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The chemical character of the Late Caledonian Donegal Granites, Ireland, with comments on their genesis

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ABSTRACT: The Late Caledonian granites of Donegal are all intruded into metasediments of the Dalradian Supergroup of Neoproterozoic age, which were metamorphosed and deformed during the Grampian Phase of the Caledonian orogeny at *c.* 470–460 m.y. They were intruded in a singular pulse well after the main tectonic event, apparently peaking at 407–402 m.y.; importantly after the strong collision of Laurentia with Baltica on closure of the Iapetus Ocean. The plutons are mainly made up of granodiorite and granite, and are all 'I' type, but different to Cordilleran 'I' types of the eastern Pacific margin. Major element chemistry indicates they are high-K calc-alkaline rocks with a large range in SiO_2 content. However three of the plutons (Fanad, Thorr, Ardara), have very high Ba and Sr contents, even higher than Mainland Scotland counterparts; they are high Ba–Sr plutons. Three plutons (Barnesmore, Rosses, Trawenagh Bay) are evolved and are low-Ba–Sr types, while one (Main Donegal) has atypical, intermediate characteristics. The origin of the magmas is still much debated; here we suggest slab breakoff on Iapetus Ocean closure accounts for the special compositions of these magmas and the other major features of Late Caledonian granitic magmatism, including the singular intrusion peak and the associated appinite–lamprophyre suite.

KEY WORDS: Appenite, high Ba–Sr granite, slab break-off

The granites of Donegal lie in the orthotectonic or metamorphosed, strongly deformed zone of the British Caledonides (Dewey 1969). They are intruded into a sequence of metasediments and metadolerites which belong to the Dalradian Supergroup of Neoproterozoic age, specifically the Ballachulish subgroup of the Middle Dalradian (Fig. 1). These rocks were metamorphosed to upper greenschist facies and deformed during the Grampian phase (McKerrow *et al.* 2000) of the British Caledonian orogeny. Until recently, timing of the tectonometamorphism in the orthotectonic zone has been contentious. However, recently Dewey & Mange (1999) have averred that the problem of timing "is now regarded as solved" (p. 56). They put forward a short orogeny from *c.* 470–460 m.y.

Caledonian granites have been divided in Scotland into 'Older' and 'Newer Granites' by Read (1961). The 'Older Granites' or 'S' types (two mica granites) are usually associated with, and generally coeval with high grade Grampian regional metamorphism which climaxed at *c.* 468 m.y. (Dewey & Mange 1999). However they also include 590–600 m.y. granites such as Ben Vuirich, which are much commoner than originally thought. The 'Newer' or 'Late Granites' (Read 1961) form a major intrusive group emplaced 40–50 m.y. later, well after the main tectonic events, towards the end of the Caledonian orogeny. These granites are referred to in the present paper specifically as the 'Late Granites' to emphasise their post-climatic orogenic character.

In Donegal, Rb–Sr intrusion ages of the granites appear to range from 418 to 397 m.y., with 75% lying between 407 and 402 m.y. (O'Connor *et al.* 1987). This is similar, though with a narrower range, to the Siluro–Devonian Late Granites of mainland Scotland, which appear to have emplacement ages of around 435 to 390 m.y., with an apparent maxima between 410 and 400 m.y. (Soper 1986). In contrast to mainland Scotland, the ages indicate the Donegal granites are all 'Late Granites', there are no 'Older' or 'S' types. U–Pb ages on zircons, titanites etc. will be needed to confirm the age range, as the Rb–Sr dates could be misleading, recording a general cooling age. Indeed, very recent U–Pb work together with assessment of the Rb–Sr data suggests emplacement of the Donegal plutons occurred *c.* 428–400 m.y. ago (Condon *et al.* 2006), closer to the Late granites of mainland Scotland.

Workers on Siluro-Devonian magmatism in Scotland have long recognised the relatively short duration of activity and a pronounced, singular age peak (Brown *et al.* 1984; Soper 1986, Thirlwall 1988). This age structure is a critical element of Late Granite magmatism which contrasts markedly with Cordilleran supra subduction magmatism e.g. the Coastal Batholith of central Peru which was assembled over 80 m.y. or more and where magmatism is distinctly episodic with quiescent periods longer than 15 m.y. and where individual segments show different age sequences (Pitcher *et al.* 1985).

1. An outline of the Caledonian Orogeny

To understand the geotectonic setting of Late Granite magmatism it is important to outline some significant aspects of the Caledonian orogeny in the British Isles and Scandinavia, particularly during the closing stages (Scandian Phase). The Ordovician Grampian Phase at *c.* 470 to 460 m.y. is generally accepted to have been due to collision of the rifted Laurentian margin with a continent facing arc (Dewey & Shackleton 1984). In this model subduction flip occurred during or after the Grampian Phase, so the Iapetus Ocean floor plus the newly accreted arc was subducting beneath Laurentia by Caradocian times. This subduction polarity continued until the Silurian closure of the Iapetus Ocean and is an important component of the Late Granite story.

Ordovician tectonometamorphism does not appear to continue into East Greenland, where the first major Phanerozoic contractional deformation, the Scandian Phase, occurred in the mid-Silurian. This event was the result of the collision of Baltica and the Scoto–Greenland margin (Soper *et al.* 1992).

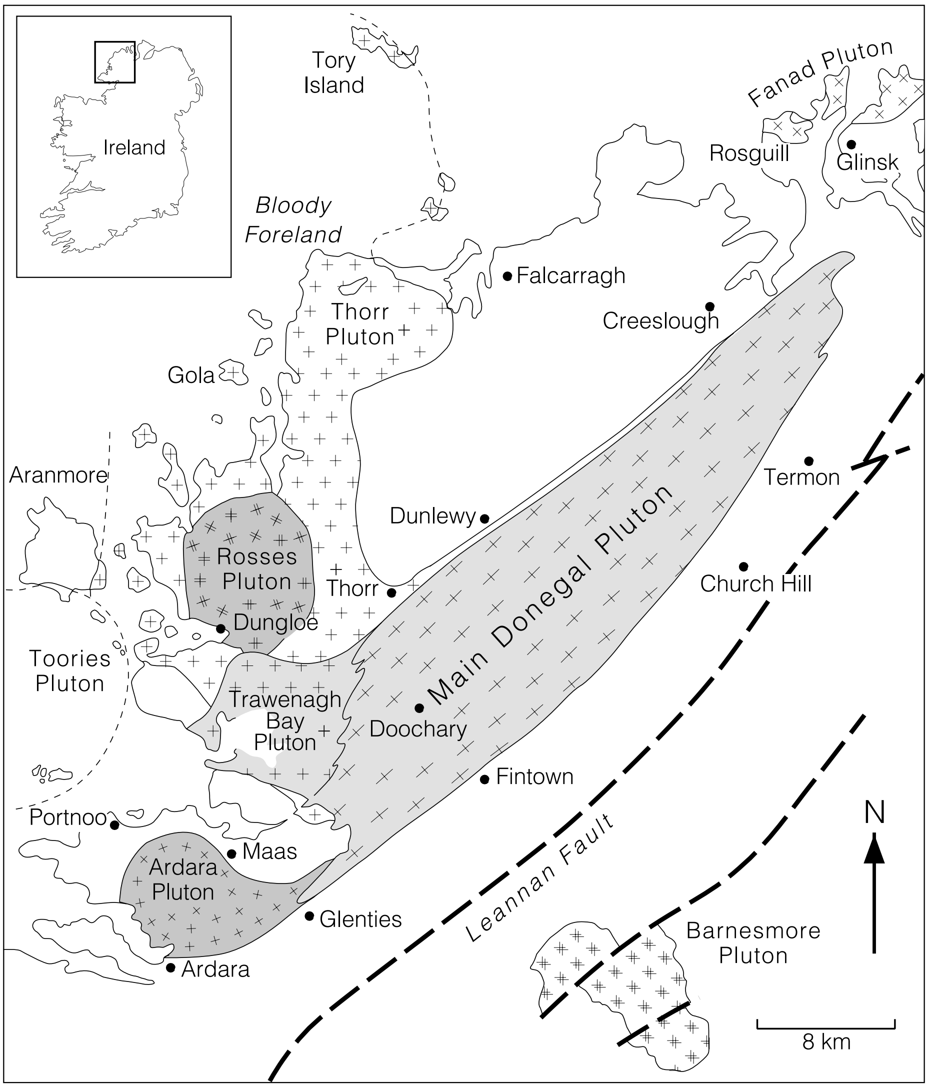

Figure 1 Simplified map of the Donegal Late Granite plutons which are intruded into metasediments and metadolerites of the Dalradian supergroup (no symbol). Note the isolated position of the Barnesmore Pluton, south of the Leannan Fault. The Toories pluton is shown for completeness but is not considered further due to lack of data and paucity of exposure.

It generated the Moine Thrust-related deformation in the Scottish Highlands and was followed by major sinistral strike slip, which was important in controlling the emplacement of the Donegal Late Granites (Hutton 1988) and those in Scotland (Jaques & Reavy 1994).

In the Scandinavian Caledonides, imbrication in a crustal scale stacking of thrust sheets marked the collision at about 435 m.y. (mid-Llandovery). Late Granite pluton emplacement in Donegal is at least 17 m.y. later, assuming intrusion ages are correct. Even if the high precision ages on zircon, etc. from appinitic rocks associated with the Late Granites in the West Highlands of Scotland (429–422 m.y.; Rogers & Dunning 1991) imply that the '400 m.y.' Late Granite ages across the whole British Isles sector may be too young, emplacement on the basis of this new data occurred between 13 and 6 m.y. *after* the strong docking or collision of Laurentia with Baltica. This is perhaps the dominant paradox of Late Caledonian calc-alkali magmatism, but is a critical element in any model put forward to explain its genesis.

2. Petrology and field relations of the Donegal Granites: a synopsis

On the basis of mineralogy, the Donegal granites are mainly made up of monzogranites and granodiorites, some quartz monzodiorites, and minor tonalite, quartz diorite and quartz monzonite (Fig. 2). They belong to the calc-alkaline granodioritic series of Bowden *et al.* (1984). Rocks from the Rosses, Barnesmore and Trawenagh Bay plutons and some from the Main Donegal pluton plot in the upper centre of the diagram; they are monzogranites and are clearly distinguished from those from Ardara, Thorr and Fanad which extend to more basic compositions.

These more basic plutons have amphibole plus sphene rock assemblages characteristic of 'I' type granites and none have the cordierite, aluminosilicates, monazite or early garnet, typical of 'S' type granites. Secondary muscovite occurs in the evolved rocks of the Main Donegal pluton and the hydrothermally altered rocks of the Rosses and Barnesmore plutons. The only 'primary' muscovite is in the muscovite granite of Trawenagh Bay. Minor late garnet is present in some pegmatitic-aplitic facies of these felsic granites (Pitcher & Berger 1972). Brief notes on the field relations, rock types and mineralogy of individual plutons are given in Table 1, and the modes in Table 2.

2.1. Major element chemistry

Harker variation diagrams for rocks of all the plutons show clear trends of decreasing TiO_2, $A1_2O_3$, FeO, Fe(total), MgO, CaO and P_2O_5 with increasing SiO_2 contents (Fig. 3, TiO_2 and

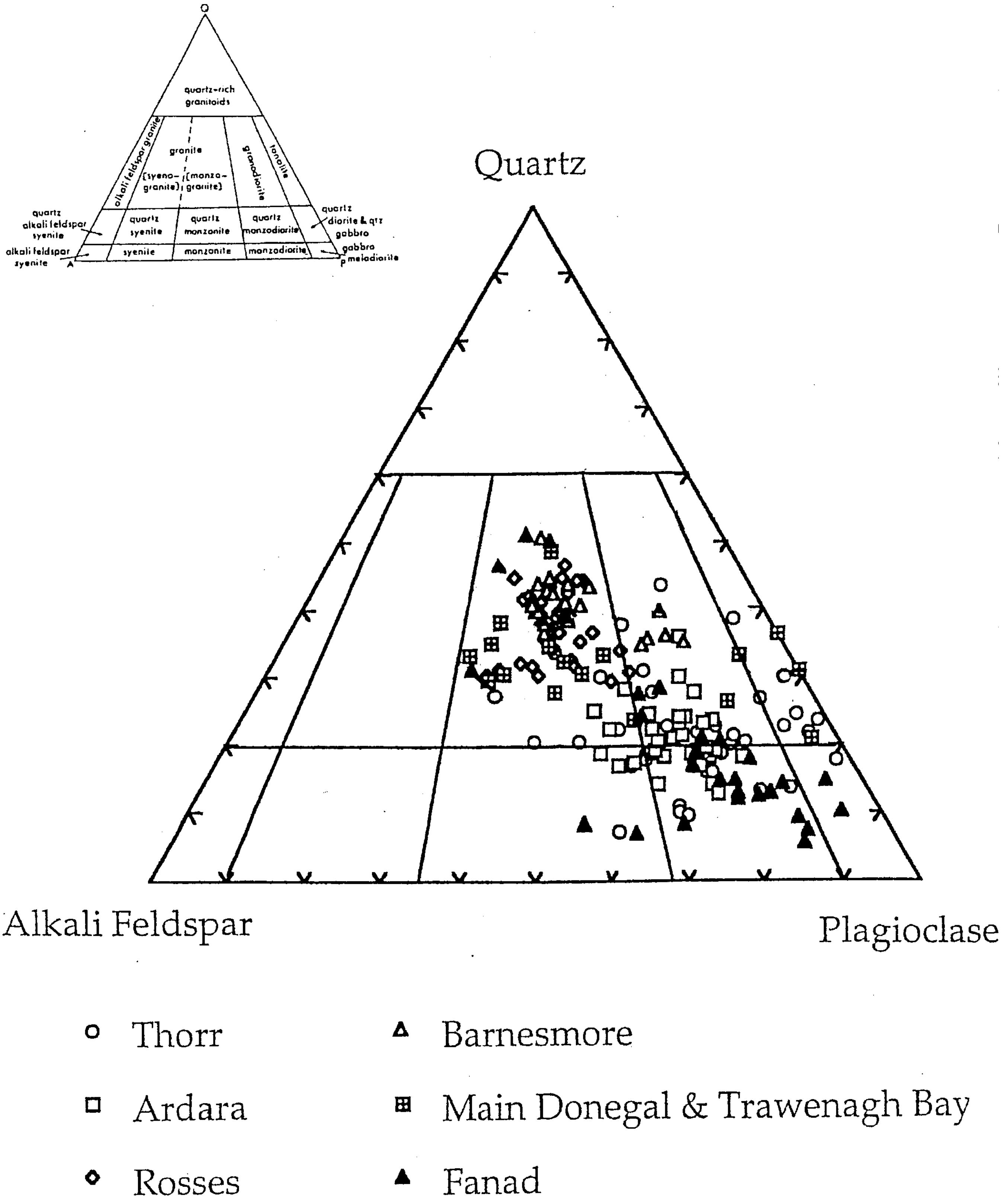

Figure 2 Modal QAP diagram of rocks from the Donegal granites, showing they belong to the calc-alkaline granodioritic series of Bowden *et al.* (1984). Note the basic character of the Fanad rocks and the K-feldspar poor character of some rocks from the Main Donegal and Thorr plutons.

Al_2O_3 are not shown). K_2O shows a slightly increasing trend with some scatter and Na_2O shows no variation with increasing SiO_2 content (Fig. 3). The trends shown by many of the major elements are typical of calc-alkali suites in general, reflecting low pressure fractionation processes in individual units involving crystallisation of plagioclase ± amphibole + biotite ± K-feldspar + apatite + magnetite.

Three plutons show a limited SiO_2 range, with no rocks below 70%, e.g. Barnesmore 72–79%, Rosses 70–77% and Trawenagh Bay 70–75% SiO_2. Rocks from these three plutons have similar major element contents, although rocks from Barnesmore extend to higher SiO_2 values (Fig. 3). The more basic plutons (Fanad, Thorr and Ardara) are readily distinguished on the basis of SiO_2 content, with ranges of

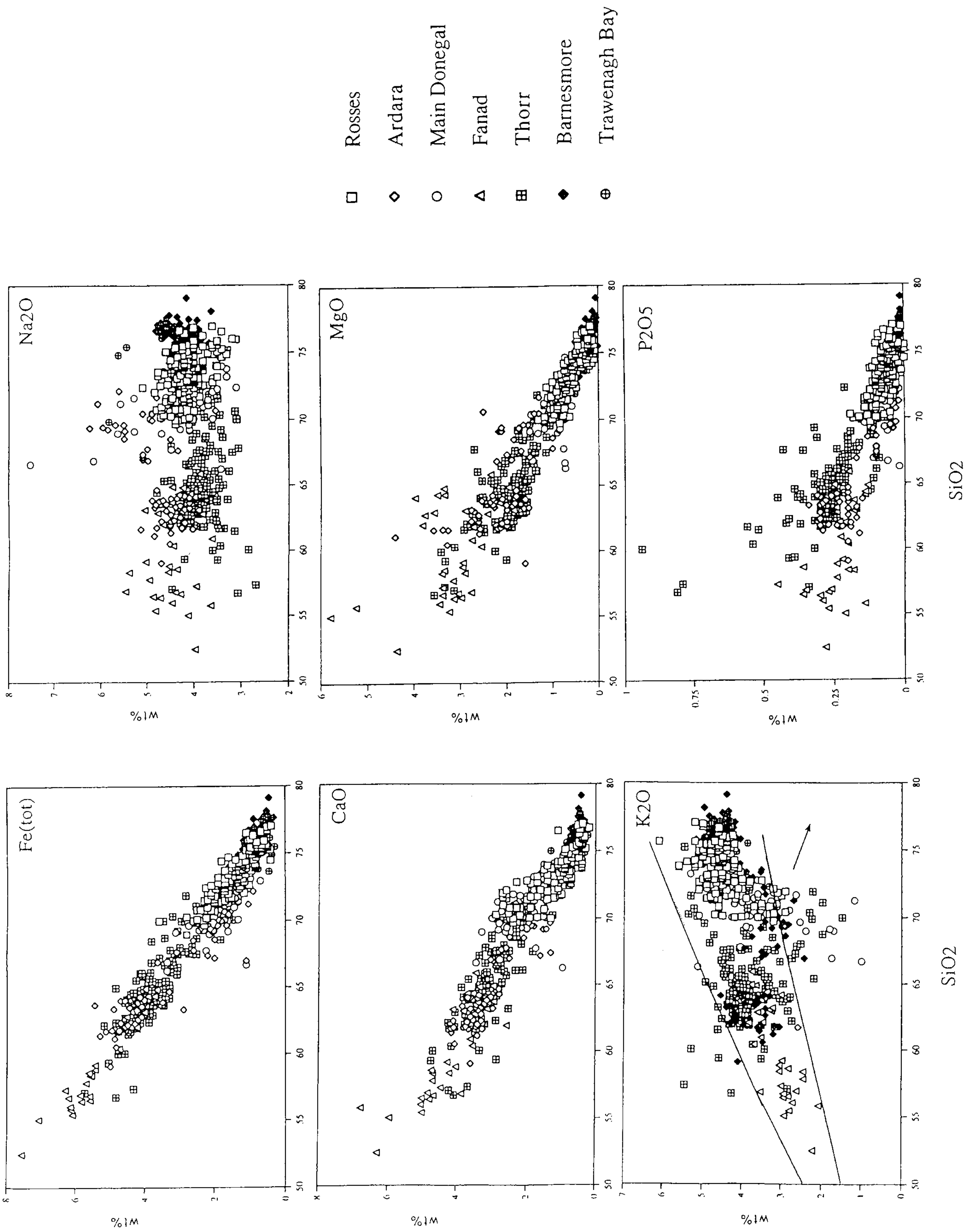

Figure 3 Harker variation diagrams for selected major elements in rocks of the Donegal plutons. Note the characteristic decreases in Fe (total), CaO and MgO with increasing SiO_2 content, typical of calc-alkali suites in general. Arrow on K_2O versus SiO_2 plot indicates time-composition trend of Ardara pluton rocks. (Filled diamond symbol). Field of high-K rocks outlined.

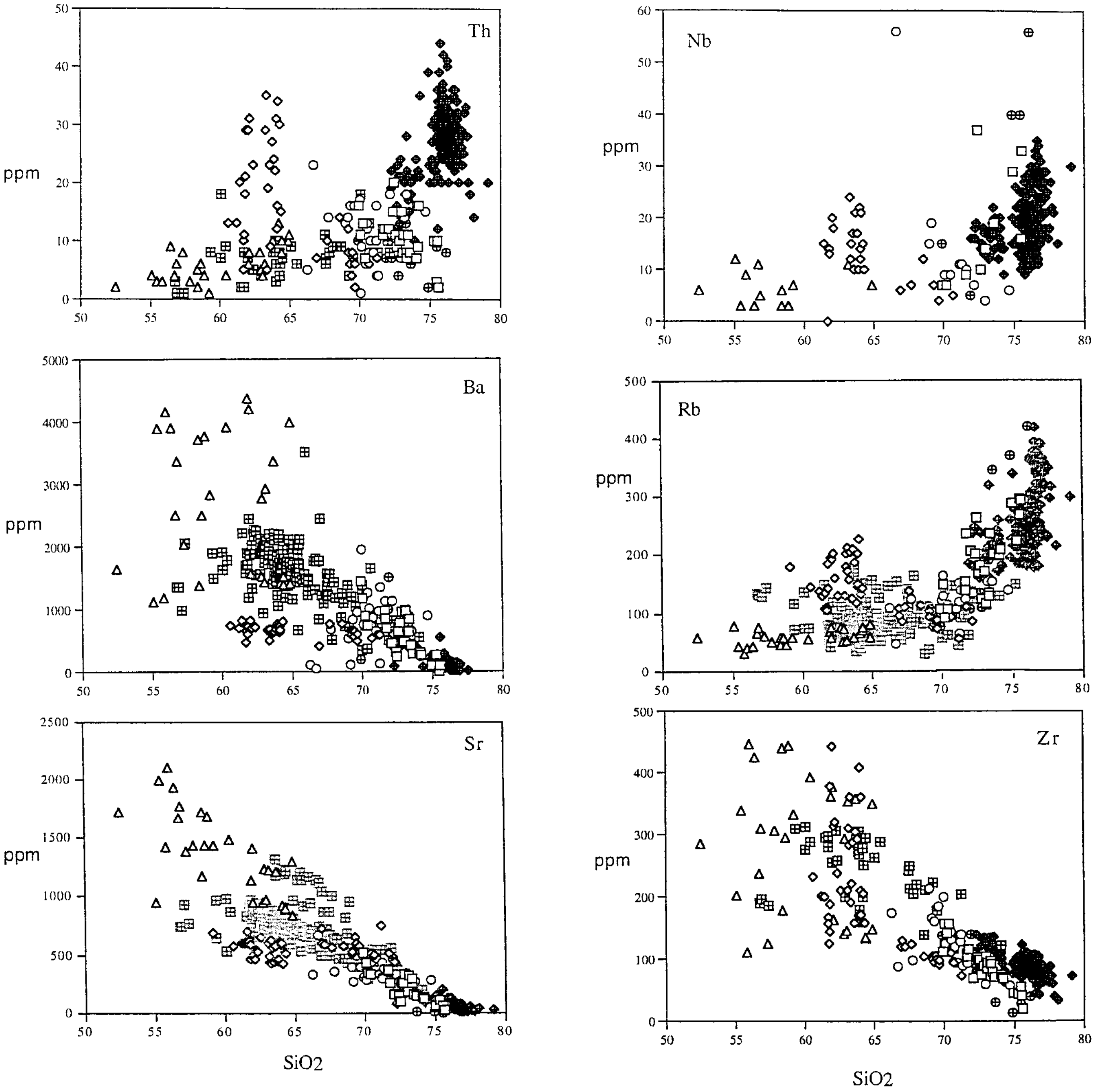

Figure 4 Harker variation diagrams for selected trace elements in rocks of the Donegal plutons. Notable are the large variations in trace element composition at a given SiO_2 content in some plutons e.g. Th, Ba and Zr in Fanad and Th, Zr in Ardara. Symbols as in Figure 7.

52–64%; 57–75% and 59–72% SiO_2 respectively, whilst rocks of the Main Donegal pluton straddle the 70% divide (Fig. 3).

The Fanad pluton contains some of the most primitive rocks of all the Donegal granites (Table 2), which tend to plot colinearly with the trends for all the granites (see particularly FeO (total) and CaO plots (Fig. 3). The Fanad pluton has appinitic affinities, with compositions related to the associated lamprophyric dykes (Pitcher & Berger 1972, p. 142). This affinity, plus the relationships seen in the major element plots, suggests a magmatic connection between all the granites and the appinites and lamprophyres. This aspect will be explored later. On a K_2O versus SiO_2 plot, the Donegal granites lie mainly in the high-K calc-alkaline field (Fig 3). However, Ardara rocks are anomalous in that they show a pronounced negative trend (Fig. 3; Table 2), very different from the evolutionary trends usual in high-K calc-alkali and other plutonic magma series, which have shallow positive slopes (Roberts & Clemens 1993).

The Donegal granitic rocks have high total alkali contents, e.g. Na_2O+K_2O between 5·9% and 9·8% (Table 2) and at a given K concentration have very high Na contents compared to other granites worldwide, such as the Variscan granites (Hall 1971) and the Caledonian granites of the Lachlan fold belt, Australia (Chappell & White 1974). Hall (1971) thought this was due to melting of the source at high H_2O pressures. From a consideration of various factors, particularly the similar alkali enrichment in the closely associated appinites, it seems more likely that the Late Granites of the NW British Isles belong to a high alkali, low K/Na province (Halliday & Stephens 1984).

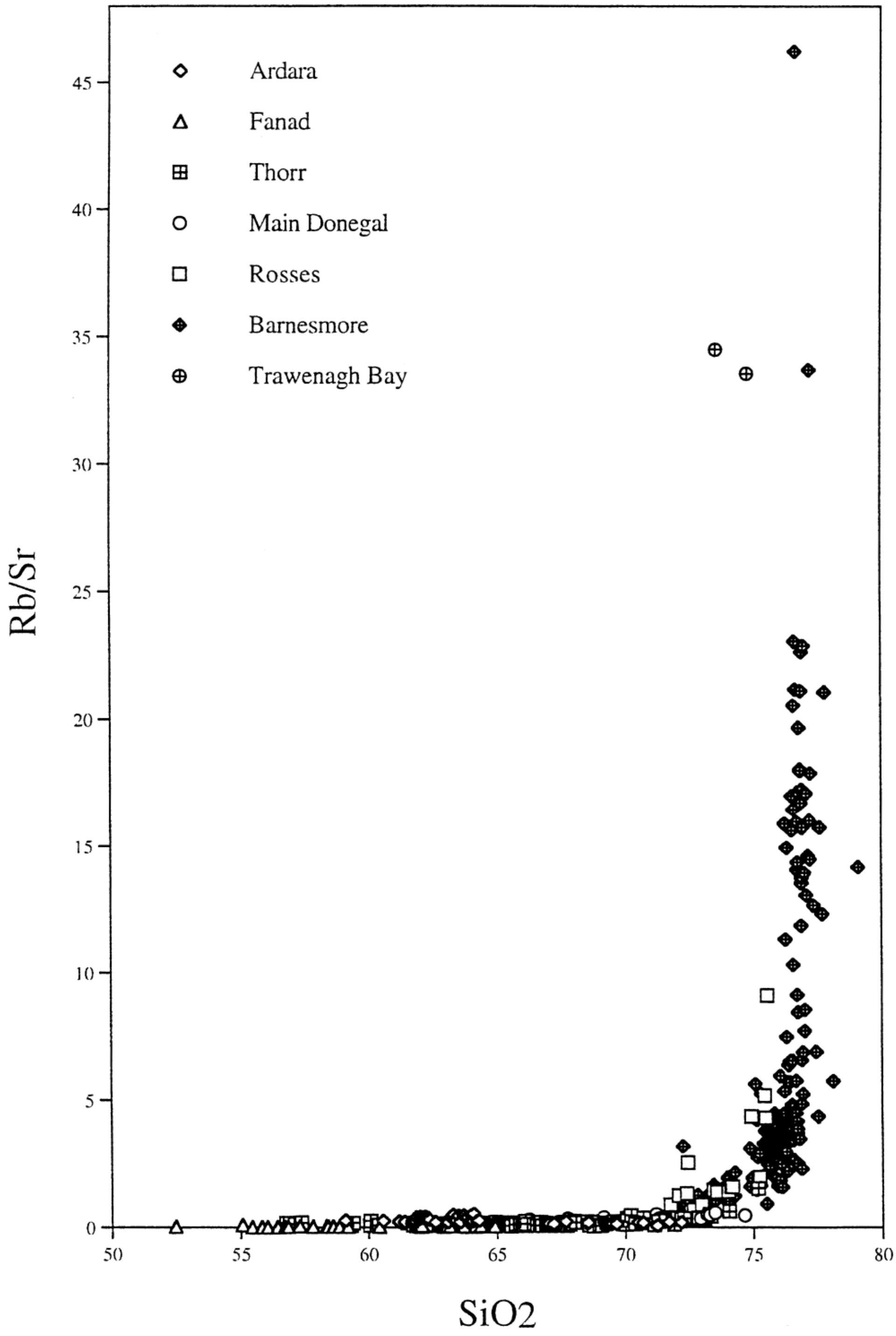

Figure 5 Rb/Sr versus SiO_2 plot of the Donegal pluton rocks showing only rocks from the Barnesmore, Rosses plutons and the Trawenagh Bay muscovite facies show extended fractionation.

2.2. Trace element chemistry

General trends for all the Donegal granites show Ba, Nd, Sc, Sr, V, Zn and Zr decrease with increasing SiO_2, whilst Nb, Pb, Rb and Th increase (Fig. 4). This is compatible with the same fractionating assemblage (plus zircon) noted in the major element trends, i.e. plagioclase+amphibole+biotite ± K-feldspar+magnetite. However, the trends are often crude and less clear than the major element variations, and concentrations at a given SiO_2 content can show a considerable range; e.g. Ba in rocks from the Fanad pluton vary from *c*. 1000 ppm to *c*. 4000 ppm at an SiO_2 content of *c*. 56%. This feature is also seen in the Zr versus SiO_2 plot (Fig. 4), where Zr varies from 100 ppm to 450 ppm at the same SiO_2 content. In this pluton, rocks with Ba contents of less than 2030 ppm and Zr below 300 ppm are restricted to the main Fanad Granite outcrop north of Glinsk, whilst higher values occur in the rocks from Rosgill (Fig. 1; Table 1). Such areal restrictions of chemistry and lack of a clear-cut variation with increasing SiO_2 content, as well as the large trace element variation at a given SiO_2 content, suggest the pluton is made up of magma batches which are not directly related.

A similar situation is seen in rocks from Ardara, where Zr contents show a similar range at *c*. 62% SiO_2, whilst Th varies from 4 ppm to 35 ppm and Nb from 10 ppm to 25 ppm at the same SiO_2 content (Fig. 4). Although Ardara is normally zoned, these variations are not those consistent with the evolution of a zoned pluton formed by closed system fractionation or partial melting (Roberts & Clemens 1993), and

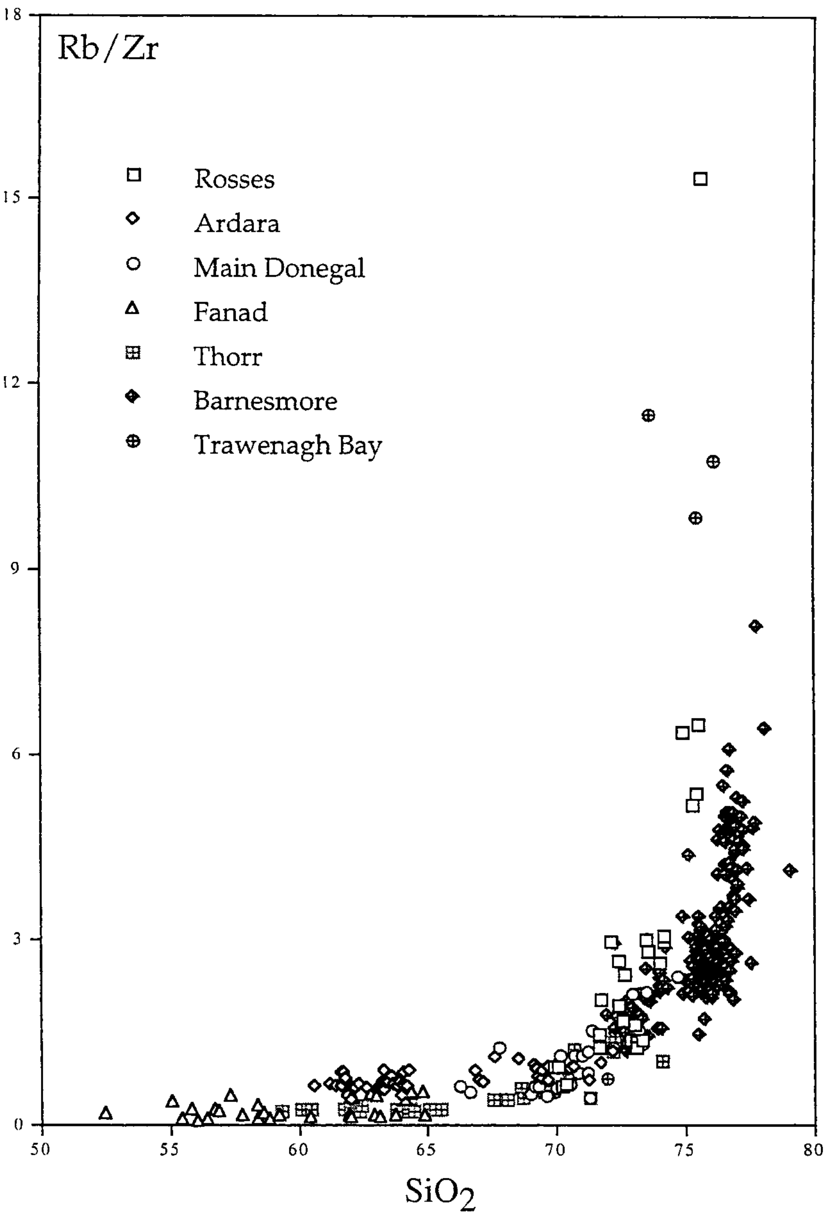

Figure 6 Rb/Zr versus SiO_2 plot of rocks from the Donegal plutons showing extended fractionation is limited in Ardara, Main Donegal, Fanad and Thorr plutons, but extensive in facies of the Rosses, Trawenagh Bay and Barnesmore plutons.

suggest, together with the anomalous K_2O behaviour, that the Ardara pluton is also made up of at least two different magma batches (Ghani & Atherton in prep.). Although the Ardara monzodiorites are indistinguishable from, and overlap with, the monzodiorites of Thorr on major element plots (see FeO (total), CaO, MgO and K_2O plots (Fig. 3), the trace element plots show the Ardara rocks form tight groups, sometimes with an extended range, e.g. Th, Zr (Fig. 4), with very different compositions to the Thorr rocks at the same SiO_2 content. These data indicate that the two monzodiorites are unlikely to be directly related.

Only the Barnesmore, Rosses and Trawenagh Bay pluton rocks have Rb/Sr values above *c.* 1 (Fig. 5) and show increasing Rb and Nb and decreasing Sr, Zr and Ba with increasing SiO_2 content (Fig. 4). They are the only plutons to show extended fractionation. A similar feature is seen in the Rb/Zr versus SiO_2 plot (Fig. 6) where Rosses and Barnesmore are the only plutons with rocks in which Rb/Zr is above about 2, apart from the muscovite-rich roof facies of the Trawenagh Bay pluton. This variation reflects the precipitation of zircon and Rb enrichment in the magmas during fractionation (Fig. 4).

Although the continuous trends on Rb/Sr and Rb/Zr versus SiO_2 plots (Figs 5, 6) may suggest that similar compositions were involved in the magmatic evolution of the Donegal granites, the very different character of each is exemplified on a Zr versus Rb plot (Fig. 7) where each pluton has a specific trend. These data indicate that there is a fine structure specific to the individual plutons which is not seen in the major and trace element Harker plots. This fine structure within and between plutons will be discussed elsewhere. Here, the defining chemical characteristics of the Donegal granites and their classification are described, and compared to the Late Granite suites in Scotland.

The most important trace elements which distinguish these Late Granites are Ba and Sr, which are enriched in some of the granites (Fig. 4; Table 2) relative to most granites worldwide, e.g. the Lachlan Fold belt and other parts of the Caledonian orogen in North America and Europe (Stephens & Halliday 1984). The highest Ba concentrations occur in rocks from the Fanad pluton (maximum *c.* 4500 ppm), followed by rocks from Thorr, then Ardara (Fig. 4). Fanad rocks have the highest Sr contents (maximum *c.* 2000 ppm) followed by rocks

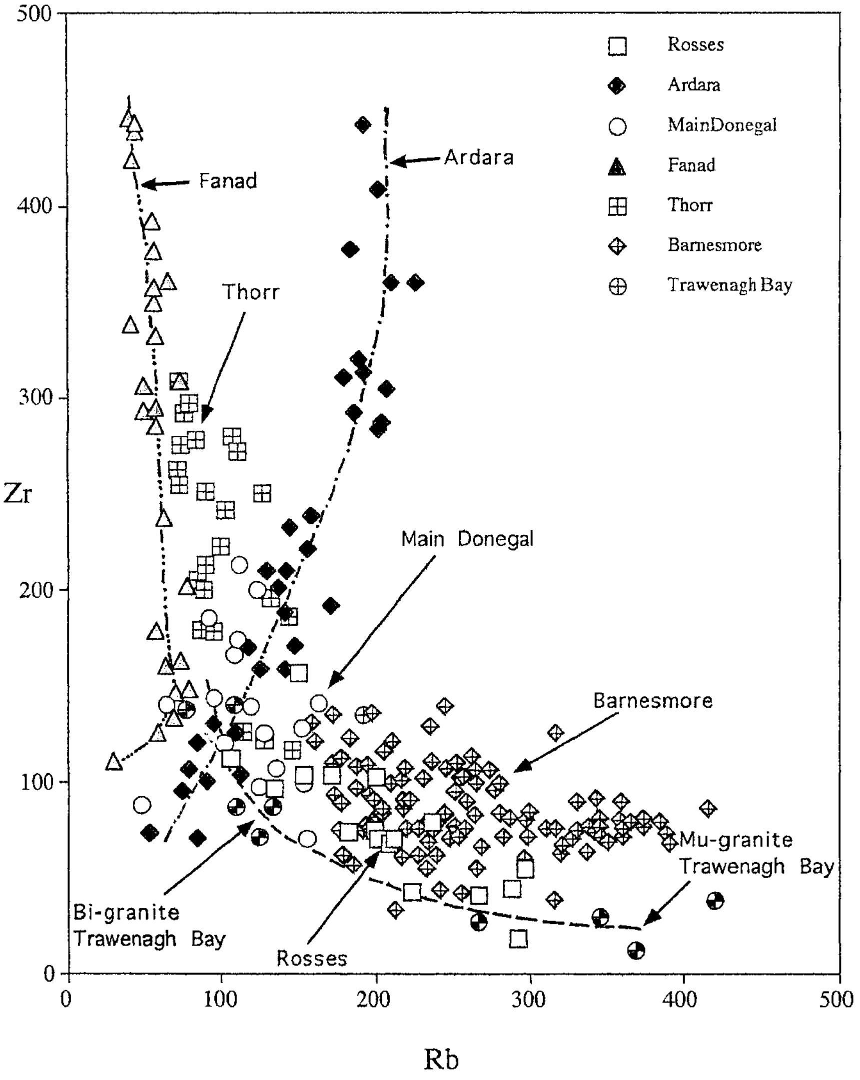

Figure 7 Zr versus Rb plot for rocks of the Donegal plutons showing that the variation in each pluton is distinctive, with paradoxically large variations in Zr in the rocks from plutons which show very limited variations in Rb/Sr.

from Thorr, and Ardara (Fig. 4). These are the high Ba–Sr granites of Tarney & Jones (1994). Although Sr is sometimes enriched in apatite, the highest Sr rocks (Fanad) do not have the highest P_2O_5 contents (Figs 3, 4), suggesting that Sr occurs dominantly in plagioclase. Most of the rocks from the Rosses, Main Donegal, Trawenagh Bay and Barnesmore plutons have much lower values of Ba and Sr (Fig. 4) and plot in, or straddle, the boundary of the low Ba–Sr field (Fig. 8) of Tarney & Jones (1994).

2.3. Chemical classification of the Donegal Granites

On a normative An–Ab–Or plot (Barker 1979) the Donegal rocks plot mainly as granodiorite and granite (Fig. 9) with minor quartz monzonite cf. modal data, whilst rocks from distinct facies of the Ardara and the Main Granite plutons lie in the trondhjemite field (Fig. 9). Tonalite is uncommon and restricted to the Fanad pluton. This is in strong contrast to the common occurrence of tonalite in Cordilleran 'I' type Batholiths (Atherton *et al.* 1979). Most rocks of the Donegal plutons plot in the high-K calc-alkaline field (Fig. 3). They are metaluminous or only slightly peraluminous (<1·1 A/CNK) and lie in the 'I' type field (Fig. 10). Rocks with A/CNK >1·1, but mostly below 1·2, are from the contaminated contact facies adjacent to the pelitic rafts of the Thorr pluton (Oglethorpe 1987; Pitcher & Berger 1972); and the muscovite-bearing greisenised varieties of G4 of the Rosses complex (Pitcher 1953; Fig. 1). On major element plots such as Na_2O versus K_2O (Fig. 11), the rocks plot in the 'I' type field of White & Chappell (1983); only two rocks from the contact facies of the Thorr pluton plot in the 'S' type field. The decrease of P_2O_5 with increasing SiO_2 (Fig. 3) indicates that the felsic granites (<70% SiO_2) are fractionated 'I' types. Thus Chappell & White (1992) showed that the most distinctive difference in composition that results from crystal fractionation of felsic 'I' and 'S' type melts of the Lachlan Fold Belt is that P_2O_5 increases in 'S' type and decreases in 'I' type granites.

In brief, the Donegal plutons are 'I' type granites and granodiorites (ss) with a late, local, hydrothermal/contamination overprint, specifically in some rocks from the Barnesmore, Rosses and Thorr plutons. The rocks show a wide range of SiO_2 contents (52%–77%) comparable to the 'I' type of White & Chappell (1983), e.g. 53%–76%. $^{87}Sr/^{86}Sr$ values are <0·707 (O'Connor *et al.* 1987; Dempsey *et al.* 1990), compatible with Lachlan Fold Belt 'I' types, but not 'S' types, e.g. >0·708 (Chappell & White 1974).

Although the Donegal granites are 'I' types using the original Chappell and White classification (1974), they are different to the 'I' type Cordilleran Batholiths of the eastern Pacific, e.g. the Coastal Batholith of Peru (Atherton *et al.* 1979). So in an extension of the original classification, Pitcher

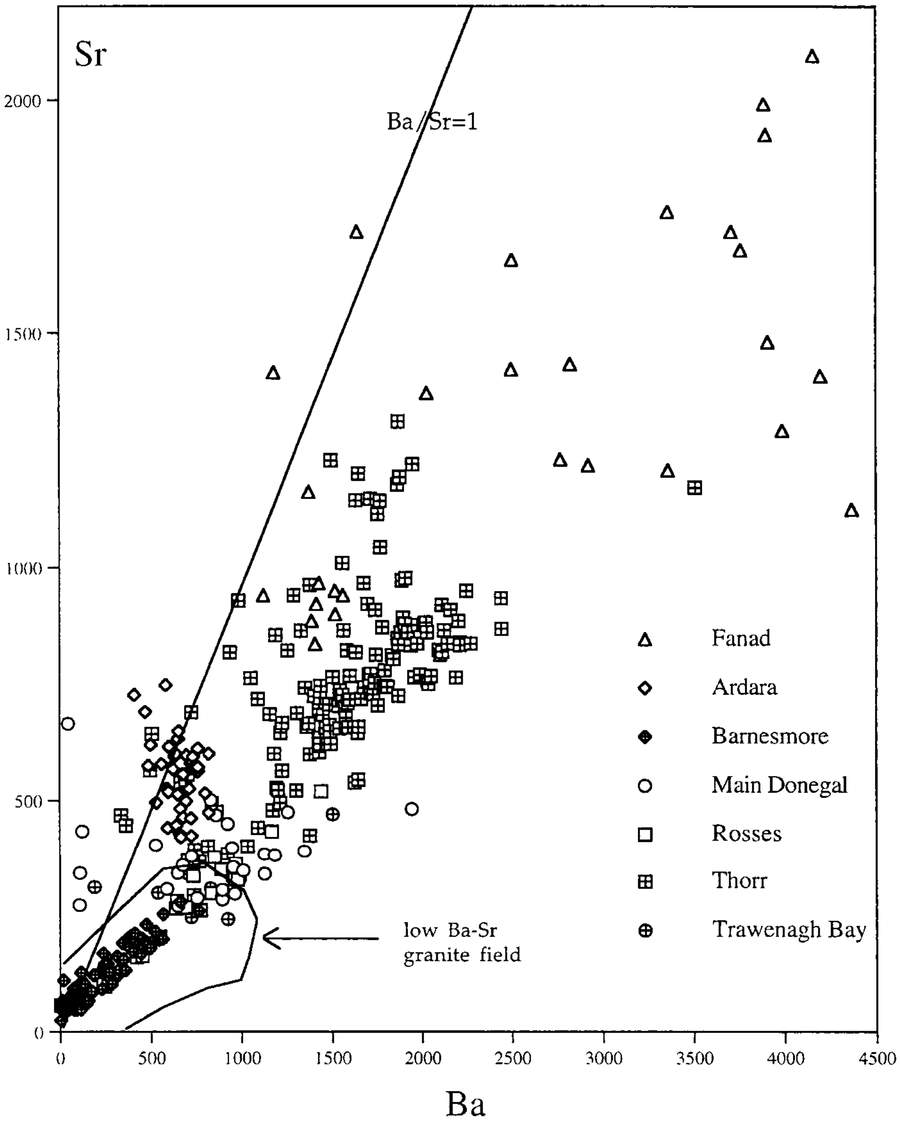

Figure 8 Sr versus Ba plot of rocks of the Donegal plutons, with the low Ba–Sr field of Tarney & Jones (1994). Note most rocks have Ba/Sr ratios greater than 1.

(1982) designated a sub-type: 'I' type Caledonian, typical of the late, uplift stage of the orogenic process.

'I' type Caledonian plutons are typically made up of granodiorite and granite with mixed xenolith populations, often with large sedimentary rafts and associated appinite bodies. Plutons are often isolated and form sheets; they are frequently composite. On an R1–R2 diagram, which uses all the major elements, the Donegal rocks plot in the Late Orogenic and Post Collision Uplift fields below typical Cordilleran rocks which lie in the Pre-plate Collision field (Fig. 12). This is consistent with their crystallisation on or after the closure of the Iapetus Ocean, in contrast to the Cordilleran Coastal Batholith of Peru, for instance, which formed in a tectonic setting where *continuous* subduction of oceanic plate beneath continental crust has occurred during the whole period of formation of the batholith (over 80 m.y.; Pitcher *et al.* 1985).

3. Comparison with Scottish Mainland Late Granites in the metamorphic (orthotectonic) Caledonides

The Donegal granitic rocks are high-K, calc-alkaline, similar to the Late granites in the orthotectonic zone of the Scottish Mainland (Stephens & Halliday 1984). Rocks in both areas are mostly metaluminous or 'I' type peraluminous (i.e. A/CNK <1·1) and on a K_2O versus Na_2O plot they both fall into the field of 'I' type granites from the Lachlan fold belt (Figs 10, 11; Stephens & Halliday 1984).

The elements which show the most remarkable variations in the Scottish suites are Sr and Ba. On the basis of these elements, plus others, Stephens & Halliday (1984) divided the Late Caledonian granites into three suites, of which two, the Argyll and Cairngorm, occur in the orthotectonic zone, so comparisons may be made with the Donegal plutons. The characteristics of these two Late Granite suites defined by Stephens & Halliday (1984) are given in Table 3. In Scotland there is a specific distribution in space; e.g. the Argyll Suite which is markedly enriched in Sr and Ba (>500 ppm and >800 ppm, respectively) is limited to the SW Highland, whilst the Cairngorm suite, which is not, is confined to the NE Highlands (Stephens & Halliday 1984). The Ba–Sr enrichment in the Argyll Suite is more pronounced at lower SiO_2 values, which "is powerful evidence they are primary features and not due to different schemes of fractional crystallisation of the same parental magmas" (Stephens & Halliday 1984, p. 267; see also Fowler *et al.* 2001). Similar chemical features are seen in the Donegal granites. Thus the SiO_2 rich granites of Barnesmore, Rosses and Trawenagh Bay have all the characteristics

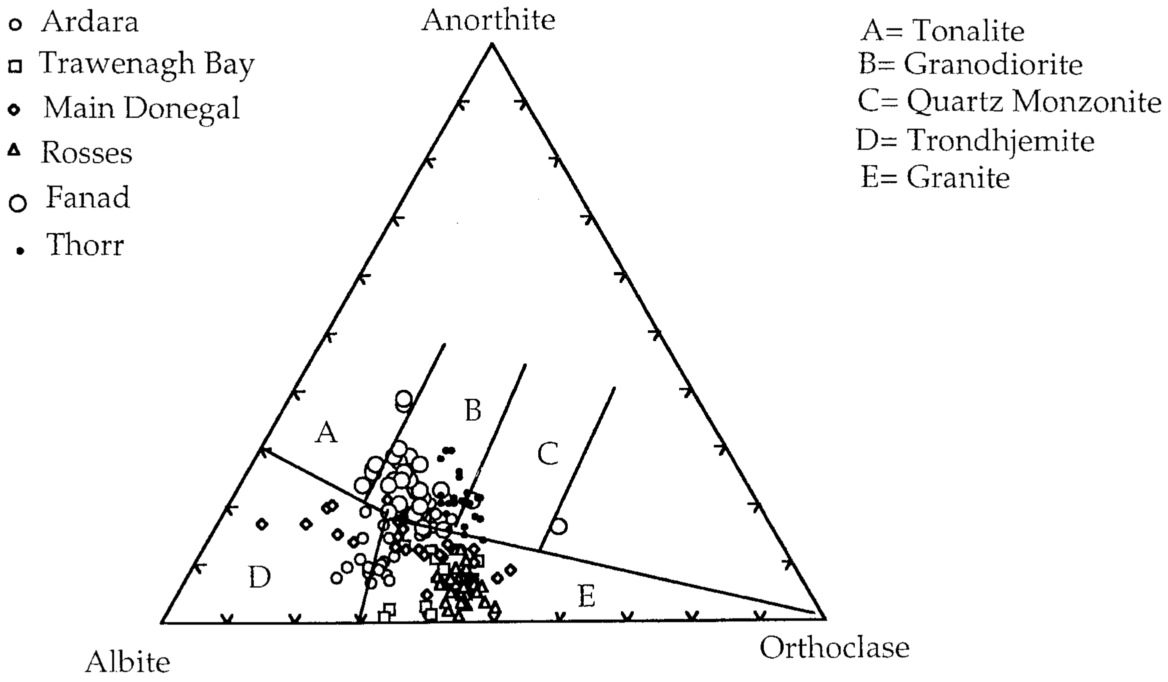

Figure 9 Normative An–Ab–Or plot (Barker 1979) of Donegal pluton rocks indicating the essentially granodiorite-granite character, with minor tonalite and the trondhjemitic nature of some rocks from Ardara and the Main Donegal Granite.

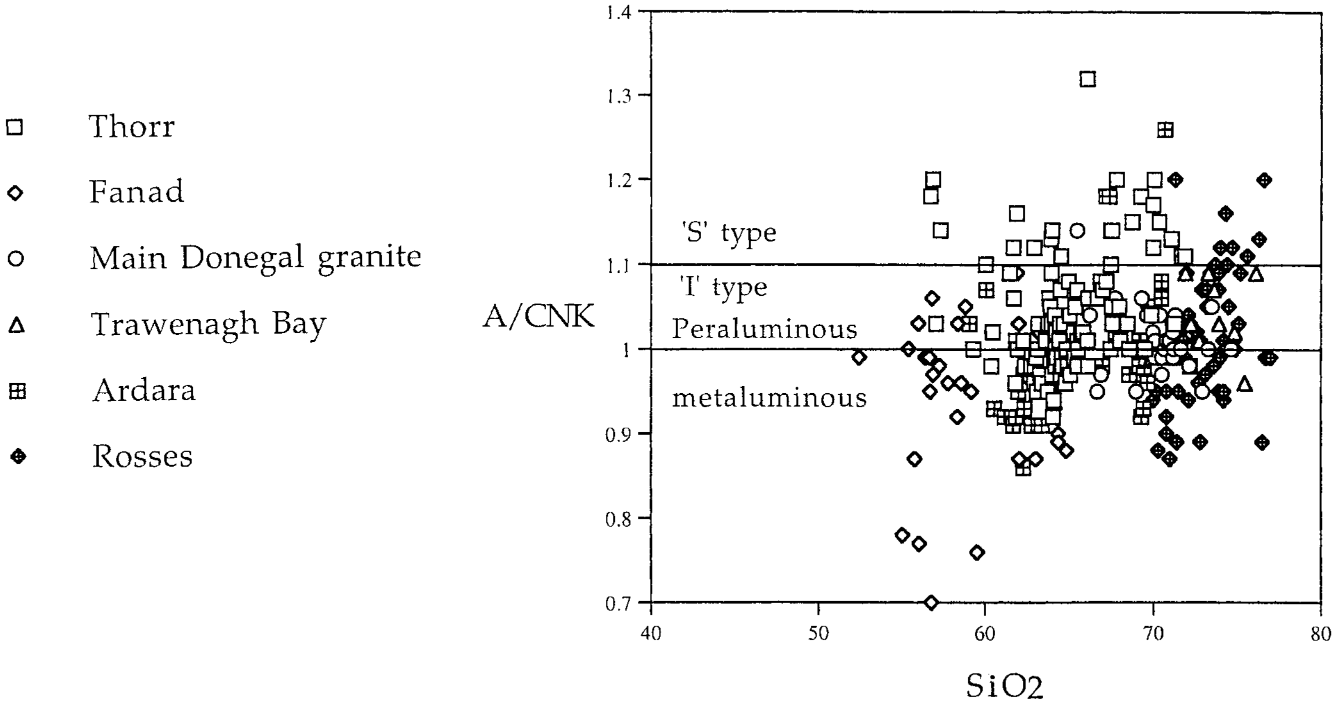

Figure 10 A/C NK versus SiO_2 plot of Donegal Granite rocks. Those plotting in the 'S' type field include the contaminated contact facies of the Thorr pluton and the greisenised varieties of the Rosses complex.

of the Cairngorm Suite granites, i.e. they are 'low Ba–Sr' types, while the more mafic plutons, i.e. Fanad, Thorr and Ardara, are similar chemically to the Argyll Suite granites; they are 'high Ba–Sr' types (Table 3).

In an Sr–Rb–Ba diagram (Fig. 13) the 'normal trend' according to Tarney & Jones (1994) is fractionation towards the Rb corner, typical of low Ba–Sr granitic rocks such as those which belong to the Cairngorm Suite of Stephens & Halliday (1984). High Ba–Sr rock-suites, according to Tarney & Jones (1994), have low Rb contents and trend towards the Ba corner, e.g. SW Highland granites which belong to the Argyll Suite (Tarney & Jones 1994). The three SiO_2 rich Donegal plutons show the 'normal trend' typical of the Cairngorm Suite. However, of the three mafic high Ba–Sr plutons, only Fanad clearly evolves towards high Ba (Argyll trend, Fig. 13). Ardara rocks trend towards the Sr corner and Thorr rocks show a limited trend. In the case of Ardara, this 'anomalous' behaviour is due to the composite nature of the pluton as indicated earlier. Furthermore the status of the Ardara pluton based on Nb and Th contents appears ambiguous (Table 3). Nonetheless, on the basis of most of the discriminant characteristics in Table 3, such as the dominance

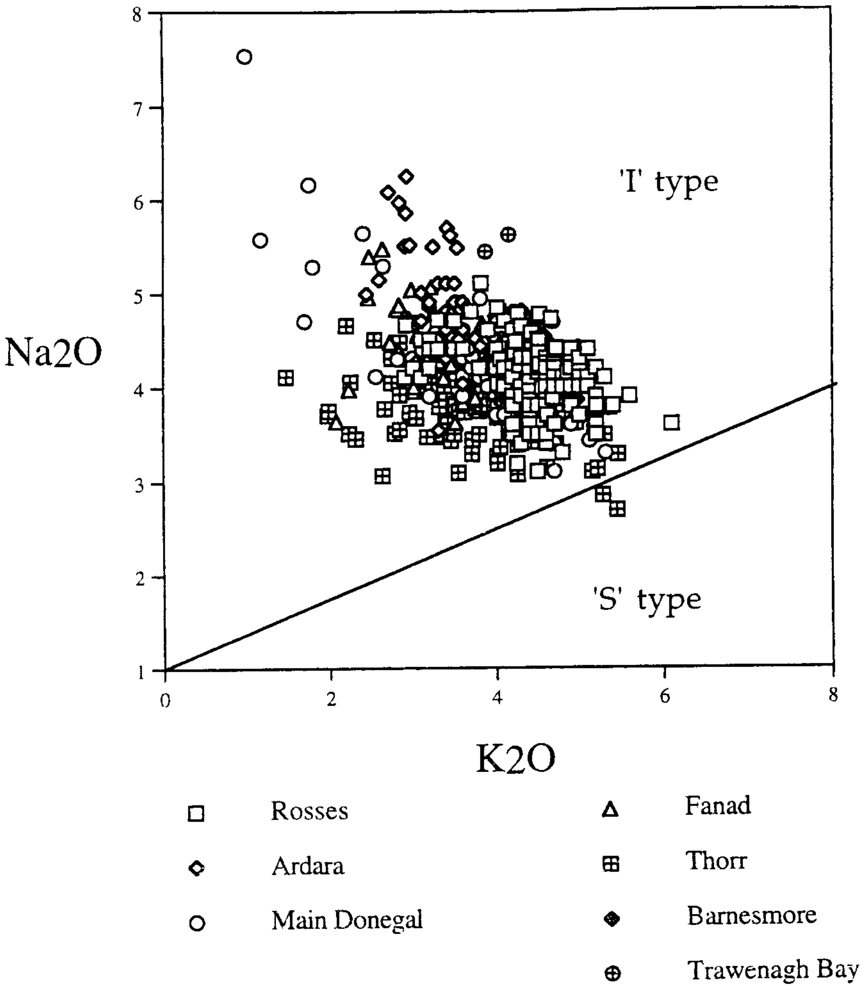

Figure 11 Na_2O versus K_2O plot of rocks from the Donegal granites, showing their clear 'I' type character. The two rocks from the Thorr pluton in the 'S' type field are from the contaminated contact facies. Fields after Chappell & White (1992).

of hornblende bearing monzodiorites, associated appinites, high Na_2O and relatively high Ba and Sr, it is provisionally assigned to the high Ba–Sr group.

A significant difference between Donegal and Scotland is that in Donegal there is no exclusive regionality as seen in Scotland, and plutons of different suites may be superposed, thus the Rosses pluton ('Cairngorm type') is intruded entirely within the Thorr pluton ('Argyll type', see Fig. 1).

The Main Donegal pluton does not fit into these simple schemes. It has a complex magmatic history, including facies of the Trawenagh Bay pluton to which it appears to be connected by a transitional boundary (Price & Pitcher 1999). It has a dark trondhjemitic phase which, together with a light granodiorite-granite, forms the characteristic 'regular banding'; a major component of the pluton (Pitcher & Berger 1972). Sr and Ba contents of some of the granodiorite-granite rocks overlap with Thorr rocks at the lower end of the high Ba–Sr field (Fig. 8), whilst the trondhjemitic rocks have low Ba contents (Fig. 8; Table 2) atypical of many trondhjemites, which commonly have Ba and other trace element contents similar to the high Ba–Sr Argyll Suite rocks (Tarney & Jones 1994). Such intermediate and atypical compositions emphasise the enigmatic character of this intriguing pluton (Pitcher & Berger 1972).

4. Conclusion and discussion of the genesis of the Late granites of Donegal

Classic studies of the Late Caledonian magmas in the Highlands of Scotland have highlighted their high K and particularly Na contents, indicating the presence of a high alkali province (Halliday & Stephens 1984). Many of these magmas have unique, extreme enrichments in Sr and Ba (Stephens & Halliday 1984, Halliday & Stevens 1984, Harmon *et al.* 1984, Fowler *et al.* 2001 – the granites; Canning *et al.* 1996 – the lamprophyres; Fowler & Henney 1996 – the appinites).

On the basis of similar chemistry of the appinites and lamprophyres and the dioritic facies (with Ni >100 ppm) of the Scottish granites, workers on Late Caledonian magmatism have concluded that the high Sr–Ba granites are mantle-derived (Fowler & Henney 1996; Canning *et al.* 1996; Fowler *et al.* 2001), although some of these granites may have a crustal component which can amount to 25% (Fowler *et al.* 2001).

Appinites are the plutonic equivalents of hornblende-rich calc-alkali lamprophyres (Bailey & Maufe 1916). These mafic, volatile K-rich magmas are widely accepted to be small degree partial melts of metasomatised sub-continental lithospheric mantle (SCLM) or melts of individual metasomatic veins within it (Mitchell 1995). The source must have K-amphibole (richterite) or phlogopite as residual phases (Mitchell 1995; Canning *et al.* 1998). In either case, a source at depths of 100 km or more is required, deep in Caledonian lithospheric mantle (Canning *et al.* 1998). This linking of Caledonian granitic magma with a deep source and K-rich mantle magmas with high Ba and Sr and low HREE and Y imply an enriched mantle source mineralogy which included garnet and or amphibole (Canning *et al.* 1998). Although these source

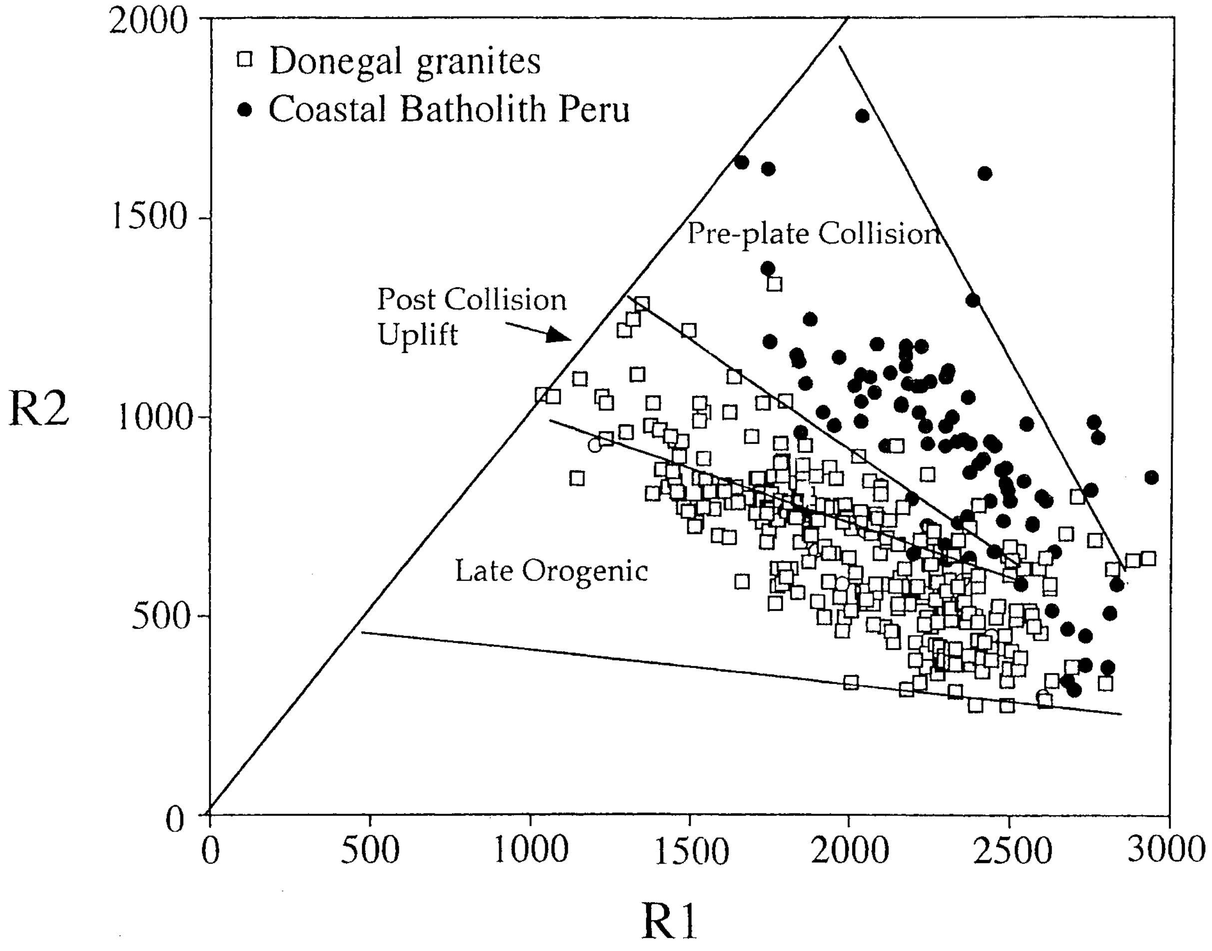

Figure 12 R1–R2 diagram (De la Roche *et al.* 1980) showing the major tectonic associations of the Donegal granitic rocks. The rocks of the Coastal Batholith, Peru (from Pitcher *et al.* 1985) are shown for comparison. R1=4 Si-11(Na+K) − 2(Fe+Ti); R2=6Ca+2 Mg+Al.

features are now well established, the mode of magma generation, the relation to Caledonian orogeny and Iapetus subduction and closure has been considered enigmatic (see Stephens & Halliday 1984; Soper 1986). Pitcher, for example, thought these Donegal Caledonian magmas were "genetically independent of subduction-related processes" (Pitcher 1982, p. 31) produced during adiabatic decompression on end-Silurian uplift and erosion. As recently as 1993, Hutton *et al.* (1993) considered the origin as either still not resolved or confused (see also Fowler *et al.* 2001). Problems with regard to the role of subduction still exist and were outlined by Atherton (1999) and Atherton & Ghani (2002). Most notable is the closure of the Iapetus Ocean, i.e. the Scandian collision of Baltica and the Scoto–Greenland margin at *c.* 435 m.y. ago (Soper *et al.* 1992), at which point conventional subduction of the Iapetus Ocean below Laurentia ceased. This is well before the apparent peak of Late Granite magmatism in Donegal. What is also critical for any model from the Donegal data, and that from mainland Scotland (Thirlwall 1988), is the apparent *short punctuated* intrusion age span of the Late Granites.

Major element chemistry indicates that these late magmas are not the same as those in classic modern magmatic arcs (Fig. 12). In addition, the radiogenic isotope data for circum-Pacific granites indicate that a depleted MORB source is intimately involved in magmas generated by normal subduction processes. However, there is no evidence of a major MORB or asthenospheric source in the Late Granites (Halliday *et al.* 1985). For these reasons a conventional arc model is inappropriate.

A new model for Late Caledonian Granite genesis must relate to Iapetus closure and continental collision, the appinite-lamprophyre connection, the singular intrusion age pulse at about 400 Ma and other characteristics including post orogenic uplift and low grade metamorphism (Atherton 1999; Atherton & Ghani 2002). In essence, continental collision on ocean closure usually involves attempted subduction of the continental passive margin following subducted ocean plate into the trench. If the resulting deformation is localised 'slab breakoff' will occur (Davies & von Blanckenburg 1995). A likely consequence is the rise of hot asthenosphere through the break to impinge on thick, overlying, metasomatised, veined, hydrated lithosphere, which melts to produce K-rich, calc-alkaline magmas (lamprophyric). These underplate and pass up through the crust, inducing melting to give granitic and associated lamprophyric magmas. The magmatic association generated by this event is a specific and a critical indicator; 'syncollisional basaltic' (appinitic, lamprophyric, high-K calc-alkaline) 'and granitoid magmatism are the most valuable witnesses of slab breakoff' (von Blanckenburg & Davies 1996, p. 114). This association is well seen in Donegal where early appinitic and lamprophyric magmas, that are consanguineous according to Pitcher & Berger (1972, p. 161), were the first to arrive at the final intrusion level; these were quickly followed by melts of underplated lamprophyric material that produced the granitic magmas with the same characteristic high Ba–Sr signatures (Atherton & Ghani 2002). Alternatively, the appinitic/amprophyric magmas may differentiate at high crustal levels to form the granitic plutons (Fowler *et al.* 2001).

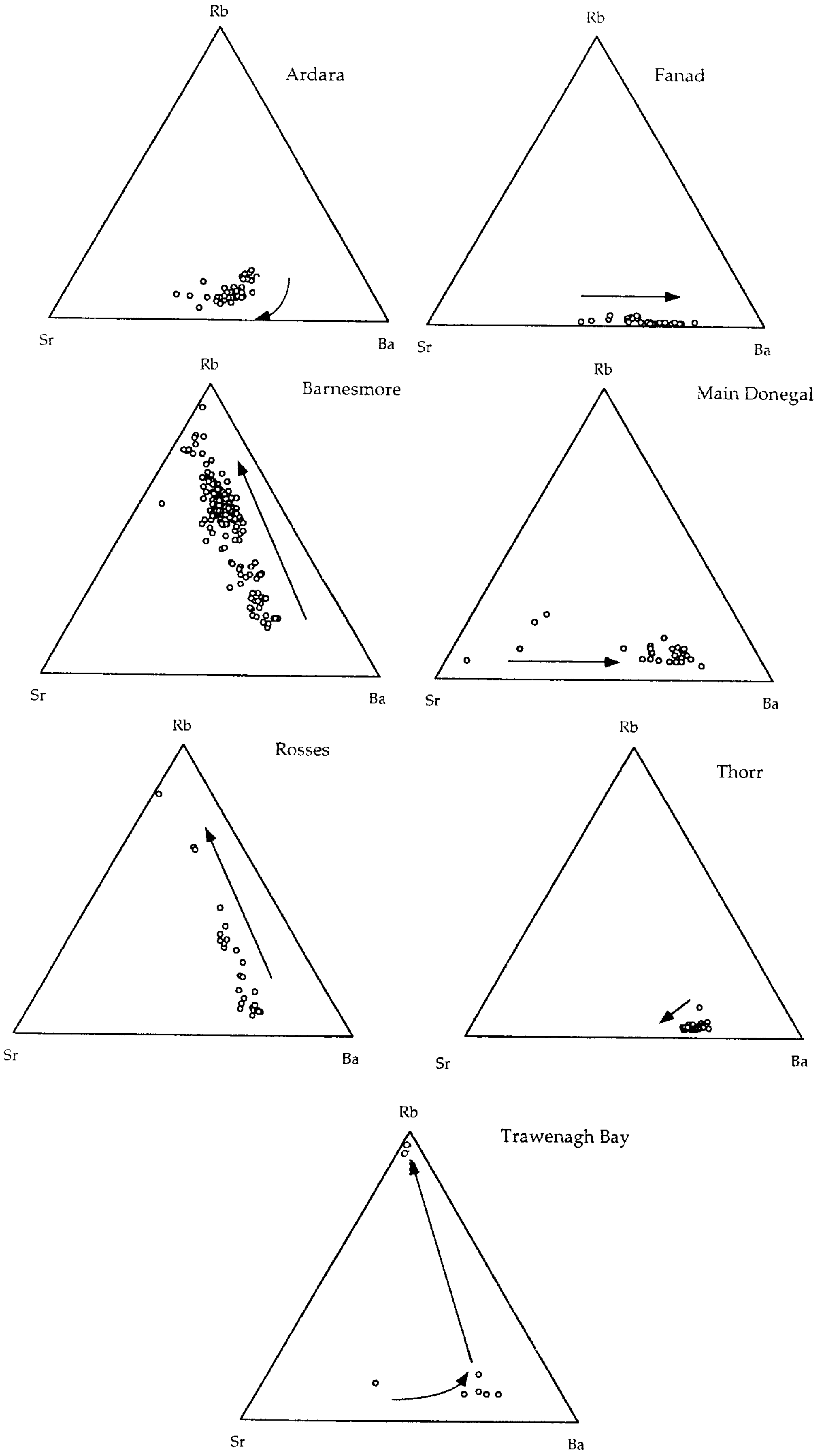

Figure 13 Sr–Ba–Rb triangular plot of rocks of the Donegal plutons indicating 'normal' behaviour in the case of Barnesmore, Rosses and Trawenagh Bay (low Ba–Sr granites) and the variable behaviour of the high Ba–Sr rocks of the Thorr, Ardara, Fanad and Main Donegal plutons (behaviour after Tarney & Jones 1994). Arrows indicate basic to felsic rock sequences.

Table 1 Notes on the field relations, rock types and mineralogy of individual plutons

PLUTON	FIELD RELATIONS	ROCK TYPE	MAIN MINERALS	ACCESSORY MINERALS	OPAQUE PHASES
Ardara	Concentric, normally zoned (three zones) , sharp contact between outer and intermediate zones	Qtz monzodiorite–granodiorite–granite	Pl^{P}, Bi, Hbl^{Py}, Kfs^{P}, Qtz	Sp^{g}, Ap, Aln, Zr, Ep (1°?)	Hemo-ilm, Mag, Py
Fanad	Three separate bodies : Rosguill, Fanad Peninsular, Melmore. The most basic among the Donegal granites	Qtz monzodiorite–granodiorite	Pl^{c}, Bi, Hbl^{Py}, Kfs, Qtz	Sp^{g}, Ap, Aln^{g}, Zr, Ep (2°)	Mag, Hem, Py, Geo, Ilm-Hem, Chalpy
Thorr	Assymetric, normally zoned. Gradational contact between outer highly xenolithic diorite and inner granite. Contact facies (10 m) around the country rock rafts	Qtz monzodiorite–granodiorite–granite	Pl^{go}, Bi, Hbl^{g}, Kfs^{P}, Qtz	Sp, Ap, Aln, Zr, Ep (2°)	Mag, Hemo-ilm, Rt, Py
Rosses	Centred sheet complex (G1–G2–G3–G4) with sharp internal contacts. Marginal microgranite sheets; porphyry dykes intrude only G1 and G2	Granite	Pl^{go}, Kfs, Qtz, Bi, Ms (2°)	Ap, Aln, Sp, Zr, Ep (2°)	Mag, Hem
Main Donegal	Highly deformed, vertically sheeted, multipulse. Gradational contact with Trawenagh Bay	Trondhjemite–granodiorite–granite	Pl^{go}, Kfs, Qtz, Bi, Ms (2°)	Ap, Aln, Sp, Zr, Gar, Ep (2°)	Mag, Ilm, Hem, Py
Trawenagh Bay	Shallowly sheeted granite grading up to muscovite granite at top of sheets	Biotite granite–muscovite granite	Pl, Kfs, Qtz, Bi, Ms (1° – in musc granite)	Ap, Gar, Aln, Ep (2°)	Mag (in biotite granite)
Barnesmore	Sheeted with three main units (G1–G2–G3)	Granodiorite (G1)–granite (G2 & G3)	Pl, Kfs, Qtz, Bi, Ms (2°)	Ap, Aln, Zr, Sp, Ep (2°)	Mag, Ilm

Abbreviations: (Pl) Plagioclase; (Bi) Biotite; (Hbl) Hornblende; (Kfs) K-feldspar; (Qtz) Quartz,; (Ms) Muscovite; (Pl ^{P}) Plagioclase phenocryst; (Pl^{go}) Plagioclase glomerocrystic; (Pl^{c}) Plagioclase with cracked corroded cores; (Kfs^{p}) K-feldspar phenocryst; (Ms(2°)) secondary muscovite; (Hbl^{Py}) Hornblende with pyroxene cores; (Hbl^{g}) Glomerocryst hornblende with apatite, biotite and allanite; (Sp^{g}) Glomerocryst sphene with apatite, biotite, hornblende and allanite; (Aln^{g}) Glomerocryst allanite with apatite, biotite, hornblende and sphene; (Ap) Apatite; (Aln) Allanite; (Zr) Zircon; (Ep) Epidote; (Gar) Garnet; (Sp) Sphene; (Mag) Magnetite; (Hem) Hematite; (Py) Pyrite; (Geo) Geothite,; (Ilm-Hem) Ilmeno-Hematite; (Hemo-ilm) Hemo-ilmenite; (Rt) Rutile; (Chalpy) Chalcopyrite.
Data after Walker & Leedal (1954), Fernandez (1969), Pitcher & Berger (1972), Atkin (1977), Oglethorpe (1987), Dempsey (1987), Ghani (1997).

Table 2 Modes and chemistry of representative rocks of the Donegal plutons

Pluton	TRA BAY	TRA BAY	MAIN	MAIN	MAIN	FANAD	FANAD	FANAD	FANAD	ARDARA	ARDARA	ARDARA	THORR	THORR	THORR	ROSSES	ROSSES	ROSSES	ROSSES	B'MORE	B'MORE	B'MORE
Sample	TRA2	TRA3	DON17	DON3	DON16	FAN7	FAN19	FAN46	FAN29	ARD1F	Y49	ARD10	OGL12	OGL50	Th5	ROS11	ROS5	ROS21	ROSG4	G18	G237	G3193
Unit	Bi-Gra	Mu-Gra	Dark	Light	Light	Fan Pen	Melmore	Rosguill	Rosguill	Outer	Inter	Inner	Hbl bear	Hbl free	contact	G1	G2	G3	G4	G1	G2	G3
Rock type	Gra	Gra	Tdhmite	Gdr	Gra	QzMzd	QzMzd	QzMzd	Gdr	QzMzd	QzMzd	Gdr	Tonalite	Gra	Tonalite	Gra	Gra	Gra	Gra	Gra	Gra	Gra
SiO_2	72·75	73·63	66·26	70·43	73·19	62·07	55·44	58·61	64·92	61·85	63·91	69·19	65·49	74·05	64·28	70·05	72·39	73·11	75·5			
Plagioclase	39·9	27·6	68·00	40	28	51·2	57·9	53	45·5	54·2	55·9	51·4	38·6	27·5	53·2	27·5	27·0	38·0	29·4	45·7	29·6	33·7
K-Feldspar	22·9	38·5	0·6	35·0	35·0	13·9	11·9	15·1	16·6	13·2	14·7	10·0	31·8	36·6	7·3	37·0	39·5	28·0	24·3	14·5	28·2	23·9
Quartz	31·2	27·9	20·7	20·0	34·0	12·5	5·9	13·3	24·2	12·2	11·3	29·4	14·7	32·8	15·0	28·5	29·4	29·0	39·4	34·1	39·3	40·5
Biotite	4·8	0·0	6·0	5·0	2·0	11·3	17·6	12·1	11·1	13·7	14·2	6·5	11·3	2·5	19·8	5·4	2·8	3·3	0·2	4·0	2	1
Hornblende	—	—	—	—	—	8·1	5·2	5·0	0·8	2·9	2·4	0·1	2·0	0·0	0·0	—	—	—	—	—	—	—
Muscovite	0·4	5·0	3·5	0·5	1·0	—	—	—	—	—	0·0	tr	0·0	0·1	3·7	0·6	0·6	0·5	6·3	0·6	0·5	—
Sphene	tr	—	0·2	tr	tr	1·0	0·5	0·8	0·3	0·8	0·5	0·4	0·7	0·6	0·0	0·0	0·0	0·1	—	tr	tr	—
Epidote	0·5	—	0·3	0·4	0·1	0·0	0·0	0·0	0·0	2·3	0·5	1·3	0·2	0·4	0·0	0·5	0·4	0·7	—	—	—	—
Allanite	tr	—	0·1	tr	0·0	tr	tr	0·2	0·3	tr	tr	tr	0·0	0·0	0·0	tr	0·0	tr	—	tr	tr	—
Apatite	0·3	0·1	0·5	0·2	0·1	0·7	0·4	0·4	0·6	0·4	0·2	0·4	0·4	0·0	0·8	0·2	0·2	0·3	—	tr	tr	tr
Opaque	tr	0·0	0·1	0·0	0·4	1·2	0·5	1·0	0·6	0·2	0·2	0·5	0·3	0·1	0·1	0·3	0·1	0·1	0·1	0·1	tr	tr
Garnet	—	0·9	0·1	tr	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	0·1			
Major element (wt%)																						
SiO_2	72·75	73·63	66·26	70·43	73·19	62·07	55·44	58·61	64·92	61·85	63·91	69·19	65·49	74·05	64·28	70·05	72·39	73·11	75·50	71·96	75·25	76·95
$Al2O_3$	14·11	14·03	0·44	0·21	0·13	15·90	20·09	18·20	17·43	16·96	16·28	15·20	16·78	13·96	16·97	14·65	13·66	14·21	13·51	14·59	13·80	13·30
TiO_2	0·18	0·03	16·72	14·88	13·76	0·64	0·87	0·91	0·57	0·85	0·61	0·29	0·69	0·29	0·63	0·31	0·25	0·17	0·09	0·28	0·11	0·08
FeO	0·79	0·13	2·32	1·58	0·65	2·57	3·66	3·23	1·86	2·79	n.d.	0·80	2·31	0·54	0·67	1·41	1·17	0·64	0·31	1·06	0·35	0·22
$Fe2O_3$	0·55	0·31	0·79	0·41	0·62	1·58	2·02	2·02	1·93	1·34	n.d.	1·14	1·61	0·60	2·60	0·74	0·67	0·64	0·18	0·63	0·44	0·29
Fetot	1·43	0·45	3·37	1·62	1·34	4·44	6·09	5·63	4·00	4·55	4·20	2·03	3·92	1·04	3·56	2·31	1·97	1·35	0·49	1·80	0·83	0·53
MnO	0·03	0·10	0·02	0·04	0·01	0·06	0·05	0·05	0·03	0·05	0·08	0·04	0·06	0·04	0·04	0·04	0·04	0·03	0·01	0·05	0·03	0·02
MgO	0·91	0·29	0·72	1·47	0·67	3·81	3·23	3·34	1·97	2·13	2·54	2·11	1·85	0·46	2·15	1·31	1·06	0·79	0·44	0·83	0·26	0·12
CaO	1·51	0·42	0·96	1·78	1·19	4·21	5·02	4·75	2·97	3·74	3·45	1·43	3·32	1·18	2·61	1·93	0·89	1·03	0·38	1·27	0·57	0·38
Na_2O	4·20	4·65	5·43	4·32	3·30	4·23	4·82	4·37	4·47	4·52	4·69	5·49	3·48	3·52	4·38	4·03	4·48	4·36	4·23	4·05	4·32	4·49
K_2O	4·04	4·35	3·12	3·71	5·31	3·46	2·80	2·83	3·76	3·97	3·39	3·24	4·42	5·18	3·86	4·02	4·50	4·22	4·52	4·52	4·71	4·42
P_2O_5	0·04	0·04	0·02	0·09	0·05	0·23	0·27	0·36	0·25	0·27	0·24	0·04	0·21	0·05	0·28	0·10	0·04	0·04	0·00	0·08	0·02	0·01
LOI	0·63	0·50	0·60	0·80	0·37	0·60	0·60	0·56	0·48	0·26	0·60	0·58	n.d.	n.d.	0·51	0·44	0·64	0·71	0·69	0·5	0·50	0·40
Total	99·82	98·49	98·66	99·36	99·33	99·65	99·28	99·61	100·85	99·16	100·18	99·65	100·22	99·77	99·27	99·20	100·70	100	99·88	99·32	100·20	100·68
Trace element (ppm)																						
Ba	708	b.d.l	110	1256	894	1561	3888	2499	3988	723	761	590	2036	1212	1467	1167	311	961	91	662	83	b.d.l.
Ce	15	9	33	43	271	61	42	50	79	117	53	25	54	64	47	41	20	33	17	n.d.	n.d.	n.d.
La	4	6	23	26	36	46	46	43	65	63	33	18	34	15	32	35	17	21	12	n.d.	n.d.	n.d.
Nb	n.d	n.d	n.d.	n.d.	n.d.	n.d.	3	n.d.	n.d.	n.d	10	n.d	23	24	n.d.	n.d.	n.d.	n.d.	16	19	18	24
Nd	12	9	20	24	73	38	23	35	34	59	n.d	16	n.d.	n.d	32	23	17	15	12	n.d.	n.d.	n.d.
Pb	23	16	17	17	29	16	14	17	18	40	41	27	20	22	183	24	30	25	24	30	29	34
Rb	109	345	110	115	153	74	42	58	57	184	118	91	76	90	11	150	200	118	267	185	236	331
Sc	b.d.l	2	7	3	2	9	4	8	2	7	—	2	5	4	667	4	4	2	b.d.l.	n.d.	n.d.	n.d.
Sr	338	10	341	474	304	940	1991	1422	1292	461	611	525	749	494	5	432	151	327	62	278	74	21
Th	4	6	5	6	14	8	3	6	11	29	22	8	6	7	55	11	15	11	10	11	22	32
V	15	—	24	22	14	77	75	89	44	106	96	36	66	45	37	29	19	14	12	n.d.	n.d.	n.d.
Y	9	19	12	9	6	18	7	14	11	23	22	11	8	12	80	10	21	20	15	19	22	13
Zn	33	22	89	50	28	63	76	78	63	62	62	48	59	60	221	59	61	33	7		14	17
Zr	87	30	174	134	99	163	338	295	349	337	170	100	288	213	—	157	103	94	41	662	80	90

Abbreviations: (TRA BAY) Trawenagh Bay; (MAIN) Main Donegal granite; (B'MORE) Barnesmore
Unit of pluton: (Bi-Gra) Biotite granite (Trawenagh Bay); (Mu-Gra) Muscovite granite (Trawenagh Bay); (Dark) Dark band (Main Donegal); (Light) Light band (Main Donegal); (Fan Pen) Fanad Peninsular (Fanad); (Outer) Outer Unit (Ardara); (Inter) Intermediate Unit (Ardara); (Inner) Inner Unit (Ardara); (Hbl Bear) Hornblende bearing (Thorr); (Hbl free) Hornblende free (Thorr); (Contact) Contact facies (Thorr)
Gdr: Granodiorite; Gra: Granite; Qz Mzd: Quartz monzodiorite; Tdhmite: Trondhjemite
Data after Dempsey (1987), Oglethorpe (1987), Ghani (1997)

Table 3 Characteristics of the Caledonian late granite suites in the orthotectonic zone of Scotland (after Stephens & Halliday 1984) and Donegal

	Argyll Suite	*Mafic Plutons, Donegal: Fanad Thorr, Ardara*	Cairngorm Suite	*Felsic Plutons, Donegal: Barnesmore, Rosses, Trawenagh Bay*
Rock types	Granodiorite and diorite Common; appinite abundant; hornblende characteristics of the diorites	Quartz monzodiorite, granodiorite, granite; appinite common; hornblende common (up to 15%)	Biotite granite common; rare intermediate types; few appinnites	Mainly biotite granite; some granodiorite; few appinites
Major oxides	High Na_2O; high-K calc-alkali compositions	High Na_2O; high-K calc-alkali compositions	SiO_2 rich; high-K calc-alkali compositions	SiO_2 rich; high-K calc-alkali; metaluminous and peraluminous; some hydrothermally altered compositions
Trace elements	Very high Sr and Ba; low Nb, Rb, Th	Very high Sr and Ba; high P, Zr; low Rb, Th, Nb, Rb/Sr [Ardara relatively high Nb and Th]	Low Sr and Ba; high Nb, Rb, Th	Low Sr, Ba, Zr; high Nb, Rb, Th, Rb/Sr
Age (Ma)	410 to 415	402 to 418	408 to 415	397 to 404
εSr	−7 to +58	+14 to +31	+24 to +33	+24 to +37
εNd	−10 to +3	−5·1 to −1·2	−8 to −1	−8 to −4·3
^{18}O	7·2 to 10·7	— —	8·2 to 11·1	— —

Continued asthenospheric upwelling caused increased temperatures and lower pressure melting, higher up in the crust, which tapped a less enriched source, more contaminated with older crustal material. This sequence is seen in detail in Donegal, where the younger Rosses magmas which are SiO_2 rich (>70% SiO_2), have negative Eu anomalies, low Ba and Sr (Fig. 8), suggesting that low fraction melts with residual feldspar in the source are intruded into the older Thorr pluton in which rocks are more basic, have high Ba–Sr contents (high Ba–Sr magma) and no Eu anomalies, suggesting a lack of feldspar in a deeper, enriched source. This is supported by the Nd–Sr data (Dempsey *et al.* 1990). Thus Thorr has mantle or mafic young crust ε Nd values of −4·8 and −5·1, whilst the outer facies (G1) of the Rosses pluton has a very negative ε Nd value of −8·0, consistent with the involvement of old, LREE enriched crust. Intriguingly, the G3 facies of Rosses has an ε Nd of −4·9, similar to Thorr, which implies Rosses magmas came from at least two sources, suggesting the lower crust had an interlayered compositional structure.

This model may be extended to all the Donegal granites, which may be put in a crude basic-acid sequence as follows: Fanad–Thorr–Ardara–Main Donegal–Rosses–Trawenagh Bay–Barnesmore. This is roughly the oldest to youngest based on field evidence (Pitcher & Berger 1972; the relative age of the isolated Barnesmore pluton is unclear). This is also a sequence of decreasing Sr–Ba (particularly Sr, see Fig. 8). Taking the Sr–Ba contents as an indicator of mantle component, it appears that this has decreased with time, which is consistent with the model in which the melting zone was initially in the lamprophyric underplate then moved higher up the crust with continued asthenospheric upwelling. This model also has a bearing upon the apparent age and areal distribution of these two magma types. Tarney & Jones (1994) argued that high Ba–Sr granitic magmas were globally dominant in the Archaean, whilst low Ba–Sr granitic magmas dominated the mid-Proterozoic and much of the Palaeozoic, and one or other type tends to be exclusively developed in a given region. This may be so on a large scale, but such distinctions are not present in detail in Donegal, where both types occur in plutons intruded at about the same time. The two types relate to differences in source mineralogy e.g. depth, as well as the composition of the lithospheric component. This being so, the spatial separation of the Late Granite high Ba–Sr Argyll Suite in the south-west and the low Ba–Sr Cairngorm Suite in the north-east of Mainland Scotland may be explained in the same way, i.e. the mantle component of the source decreased from the west to the north-east of Scotland as the crustal component increased and melting depth (P and T) decreased (Atherton & Ghani 2002).

Appinitic, lamprophyric magmas are a major component of the high Ba–Sr Late Granite magmas emphasising these granites were not produced *only* by recycling old continental crust as suggested by some workers (Pitcher 1987; Brown 1991). Rather it relates to a major mantle input, on slab breakoff, into the crust, with some recycling of old crust.

Tarney & Jones (1994), in a discussion of high Ba–Sr granitic rocks world-wide, pointed out that the mafic source for such rocks must be 'enriched' in the same way. They thought there were three possible explanations for this specific chemistry:

1. Melting of subducted oceanic plateaus, possibly by mantle plumes.
2. Underplating of crust by 'enriched' mafic magmas which then undergoes hydrous partial melting as suggested by Atherton & Petford (1993) for plutons along the spine of the Andes. This could be linked to mantle plumes as suggested by Hill *et al.* (1992), as some mantle plumes may just be able to underplate thick lithosphere, but not break through, but could provide sufficient energy for melting.
3. Penetration of lower lithosphere by small volume asthenospheric carbonatitic melts as described by Green & Wallace (1988). These may also be linked to mantle plume activity (Hauri *et al.* 1993).

A major consequence of these explanations is that they are episodic, not continuous, marking a thermal pulse in the evolving thermal regime of the mantle entirely different from the thermal regime in the mantle wedge produced on continuous subduction. Interestingly, slab break-off produces a form of linear shallow mantle upwelling, melting enriched continental lithosphere, which fulfils the major requirement of a heat source in all of Tarney & Jones (1994) explanations and neatly accounts for the characteristics of Late Granite magmatism.

Clearly, if slab break-off can explain the genesis and evolution of Donegal Late Granites and appinites, it can be considered a cypher for Late Caledonian magmatism across the whole Caledonian outcrop of the North West British Isles

(Atherton 1999; Atherton & Ghani 2002) from Donegal through Scotland to the Shetland Isles.

5. Acknowledgements

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