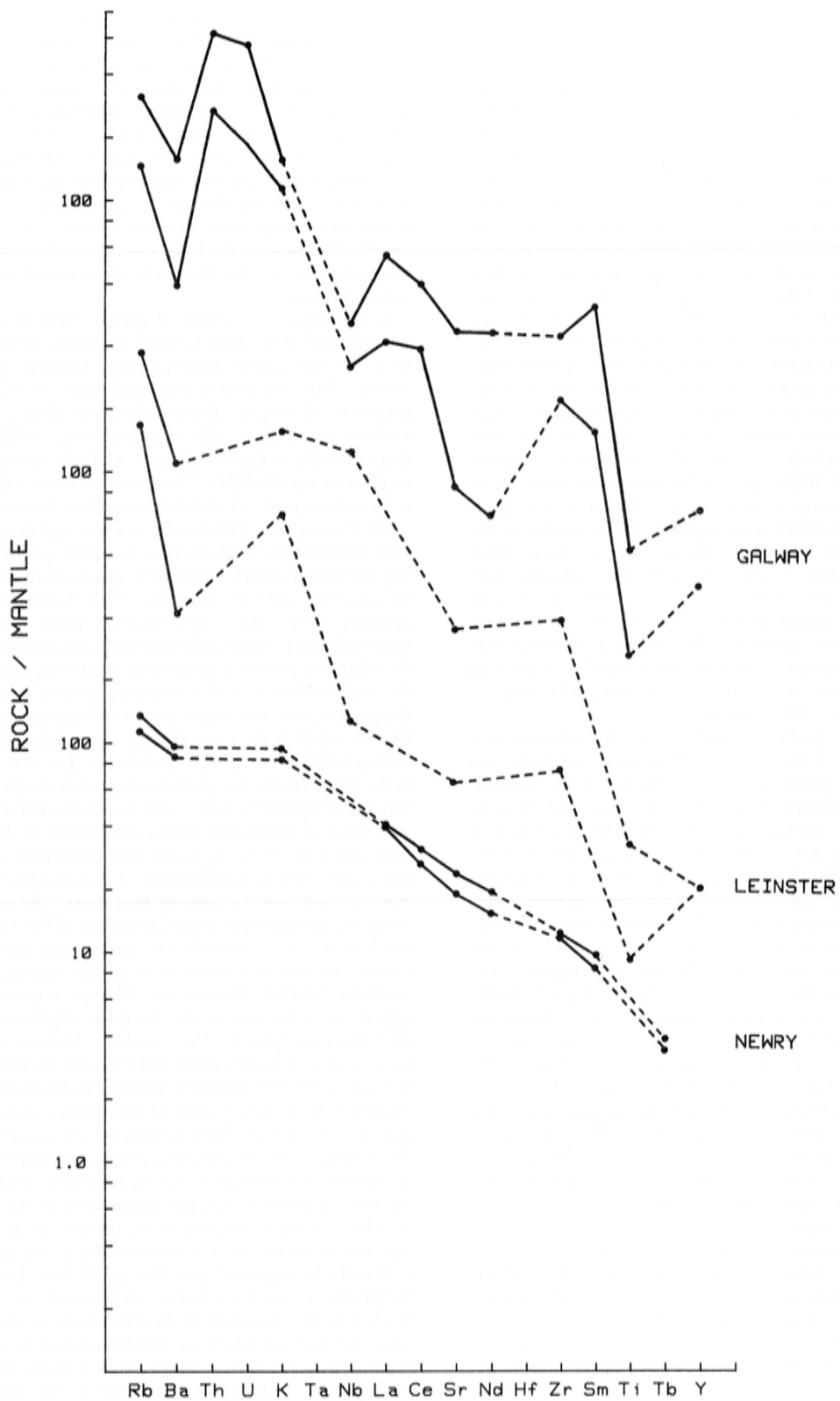


Figure 14. Primordial mantle normalized trace element plot for Irish granites. (Data from Coats and Wilson, 1971; Brück and O'Connor, 1977; Meighan and Neeson, 1979.)

and Eskdale, like those of the Southern Uplands, have been described as 'S' type (Halliday, 1983; Harmon, 1983) mainly on the basis of Sr and O isotope systematics. Detailed geochemical and petrological studies (O'Brien et al., 1985; in press) in relation to O isotope studies (Greenwood et al., in press) indicate however that the Shap, Skiddaw and Eskdale Granites have been affected by pervasive high to low temperature metasomatism accompanied by large scale remobilization of such elements as K, Rb, Sr, U, Li, B, and Pb (e.g. Fig. 6b) and of REE and some HFS elements near to 'greisen' veins. Re-equilibration of the K-Ar, Rb-Sr and U-Pb systems is thus likely to have occurred. The Eskdale, Shap and Skiddaw Granites are shown by O'Brien et al. (1985, in press) to be 'I' type intrusions with a progressive evolution towards more complex geochemical patterns reflecting decreasing hornblende and increasing plagioclase control of magmatism as in the case of granites in the Orthotectonic Caledonides; these Granites fit most closely into the group of evolved calc-alkaline intrusions of porphyry-Mo association. A model of subcrustal magma genesis beneath an evolving arc or continental margin comparable with that used for the Etive Complex is considered appropriate for the granites of the Lake District while the episodic mineralization which affects the area is related to a broad geothermal field consequent upon emplacement of the HHP Lake District batholith. A similar model for mineralization in the North Pennines seems appropriate. Preliminary geochemical data suggest that garnet was a particularly important control on magma genesis, as indicated by low heavy REE contents (Brown et al., 1986, in press).

In Ireland, the Leinster batholith which is emplaced into a sequence of folded Lower Palaeozoic sediments and volcanics at greenschist facies (Brindley, 1973; Stillman, 1981) is contemporaneous with the Shap and Skiddaw intrusions of the Lake District, with a Rb-Sr whole-rock age of about 404 ± 24 Ma (O'Connor and Brück, 1978; Murphy, 1981). It is a large composite body comprising five simultaneously intruded diapiric units, between which screens of country rock pass into zones of xenoliths in the Granite. Several types of granite occur within each unit among which adamellites generally predominate. The Northern Unit has been shown to range from quartz-diorite to granodiorite to adamellite (Brindley, 1973; Brück and O'Connor, 1977). Trace element patterns are consistent with evolved calc-alkaline intrusions of porphyry-Mo association (Fig. 14), although they suggest that U and other radioelements may have been depleted (Fig. 13b). The primary units are all affected to varying degrees by megacrystic growths of such minerals as K-feldspar and muscovite, with the development of late tourmaline and topaz locally, particularly in Type III granites. Veins of aplite and pegmatite containing muscovite, accessory zircon, tourmaline and garnet are particularly common in the Leinster Granite. Type III and IV granites of the complex, which are essentially muscovite-granites, have been interpreted as having been affected by late hydrothermal alteration (Brück and O'Connor, 1977) and it is tentatively suggested here that such features as the pegmatites, aplites and the extensive growth of late megacrysts are generally indicative of large-scale reaction between the batholith and its host rocks through a fluid phase. The re-equilibration of isotope systems by interaction of fluids derived from the Ordovician host rocks would provide additional evidence of such a process. The Leinster batholith may be broadly equivalent to the buried HHP batholiths of Northern England, representing a lower structural level

of a related geothermal field. Th/U ratios show a wide scatter (O'Connor et al., 1982) and are considered to be affected by hydrothermal and other alteration. Hence it is likely that early high-temperature mineralizing events, and several episodes of low-temperature mineralization (U, Zn, Pb) driven by residual heat production of the Granite, might occur in the region. The Leinster Granite is also interesting in its association with appinites and lamprophyres which are used elsewhere in the Caledonides as evidence of control of magmatism by deep faulting. The Leinster Granite like those of the Lake District is interpreted here as juvenile, but affected by high to low temperature water-rock interaction.

Several separate outcrops of granite occur beyond the southern end of the main Leinster batholith, extending as far as the Slievenamon area of County Tipperary (Charlsworth, 1963), but little is known of these. The Carnsore granite in SE Ireland (Baker, 1968) has given an Rb-Sr isochron age of 536 ± 6 Ma (Leutwen et al., 1972), and is therefore early or Pre-Caledonian, while the Saltees Granite gives an age of 430 Ma. These intrusions are considered to be unfavourable for metalliferous mineralization.

The Paratectonic Caledonides granites and their associated metalliferous mineralization, therefore, can be divided into two broad groups which were emplaced in the accretionary prism and European plate of the Caledonides respectively. In the accretionary prism recorded mineralization is mainly porphyry-type and connected with the relatively primitive precursors of granite plutons. In the southern belt it is of a relatively evolved continental margin character, and is associated with large granite batholiths for which in the Lake District and northern England there is evidence of high heat production (Lee et al., 1984). In the southern belt the granites are predominantly 'I' type which have acquired 'S' type O and Sr isotopic characteristics as a result of interaction with a fluid phase in the crust. Although some of the intrusions give Ordovician ages this may result from re-equilibration of isotope systems with fluids derived from Ordovician host rocks. The extensive muscovite development in the Cairnmore of Fleet Granite, which is associated with Pb-Zn veining, may represent a similar phenomenon rather than partial melting. If the Southern Uplands granites are 'S' type however, they appear, as in the case of the Northern Highlands, to be predominantly barren. The Southern Uplands granites occur in an accretionary prism and Cu porphyry mineralization associated with primitive magmas might therefore be predicted. Nevertheless some of the granites of the region appear to be more evolved. Isotope information precludes the melting of ancient granulites which are thought to form the basement of the region, but the possibility remains that the evolved granites and their sequence of evolution may be related to the foundering of the remains of the Iapetus slab into the mantle after active subduction had ceased. It is tentatively suggested that this could have led to the progressive removal of fusible components as the slab reached depths equivalent to the amphibole-out and phlogopite-out reactions which are passed sequentially at depth along dipping subduction zones. Such a model may also explain the close temporal association of the three main types of metalliferous granites in the East Grampians of Scotland.

Discussion and conclusions.

In the Caledonides, the distinction between barren,

metalliferous and mineralized intrusions is temporal. In northern Scotland orogenic and late-orogenic granites which contain large upper and lower crustal components ('S' and 'A' type granites respectively) are mainly barren. Increased contents of Mo, U and other metals are associated with 'A' type granites such as the Helmsdale intrusion only where they occur in the large transcurrent fault systems which cut the Old Moine — Lewisian block after c.430Ma. In the southern Caledonides the Ordovician intrusions of Threlkeld, Ennerdale and the Carrock Fell Complex in the Lake District are barren.

The main metalliferous granite suite was emplaced in the northern and southern plates and in the accretionary prism of the Caledonides following uplift and recovery of the crust shortly after the main suturing event. In Ireland the Late Caledonian granites of Donegal, Galway, Newry and Leinster are considered to represent this suite on the basis of their age, low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Table 5b) and trace element patterns (Figs. 13a, 13b and 14).

Three types of metalliferous granites, including Cu and Mo porphyries and granites of Sn-U association, are distinguished. Intrusions of porphyry Cu association occur mainly in the south and southwest Grampian Highlands and in the Southern Uplands of Scotland. They comprise small calc-alkaline complexes associated with ultramafic or mafic rocks and have juvenile isotopic compositions and relatively unfractionated trace element patterns. The primitive geochemistry of Cu porphyries makes identification difficult. Nevertheless the small intrusions cutting Ordovician and ORS rocks in Tyrone may merit investigation. The leading edge of the European plate which forms the basement of southern Ireland, and over which several occurrences of Ba-Pb-Zn mineralization are developed in the Carboniferous cover sequence, may also contain buried Cu porphyries similar to Crossdoney. In England this zone is missing north of the Lake District (Phillips et al., 1976).

Sn-U granites which have distinctive geochemical and geophysical characteristics occur only in the East Grampian Highlands of Scotland. No granites of this association have been identified in Ireland on the basis of available data.

The third group of metalliferous granites are the evolved calc-alkaline diorite — tonalite — granodiorite — granite complexes many of which are associated with appinites and enrichments of Mo and/or U. They have predominantly juvenile isotopic compositions although the Etive intrusion which lies along the faulted edge of the Pre-Caledonian crystalline Moine complex contains a lower crustal component. It is these granites which, on the basis of their age-relations, geophysical expression and trace element patterns, are considered to be most like those of Donegal, Galway and Leinster. In England the Shap and Skiddaw intrusions have similar trace element patterns and are assigned to this suite, together with the buried Lake District and Weardale and Wensleydale batholiths.

The composition of the different granite suites cannot be related simply to melting of distinct source regions as suggested by Browne and Locke (1979) or simply to different degrees of fractionation as suggested by Halliday and Stephens (1984). Hence Mo porphyries are considerably more fractionated than Cu porphyries consistent with the emplacement of large quantities of more evolved calc-alkaline magmas in subcrustal magma chambers and a change from hornblende-dominated to hornblende-and-plagioclase-dominated fractionation. The appinites with which such granites are commonly associated perhaps represent the sub-crustal cumulate assemblages. Sn-U granites involve increased quantities of magma of more evolved

composition in which fractionation is dominated by plagioclase and K feldspar and in which hornblende and sphene are unimportant. The distinctive geochemical features of such granites point to common features in the processes of partial melting and subsequent magmatic evolution (Lehman, 1982).

Some of the highly incompatible elements (particularly Mo) show little relation to fractionation, and elevated levels occur in granites ranging from low to high SiO_2 contents. In Scotland U contents are also poorly correlated with radiogenic Pb isotopes. In the East Grampians, Sn-U granites, evolved calc-alkaline Mo porphyries, and Cu porphyries were all emplaced in a relatively narrow zone over the same time interval. Moreover, the Lochnagar intrusion which has a closely similar trace element geochemistry and setting to the Etive Complex, but which occurs near to the Sn-U granites, has higher levels of Sn than the Etive Complex but low Mo levels. Further evidence of regional changes in source composition is suggested by appinites which are enriched in similar suites of metals to granites in the same region, their composition varying across Scotland (Stephens, pers. comm.). Compositional zoning of the mantle/lower crustal source region of the metalliferous granites is thus required to account for changes in the levels of the highly incompatible elements. Such a model is also required to account for such differences as the paucity of Sn-U granites in the Caledonides compared to the Hercynian province. In Scotland all the metalliferous granites are located along major lineaments, those of Sn-U and Cu porphyry association lying on easterly trending faults, with those of evolved calc-alkaline intrusions of U-Mo association lying on faults of different orientations. Geochemical changes are thus not progressive across Scotland as suggested by Thirlwall (1982) but are discontinuous and are related to the emplacement of granites in deep crustal lineaments.

In Scotland significant mineralization is reported mainly from intrusions such as Ballachulish and Kilmelford in the SW Highlands and the Grudie and Helmsdale Granites in the north. The general lack of mineralization has been attributed to the anhydrous crustal setting during granite emplacement and the depth of erosion; moreover metalliferous intrusions are mostly emplaced in the subsidiary easterly or NW-trending fault sets. In England mineralization occurs mainly in the Paratectonic Caledonides where in the Lake district and North Pennines it is spatially associated with large buried HHP granite batholiths. The change in the isotopic compositions (particularly oxygen) of mineralized intrusions is related to high level reactions between granites and their host rocks by means of a fluid phase. In Ireland mineralization is favoured by the occurrence of the most evolved granites in the major NE-trending fault zones which affect the Caledonides. This may be reflected by the elongated form of most of the Irish granites, although differences between the shape of British and Irish granites may in some cases reflect the depth of erosion. The low metamorphic grade of the host rocks in which the Leinster and Newry Granites and the southern part of the Donegal Granite are emplaced would also have favoured water-rock interaction during emplacement of the Granites in the crust. Evidence of re-equilibration of isotopic age dates, dispersion of Rb/Sr and U/Th ratios and the occurrence of tourmalinization, albitization, muscovite and microcline megacrystic growths, particularly in the Leinster Granite and parts of the Donegal and Galway intrusions may also indicate hydrothermal activity.

In Britain the Caledonian post-orogenic metalliferous

granites provided large volume sources of metals which became enriched in the Old Red Sandstone basin of Caithness and Orkney (Plant et al., 1984a; in press). They were also important in localizing Permian-Carboniferous Ba-Pb-Zn-F mineralization in the Pennines of Northern England partly as a result of their high heat production (Brown et al., 1979). In Ireland the Main Donegal and Leinster Granites contain evidence of a late post-magmatic episode of pitchblende mineralization and such granites, if they occur in the basement, may have played a role in localizing Irish style mineralization in the cover sequence. Hydrothermally altered granite ('syenite') appears from gravity data (Murphy, 1981) to extend beneath the Navan orebody, for example, and similar negative gravity anomalies associated with Irish style mineralization are described by Phillips and Sevastopulo (this vol.). The emplacement of the Caledonian post-orogenic granite suite during the late Silurian — Lower Devonian thus introduced large quantities of metals and heat producing elements to high levels of the crust in an event which may have influenced metallogenesis in northern England, Scotland and Ireland until at least Permian times.

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