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The Neoproterozoic (ca. 870 Ma) West Highland Granitic Gneiss, exposed in the Northern Highlands Terrane of Scotland, has elemental characteristics that are strikingly similar to those of the host Moine metasediments, which are thus consistent with an origin involving major Moine melting. Most of the constituent bodies have compositions significantly removed from minimum melts of pelites, and trace element constraints suggest variable but significant restite entrainment leading to less silicic bulk compositions with enhanced REE, Zr and Y. However, initial Nd and Hf isotope ratios are not coincident with contemporary Moine and imply a significant juvenile contribution. Close association with a regional suite of metabasites prompts consideration of mafic magma input, for which binary mixing models offer qualitative support. Quantitative difficulties with typical Moine metasediments are eased with radiogenic pelites or by partial melting of the mafic component. A possible alternative is currently unexposed Grenvillian felsic crust. Subsequent interaction of the granitic gneisses with meteoric water has significantly perturbed the oxygen and Sr isotope systems, the timing of which is equivocal but probably occurred during Caledonian events.

The elemental characteristics of the West Highland Granitic Gneiss show many similarities with Scandinavian (rift-related?) granites of the same age, but since their geochemistry is largely inherited from the protolith it would be unwise to pursue palaeotectonic attribution on this basis. However, the probable incorporation of significant mantle-derived mafic magma of MORB-like affinity is consistent with an extensional setting.

Fowler et al West Highland Granitic Gneiss Highlights.

- We provide the first comprehensive elemental and isotopic study of these metamorphosed intrusions
- They are derived by metasediment anatexis but have incorporated significant juvenile material
- Restite entrainment and inefficient melt extraction are important influences on their primary geochemistry
- Subsequent hydrothermal alteration has affected Sr and O isotope systems

# **Petrogenesis of the Neoproterozoic West Highland Granitic Gneiss, Scottish Caledonides: cryptic mantle input to S-type granites?**

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## **Abstract**

The Neoproterozoic (ca. 870 Ma) West Highland Granitic Gneiss, exposed in the Northern Highlands Terrane of Scotland, has elemental characteristics that are strikingly similar to those of the host Moine metasediments, which are thus consistent with an origin involving major Moine melting. Most of the constituent bodies have compositions significantly removed from minimum melts of pelites, and trace element constraints suggest variable but significant restite entrainment leading to less silicic bulk compositions with enhanced REE, Zr and Y. However, initial Nd and Hf isotope ratios are not coincident with contemporary Moine and imply a significant juvenile contribution. Close association with a regional suite of metabasites prompts consideration of mafic magma input, for which binary mixing models offer qualitative support. Quantitative difficulties with typical Moine metasediments are eased with radiogenic pelites or by partial melting of the mafic component. A possible alternative is currently unexposed Grenvillian felsic crust. Subsequent interaction of the granitic gneisses with meteoric water has significantly perturbed the oxygen and Sr isotope systems, the timing of which is equivocal but probably occurred during Caledonian events.

The elemental characteristics of the West Highland Granitic Gneiss show many similarities with Scandinavian (rift-related?) granites of the same age, but since their geochemistry is largely inherited from the protolith it would be unwise to pursue palaeotectonic attribution on this basis. However, the probable incorporation of significant mantle-derived mafic magma of MORB-like affinity is consistent with an extensional setting.

**KEYWORDS:** S-type granite, restite entrainment, mantle input, Neoproterozoic, Nd-Hf-Sr-O isotopes, petrogenesis.

## 1. Introduction

Establishing the early history of polymetamorphic terrains is complex, as textural, mineralogical, geochemical and geochronological evidence may be modified or obliterated by later tectono-metamorphic events. Determining the tectonic setting of deformed granitic rocks may provide useful information. Granites may form as ‘anorogenic’ melts formed during rifting of continental crust; as calc-alkaline melts in a magmatic arc constructed along a continental margin; or as intracrustal melts formed during collisional thickening and/or extensional collapse of the orogen. Diagnostic criteria have been established for the recognition of past geodynamic setting, using detailed knowledge of structural relations, geochronology and geochemistry (e.g. Pearce et al., 1984). As well as providing age constraints, isotopes are often used to refine conclusions based on elemental work and elucidate petrogenetic processes. Interpretation becomes increasingly difficult as the degree of reworking increases, such that in many polymetamorphic terrains the tectonic setting of early, deformed granites is controversial. In this contribution, such techniques are used in an attempt to establish the petrogenesis and tectonic setting of an enigmatic suite of granitic gneisses exposed within the metasedimentary rocks of the early Neoproterozoic Moine Supergroup in northern Scotland (Fig. 1).

The Moine Supergroup of northern Scotland crops out between the Great Glen Fault and the Moine Thrust (Fig. 1). It was affected by Neoproterozoic ‘Knoydartian’ orogenic events at c. 820-790 Ma and c. 730 Ma (Rogers et al., 1998; Vance et al., 1998; Tanner and Evans, 2003; Cutts et al., 2010). This was followed during the Ordovician-Silurian by widespread reworking during Caledonian (s.l.) orogenic events that resulted from closure of the Iapetus Ocean (e.g. Soper and Hutton, 1984; Soper et al., 1992; Dewey and Strachan, 2003; Strachan et al., 2010). High-grade Caledonian metamorphism of the Moine Supergroup disturbed the geochronological record of Neoproterozoic events, the interpretation of which is not straightforward. The Moine Supergroup is intruded by felsic meta-igneous rocks known as the West Highland Granitic Gneiss (Johnstone, 1975). Members of the suite have yielded U-Pb zircon ages of c. 870 Ma (Friend et al., 1997; Rogers et al., 2001). Whether the granitic protolith was formed by crustal melting during an orogenic event (Barr et al., 1985; Friend et al., 1997) or extensional rifting and development of the Moine sedimentary basin(s) (Soper and Harris, 1997; Dalziel and Soper, 2001; Ryan and Soper, 2001) has implications for regional tectonic models for the Neoproterozoic evolution of this part of the North Atlantic region. This contribution documents a systematic geochemical and isotopic investigation of the West Highland Granitic Gneiss in an attempt to constrain the source(s) of the felsic melts and the palaeotectonic significance of this early magmatic event.

## 2. Geological background

The Moine Supergroup comprises thick sequences of psammites and pelites, subdivided into the Morar, Glenfinnan and Loch Eil groups (Fig. 1; Holdsworth et al., 1994 and references therein). These are interfolded and intersliced with inliers of Archaean 'Lewisianoid' gneisses, which are thought to represent the basement on which the Moine rocks were deposited unconformably (Fig. 1; Holdsworth et al., 1994; Friend et al., 2008). Detrital zircons yield U-Pb ages mostly in the range 1800-1000 Ma, consistent with derivation from sources in eastern Laurentia (Friend et al., 2003; Cawood et al., 2007; Kirkland et al., 2008). The youngest detrital zircon grains in the Glenfinnan and Loch Eil groups yield ages of c. 900-920 Ma (Cawood et al., 2004; Cutts et al., 2010), providing an upper limit for deposition. Early metabasic intrusions within the Moine Supergroup display a tholeiitic chemistry, consistent with intrusion into thinned continental crust during extension and rifting (Moorhouse and Moorhouse, 1979; Winchester, 1984; Winchester and Floyd, 1983; Rock et al., 1985; Millar, 1999). Continental reconstructions for the early Neoproterozoic (Fig. 2) place the Moine basins either well within the Rodinia supercontinent (Dalziel and Soper, 2001) or much closer to its margin (Li et al., 2008), depending upon the location of Baltica relative to Greenland.

The West Highland Granitic Gneiss (Harry, 1953; Dalziel, 1966; Johnstone, 1975; Barr et al., 1985) comprises a number of separate intrusions, including those at Ardgour, Loch Arkaig, Fort Augustus, and Glen Moriston (Fig. 1). These intrusions mainly crop out close to the boundary between the Glenfinnan and Loch Eil groups (Fig. 1). East of Loch Quoich, granitic gneisses occur entirely within the Loch Eil Group. The granite suite is therefore discordant to the regional lithostratigraphy, although contacts with host Moine rocks are concordant at outcrop. While sharp at some localities, contacts between gneiss and metasedimentary country rock are apparently rapidly transitional at others, especially where the latter are migmatized. The gneiss is a coarsely-foliated, microcline-oligoclase-quartz granite with subordinate biotite and local hornblende and accessory garnet, sillimanite and ore. It carries abundant, sub-concordant quartzofeldspathic segregation pegmatites, bordered by biotite selvages. The granitic gneisses are compositionally and texturally relatively homogeneous, although the southern part of the Ardgour body includes a distinctive augen facies (Bailey and Maufe, 1916).

The granite gneiss suite has been interpreted as magmatic (Bailey and Maufe, 1916; Mercy, 1963), metasomatic (Harry, 1953; Dalziel, 1963; 1966), and as a tectonically-emplaced slice of pre-existing basement (Harris, in discussion of Winchester, 1974). Barr et al. (1985) interpreted the granitic protolith of the

gneisses to be a magmatic intrusion formed by anatexis of Moine rocks. This was consistent with chemical analyses of the gneisses, which have a restricted range of bulk composition with high SiO<sub>2</sub>, low Na<sub>2</sub>O/K<sub>2</sub>O and Fe<sub>2</sub>O<sub>3</sub>/FeO, an initial <sup>87</sup>Sr/<sup>86</sup>Sr ratio of 0.709, and are corundum normative. Other reasons which led Barr et al. (1985) to support a magmatic origin include: (1) the discordance of the suite with the regional lithostratigraphy; (2) the sharpness of contacts with host metasediments, although some are locally sheeted; (3) the presence of rare inclusions of psammite and hornblende schist, interpreted as xenoliths, and (4) the difficulties involved in converting a diverse series of metasediments into a uniform, homogeneous gneiss by metasomatism.

U-Pb (SIMS) dating of zircon needles and rims within the Ardgour granitic gneiss and its segregation pegmatites yielded an age of 873 ± 7 Ma (Friend et al., 1997). An age of 870 ± 30 Ma has also been obtained for formation of the granitic protolith of the Fort Augustus granitic gneiss (Rogers et al., 2001). A range of older Proterozoic ages, mainly between c.1800 Ma and c.1000 Ma, has been obtained from the cores of zircons in the granitic gneisses. These zircons were interpreted as detrital grains within the Moine sediments that melted to form the granitic gneiss protolith (Friend et al., 1997, 2003; Rogers et al., 2001). Metagabbros thought to have been intruded contemporaneously with the granitic gneiss in Glen Doe (Fig. 1) were intruded at 870 ± 6 Ma (U-Pb zircon, Millar, 1999).

### 3. Tectonic setting of the granitic gneiss suite

Barr et al. (1985) viewed the granitic gneiss intrusions as syn-orogenic and formed during regional migmatization, melting and early isoclinal folding of the Moine sediments. The absence of a thermal aureole adjacent to the granitic gneiss bodies implied to them that the country rocks were already at elevated temperatures when the granites were emplaced. Furthermore, they showed that the segregation pegmatites locally cross-cut the earliest gneissic fabric within the granitic gneisses which was therefore thought to have developed during this high-grade event.

The alternative view is that the granitic protolith of the gneiss was formed during crustal extension, development of the Moine basin(s), and emplacement of the regional metabasic suite that provided the heat source necessary to melt the Moine sediments. Millar (1999) and Dalziel and Soper (2001) argue that there is no evidence for any regional deformation or metamorphism of the Moine rocks, either prior to or during the emplacement of the protoliths of the granitic gneisses and the metabasic rocks, so both are pre-tectonic. Dalziel and Soper (2001) interpreted the zircons within the segregation pegmatites dated by Friend et al. (1997) to be xenocrysts inherited from the granitic protolith, and therefore considered that gneissification and melting to form the segregation pegmatites occurred much later

during the Caledonian orogeny.

In contrast to previous workers, Ryan and Soper (2001) envisaged that the protoliths of the granitic gneisses resulted not from the melting of the Moine sediments, but from anatexis of the basement rocks thought to have floored the Moine basin. They presented the results of mathematical modelling to show that emplacement of basaltic intrusions at depth could have provided sufficient heat to locally melt the underlying basement to produce granitic melts that migrated up through the sedimentary pile to their present locations. They suggested that the inferred basaltic intrusions are represented at a higher structural level within the Moine rocks by the regional metabasic suite. In view of the Archaean age of the basement inliers within the Moine Supergroup (Moorbath and Taylor, 1974; Friend et al., 2008), the absence of inherited zircons of this age within the granitic gneisses is surprising if they were produced by anatexis of the basement. However, Ryan and Soper (2001) account for this apparent inconsistency by suggesting that the basement source for the granite melts might in fact be Proterozoic.

#### **4. Sampling and analytical techniques**

5-6 representative samples were collected from the largest granitic gneiss bodies at Ardgour, Loch Arkraig, Fort Augustus and Glen Moriston, supplemented by a smaller number of samples collected from Loch Quoich and Glen Doe. The samples were texturally relatively uniform with little variation in mineralogy. They were split, subsampled and crushed in a carbide shatterbox to pass 200# (<75 µm). Major elements and Ba, Sr, Y, Cr and Zr were determined by ICPAES at Oxford Brookes University by fusion dissolution followed by analysis against calibrations defined with international standard rock materials (SRMs). Accuracy and precision are estimated to be better than 1% relative standard deviation (rsd), on the basis of SRM analytical results and precision tests. Rare earth elements (REE) were also analysed by ICPAES, following fusion dissolution and cation-exchange preconcentration, at Oxford Brookes University. Natural SRMs were used to define the calibrations and monitor the quality of the data. Cr, Cu, Ga, Nb, Ni, Pb, Rb, Sr, Th, V, Y, Zn and Zr were analysed by XRF at Keele University and the British Geological Survey. Accuracy and precision of all the trace element analyses are better than 5% rsd, estimated as for the major element determinations.

Oxygen isotope analyses were performed using the laser fluorination method of Sharp (1990) as adapted for ClF<sub>3</sub> by Macaulay et al. (2000). Oxygen was released from c. 1mg samples following vacuum degassing, and converted to CO<sub>2</sub> by Pt-catalysed reaction with hot graphite. An in-line Hg-diffusion pump ensured rapid and quantitative transfer of O<sub>2</sub> to the conversion chamber and acted as a getter for residual halogen compounds. Isotope ratios were measured with an on-line VG PRISM III dual-inlet, triple-collector mass spectrometer. Data are reported in the



conventional  $\delta^{18}\text{O}\text{‰}$  notation relative to V-SMOW. Precision at  $1\sigma$  is  $\pm 0.2\text{‰}$  or better and NBS28 quartz gives  $9.6\text{‰}$ .

Nd and Sr for isotopic analysis were separated from whole-rock powders by standard cation exchange procedures following HF/HNO<sub>3</sub> dissolution. Isotopic analyses were performed at NIGL using a Finnigan-Mat automated thermal ionisation mass spectrometer. Determinations on standards covering the period during which the analyses were made are as follows: in-house Johnson and Mathey standard  $^{143}\text{Nd}/^{144}\text{Nd} = 0.511119 \pm 10$  ( $2\sigma$ ),  $n = 13$  (batch 1);  $0.511124 \pm 13$ ,  $n = 20$  (batch 2) and  $0.511113 \pm 9$ ,  $n = 16$  (batch 3); NBS 987  $^{87}\text{Sr}/^{86}\text{Sr} = 0.710217 \pm 24$  ( $2\sigma$ ),  $n = 10$  (batch 1);  $0.710222 \pm 18$ ,  $n = 20$  (batch 2) and  $0.710187 \pm 12$ ,  $n = 24$  (batch 3).  $^{143}\text{Nd}/^{144}\text{Nd}$  isotope ratios from are quoted relative to a value of 0.511123 for this standard (equivalent to 0.511860 for La Jolla).  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratios have been normalised to a value of 0.710250 for NBS987.

Hf was separated using a single LN-SPEC column procedure following the method of Munker et al. (2001). The Hf isotope composition was then analyzed at the NERC Isotope Geosciences Laboratories on a Nu-plasma HR multicollector plasma ionization mass spectrometer, using static multicollection. Correction for Lu and Yb interference on mass 176 was performed by standard reverse-mass-bias correction using empirically predetermined values for  $^{173}\text{Yb}/^{176}\text{Yb}$ .  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios were  $< 5 \times 10^{-6}$  and  $^{176}\text{Yb}/^{177}\text{Hf}$  ratios were  $< 2 \times 10^{-4}$  for all samples. Analyses of the JMC475 solution standard gave a value of  $0.282144 \pm 0.000008$  ( $2\sigma$ )  $n=14$ . One analysis of the BCR-2 rock standard analyzed with the samples gave a  $^{176}\text{Hf}/^{177}\text{Hf}$  value of  $0.282866 \pm 0.000006$  (2SE), after normalization to a value of 0.282160 for JMC475.

## 5. Results

The major element oxide abundances (Table 1) of the West Highland Granitic Gneiss are generally rather uniform, as befits the limited lithological range, with most samples falling between 67.5 - 76.8 wt% SiO<sub>2</sub>, 0.13 - 1.6 wt% MgO, 0.9 - 3.3 wt% CaO and 3.5 - 5.7 wt% K<sub>2</sub>O for example. However, those variations that do exist are systematic, as shown in the Harker diagrams (Fig. 3). Negative correlations with silica exist for TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MnO, MgO and P<sub>2</sub>O<sub>5</sub> (not shown), broadly convex-down with CaO and Na<sub>2</sub>O and broadly positive with K<sub>2</sub>O. There is a systematic arrangement of the various discrete granitic gneiss bodies, with Ardgour, Loch Arkaig and Fort Augustus consistently less silicic than Glen Moriston and Glen Doe – a roughly SW to NE trend. Data for local Moine metasediments, plus restite data from Watt et al. (1996) all lie to the silica-poor side of the granitic gneiss fields (Fig. 3). Trace elements (Table 1) are similarly coherent, as summarised by the chondrite-normalised plots (Figs. 4 and 5), and

bivariate plots (Fig. 6). All the granitic gneiss bodies show similar chondrite-normalised patterns characterised by relatively high trace element abundances overall, with a gentle increase from Yb at less than 50 times chondrite to Rb at several hundred times chondrite (Fig. 4). Superimposed upon this general increase towards the left (the most “incompatible”, with respect to mantle peridotite) are significant troughs at Ba, Nb, Sr, P and Ti, all of variable depth. The overall patterns are strikingly similar to those generated by Moine metasediments (Fig. 4). The REE group (Fig. 5) shows moderate light REE enrichment, variable negative Eu anomalies and relatively high but essentially flat heavy REEs. One sample from Glen Moriston lies significantly below the main group, with a large negative Eu anomaly. The Moine metasediments display a range of sub-parallel patterns of the same general shape, with mild light REE enrichment, negative Eu anomalies and relatively high but flat heavy REEs (Fig. 5), especially in pelitic samples. On average, the granitic gneisses have heavy REE (and Y) values closer to these than the more siliceous Moine samples. Within the bivariate trace element plots (Fig. 6), the systematic data disposition reappears, within well-defined arrays generally from Ardgour, Loch Arkaig and Fort Augustus to Glen Moriston and Glen Doe. Restite data, where available, fall to the trace-element-rich side of the granitic gneiss fields, and data for Moine pelites and semipelites vary but generally do not exceed those seen in the granitic gneisses.

The isotope data (Table 2) are summarised on plots of  $\epsilon\text{Nd}$  vs  $^{87}\text{Sr}/^{86}\text{Sr}_i$  annotated with  $\delta^{18}\text{O}$  values (Fig. 7a), and  $\epsilon\text{Nd}$  v  $\epsilon\text{Hf}$  (Fig. 7b). The granitic gneiss bodies define distinct fields whose  $\epsilon\text{Nd}$  varies from +2 to -5,  $\epsilon\text{Hf}$  from +4.7 to +13.6,  $^{87}\text{Sr}/^{86}\text{Sr}_i$  from 0.708 to 0.717, and  $\delta^{18}\text{O}$  from +3.0 to +7.8‰, all of which are considerable ranges. Also plotted on the diagrams are data for Moine metasediments (Millar, 1999 plus new Hf data), and local metabasic magmas (Millar, 1999 plus new Hf data). Available oxygen isotope data for Moine lithologies are sparse, but noted where available. They do not extend to the low values of some of the granitic gneiss samples.

## 6. Petrogenesis

There are many processes which might contribute to an explanation of the data. These include melting of local metasedimentary rocks with or without restite entrainment and crystal-liquid separation, melting of underlying basement rocks, introduction of juvenile mafic magmas, mixing of components from several such sources, subsequent metamorphism and alteration of elemental and isotopic characteristics, and so on. Many of these are considered below, starting with those most likely on geological grounds, with additions and modifications as required to explain as much of the data as possible.

### 6.1. Primary petrogenetic controls

Representative data for local Moine metasediments are available in Table 1. Pelites and semipelites are most likely to have melted, and have been plotted on Fig. 3. to indicate the potential Moine source. In all cases the granitic gneisses are displaced from the potential source – lower in MgO, Fe<sub>2</sub>O<sub>3</sub>, MnO, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and higher in Na<sub>2</sub>O, K<sub>2</sub>O and P<sub>2</sub>O<sub>5</sub>. This is expected for metasediment melting, as shown by experimental minimum melts derived from pelites under different melting conditions and, which plot closest to the compositions of the gneisses from Glen Moriston and Glen Doe (e.g. filled circles on Fig. 3 represent data from Patiño Douce and Harris, 1998, though note significantly higher Al<sub>2</sub>O<sub>3</sub>). However, it is clear from the ranges of the major element data that the other gneiss bodies cannot represent simple minimum melt compositions. Studies of migmatites have frequently suggested that biotite-rich selvages represent refractory material remaining after leucosome removal. Incomplete separation of melt from residue may modify melt compositions by “restite entrainment”. Watt et al. (1996) demonstrated that during Moine melting (albeit in the Kirtomy nappe now exposed near the north coast, and during the Caledonian orogeny) melanosomes had the assemblage quartz + plagioclase + k-feldspar + biotite + zircon + apatite + monazite + rutile, with SiO<sub>2</sub> as low as 35.99 wt%, K<sub>2</sub>O and MgO as high as 9.46 wt% and 6.86 wt% respectively, and Fe<sub>2</sub>O<sub>3</sub> up to 23.42 wt %. Two mafic restites (Watt et al., 1996) have been plotted on Fig. 3, from which it is apparent that the more mafic West Highland Granitic Gneiss bodies at Ardgour, Loch Arkaig and Fort Augustus may incorporate a small but significant excess of entrained palaeosome or biotitic restite – of the order of 20% (following the lever rule with the Glen Moriston and Glen Doe bodies as parental compositions).

The comparability of trace element abundances and ratios between the West Highland Granitic Gneiss and Moine pelites and semipelites is amply illustrated on the chondrite-normalised diagrams (Figs. 4 and 5). The closest comparisons are with the “restite-rich” Ardgour, Fort Augustus and Loch Arkaig bodies, with whose patterns the pelitic Moine is essentially identical, except for enhancement in P and depletion in Sr in the gneisses. The other gneiss bodies – Glen Moriston and Glen Doe – have systematically differing patterns with deeper troughs in Ba, Sr, P and Ti; lower Zr, Y and total REE contents and deeper negative Eu anomalies. One sample is particularly extreme, suggestive of minor feldspar (many of the gneisses carry K-feldspar augen), apatite, zircon and titaniferous accessory mineral fractionation. Bivariate, logarithmic trace element plots (Fig. 6a-f) against Zr may be used to constrain these possibilities. Zr is used since it is sensitive to both proposed processes – crystal fractionation and restite entrainment – and is available in the dataset of Watt et al. (1996). Data for Ce and Sm are also available for the restite (Watt et al., 1996), which then plot beyond the trace

320 element-rich Loch Arkaig, Ardgour and Fort Augustus bodies on Fig. 6a and b,  
321 consistent with restite entrainment as suggested above. Although qualitatively  
322 correct, simple mass balance suggests a significantly higher restite proportion than  
323 the major element data. The Ba and Sr plots (Fig. 6c, d) display marked inflections  
324 towards low abundances, consistent with zircon and feldspar removal from the most  
325 evolved samples from Glen Moriston and Glen Doe. Restite data are not available  
326 for these elements, nor for Th and Y, but it seems reasonable to suppose high  
327 concentrations of the latter in a zircon and monazite-bearing component (Watt et  
328 al., 1996, Fig. 6e, f).

329 Thus, the elemental evidence seems to be consistent with large-fraction  
330 melting of a Moine precursor. It might therefore be expected that the radiogenic  
331 isotopes in the gneisses reflect closely those of the Moine at the time of melting.  
332 However, there is good evidence for disruption of the Sr system as a result of late  
333 fluid activity, hinted at by the disparate  $^{87}\text{Sr}/^{86}\text{Sr}$  at similar  $^{143}\text{Nd}/^{144}\text{Nd}$  (Fig. 7a),  
334 and confirmed by correlations with abnormal  $\delta^{18}\text{O}$  and a variety of mobile  
335 elements. This will be dealt with in more detail later. First, the petrogenetic  
336 significance of the Nd and Hf isotope variations is addressed, since these are  
337 generally thought to be robust tracers of parental reservoirs. On the basis of the few  
338 data available for both Nd and Hf isotopes, Moine metasediments define a broad  
339 field from the characteristic negative  $\epsilon\text{Nd}$  and  $\epsilon\text{Hf}$  of Proterozoic continental crust  
340 to relatively radiogenic pelitic samples (Fig. 7b). A compilation of available Nd  
341 isotope data for the Moine (ILM unpublished) suggests that the former are  
342 dominant. The granitic gneisses from Loch Arkaig and Fort Augustus have small  
343 *positive*  $\epsilon\text{Nd}$  values, those for Ardgour and Glen Moriston are small and negative,  
344 while only those of Glen Doe in any way approach normal Moine values (Fig. 7b).  
345 All the granitic gneiss samples have positive  $\epsilon\text{Hf}$ . At first sight, this flatly  
346 contradicts the evidence presented above for a “normal” Moine source and requires  
347 something significantly more juvenile, and/or a completely different source. Other  
348 potential sources include Archaean to Proterozoic basement lying beneath the  
349 Moine Supergroup, and contemporaneous mafic magma.

350 The Lewisian basement is exposed to the west of the Moine Thrust, and is  
351 dominated by late Archaean (2.9-2.7 Ga) TTG-suite gneisses (at amphibolite or  
352 granulite facies) with minor mafic components. These show characteristic heavy  
353 REE depletion with variable positive Eu anomalies that result from amphibolite  
354 melting with minor garnet in the residue (e.g. Rollinson and Fowler, 1987), and are  
355 most unlikely to generate granites with high heavy REEs. Furthermore, the Nd  
356 isotope system of Lewisian gneisses would have evolved far away from the initial  
357 values of the West Highland Granitic Gneiss by 870 Ma (to ca. -15, Fig. 7b, based  
358 on data from Whitehouse et al., 1996), and Watkins et al. (2007) noted that the  
359 products of experimental melting of Lewisian gneisses are sodic granites and

granodiorites. Therefore, a Lewisian source can confidently be ruled out.

A Proterozoic basement source has been favoured by Ryan and Soper (2001). Unfortunately, exposures in Northern Scotland are small and may not be representative. Nevertheless, 1.8 Ga Rhinnian basement is exposed on Islay and Colonsay, and possibly extends to Inishtrahull off the coast of Northern Ireland (Muir et al., 1994). It is composed of deformed syenite and gabbro, with minor felsic and mafic intrusions. Geochemically, the major components (syenite and gabbro) show subduction-related characteristics (enrichment in light REE and other LILEs, relative depletion in HFSEs including large negative Nb anomalies on primitive-mantle-normalised multi-element plots, Muir et al., 1994). Nd isotope data (Muir et al., 1994) favour a juvenile source ( $\epsilon\text{Nd} = +0.6 - +2.0$ ), and by 870 Ma these would have evolved to  $\epsilon\text{Nd} = -6$  to  $-9$  (Fig. 7b), which is also considerably more negative than the initial values of West Highland Granitic Gneiss, discussed above.

There has been much discussion in the literature concerning the extent of possible Grenvillian basement and/or events in Northern Scotland, but since very little is actually exposed (Storey et al., 2004), published elemental and Nd isotope data are conspicuous by their absence. The best that can be done is to seek representative data for juvenile Grenville crustal additions from elsewhere. Not surprisingly, these also appear to be various products of subduction-related magmatism. For example, Blein et al. (2003) documented the 1.4 Ga Bondy gneiss complex from the Central Metasedimentary Belt of the Grenville Province in some detail, assigning mafic granulites, intermediate gneisses and metatonalites to a mature island-arc setting, and equating minor quartzofeldspathic gneisses with back-arc high-silica rhyolites. The Nd isotope signature of such rocks (Blein et al., 2003), recalculated to 870 Ma, overlaps that of the West Highland Granitic Gneiss ( $\epsilon\text{Nd}_{870}$  for the mafic rocks =  $+1.3$  to  $+6.1$ , for the felsic rocks =  $-0.8$  to  $-2.7$ , Fig. 7b).

Broadly-contemporaneous mafic magmas have been identified within the Moine Supergroup (Millar, 1999), and although obvious field evidence for extensive mixing or dispersal within the granitic gneisses is absent, this may have been obscured by subsequent deformation, or the process could have occurred at a deeper structural level prior to migration of melts to their present locations. Significant volumes of contemporary mafic magma would also represent a sensible heat source for large-fraction melting. Major element data are consistent with limited admixture of mafic magma – the composition of which has been marked on Fig. 3 (data from Millar, 1999). Trace element data (Fig. 6) are less accommodating, but some combination of restite entrainment and magma mixing certainly would be possible. In more detail, binary mixing calculations (Fig. 8a) suggest that several tens of percent admixture of a MORB-like composition would

not appreciably affect trace element relative abundances, since most are dominated by the granitic end member. Nd-Hf isotope constraints generally support such interaction (Fig. 8b), but because of the relative Hf and Nd budgets of Moine and MORB, simple binary mixing would require large proportions of mafic magma (many tens of percent), that are difficult to reconcile with major element mass balance. If the melted Moine is of less usual isotopic composition, towards the high  $\epsilon_{\text{Nd}}\text{-}\epsilon_{\text{Hf}}$  (pelitic) part of the range, this problem reduces considerably. Alternatively, if the “mafic” isotopic contribution were in the form of a partial melt, a larger contribution of this silicic magma could remain within the elemental constraints. In either case, Hf isotope compositions remain excessive.

Further source region evidence is available from inherited zircons, which have been studied by Friend et al. (1997, 2003), and Rogers et al. (2001). These show a range of Proterozoic ages, but a complete absence of Archaean grains (Friend et al., 2003). The dominant peaks are at ca. 1400 and 1100 Ma, with very few analyses near 1800 Ma. These data are consistent with no source contributions from Lewisian or Rhinnian basement, but do allow a substantial Grenvillian (and older) component. On the other hand, they are also perfectly consistent with major Moine melting, since the inherited zircons from the West Highland Granitic Gneiss overlap detrital grains from the local Lochailort pelite (Friend et al., 2003).

In summary, major and trace element data are consistent with major Moine melting, with variations attributable to restite entrainment and minor fractionation. Nd-Hf isotope relationships require that any Moine component comes from isotopically unusual lithologies, and/or is mixed with a juvenile component. This likely derives from local mafic magmas, either directly or via partial melting, but recently-juvenile felsic material such as unexposed Grenvillian basement is another possibility. Such suggestions are not mutually exclusive, and attest to the well-known complexities of intracrustal granite petrogenesis.

## 6.2. Secondary petrogenetic processes

Stable isotopes are powerful indicators of fluid movements in the Earth’s crust, and much is known about normal ranges within igneous, sedimentary and metamorphic rocks. Moine metasediments have typical  $\delta^{18}\text{O}$  values between +8.0 and +10.2‰ (Table 2, and MF unpublished data). Therefore, the low extreme of the range of values for the West Highland Granitic gneiss samples (+7.7 to +3.0‰) is surprising and requires explanation. During anhydrous melting, the oxygen isotope signature is little changed, since mineral-melt fractionation factors are small at high temperature. However, most crustal melts form under hydrous conditions, when stable isotope systematics may be considerably modified, sometimes generating low  $\delta^{18}\text{O}$  magmas (see review by Taylor, 1990). On the other hand, similar low  $\delta^{18}\text{O}$  values in high-grade regional metamorphic rocks elsewhere have also been

attributed to deep penetration of surface-derived water (e.g. Miller and Cartwright, 1997). It is therefore possible that variations in  $\delta^{18}\text{O}$  may be the result of melting or later fluid involvement (or both). Correlations between  $\delta^{18}\text{O}$ , elements and the other isotope systems were sought in order to investigate these possibilities. Rb,  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\text{K}_2\text{O}$  generally increase with falling  $\delta^{18}\text{O}$ , whereas elemental Sr, CaO and  $\text{Na}_2\text{O}$  generally decrease *within* gneiss bodies. These observations are consistent with alteration of feldspar, commonly the most susceptible mineral to O isotope exchange in hydrothermal systems. The fluid responsible likely had high Rb/Sr and probably also high  $^{87}\text{Sr}/^{86}\text{Sr}$ , in accord with the suggestion of Millar (1999) in relation to local metabasite alteration.

## 7. Palaeotectonic affinities and correlations

The palaeotectonic setting of the West Highland Granitic Gneiss is controversial (Barr et al., 1985; Friend et al., 1997; Soper and Harris, 1997; Millar, 1999; Dalziel and Soper, 2001; Ryan and Soper, 2001). Paulsson and Andreasson (2002) have discussed possible correlations of Neoproterozoic bimodal basic – granitoid magmatism within the Scandinavian, Scottish and Siberian Caledonides, with respect to attempted rifting of Rodinia at c. 845 Ma. They drew specific comparison between the West Highland Granitic Gneiss and the Vistas Granite of the Seve Nappe Complex, northern Sweden, whose petrogenesis was ascribed to an S-type origin yet plotting in the field of within-plate granites on the discrimination diagrams of Pearce et al. (1984). The chemical data presented above allow this proposed correlation to be tested further. Figure 9 (a,b) shows chondrite-normalised multi-element patterns for the Vistas Granite (data from Paulsson and Andreasson, 2002) for comparison with those of the West Highland Granitic Gneiss. The similarity is striking, at first sight strengthening the proposed correlation between these broadly contemporaneous anatectic granites.

However, it is clear from this study that the main control on the chemistry of the gneiss suite is that of the protolith. Similar conclusions have been reached for anatectic granites elsewhere. For example, Brown and D'Lemos (1991) related the calc-alkaline signature of Cadomian (late Neoproterozoic) granites from the French Armorican massif directly to the geochemistry of their source Brioverian sediments. Therefore, it is unwise to ascribe any particular palaeotectonic setting on the basis of granitic gneiss geochemistry. However, the likely incorporation of significant volumes of MORB-like mafic magma is consistent with contemporaneous crustal extension (as concluded by Millar, 1999).

## 8. Conclusions

The present study illustrates many of the complexities inherent in the constraint of petrogenesis and tectonic setting of deformed and metamorphosed

granites in orogenic belts. The weight of elemental evidence suggests derivation of the West Highland Granitic Gneiss by anatexis of Moine metasediments, with restite entrainment, mixing of magmas from different sources and minor crystal fractionation to explain the range of elemental data. The Nd and Hf isotope system record the significant contribution of isotopically more-juvenile materials, and the Sr and O isotope systems were altered as a result of late fluid percolation. Since elemental chemistry is inherited largely from the protolith, it cannot be diagnostic of a later tectonic setting. Nevertheless, the involvement of significant volumes of local mafic magma with MORB-like chemistry is consistent with crustal extension.

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Figure Captions

Fig. 1. Geological sketch map of the Northern Highland Terrane (NHT), northern Scotland, showing the distribution of West Highland Granitic Gneiss. GGF = Great Glen Fault, SBT = Sgurr Beag Thrust, MTZ = Moine Thrust Zone. Agg = Ardgour Granitic Gneiss, FAgg = Fort Augustus Granitic Gneiss, GM = Glen Moriston, GD = Glen Doe, LA = Loch Arkaig, LQ = Loch Quoich. S = Strontian, G = Glenfinnan, LS = Loch Sunart.

Fig. 2. Schematic reconstructions of Laurentia, Baltica and Amazonia at c. 1000 Ma, following amalgamation of Rodinia and Grenville and Sveconorwegian (SN) orogenesis: (a) after Dalziel and Soper (2001), and (b) after Cawood et al., (2010). M, Moine Supergroup. Other abbreviations: Hb, Hebridean foreland; T, Torridon Group; YS, Yell Sound Group; K, Krummedal succession; Sw, NW Svalbard; Sc, Central Svalbard; Se, Eastern Svalbard; Sa, Sværholt Succession; So, Sorøy Succession.

Fig. 3. Harker diagrams presenting West Highland Granitic Gneiss major element data. Circles = Ardgour, triangles = Loch Arkaig, diamonds = Loch Quoich, squares = Fort Augustus, pluses = Glen Moriston, inverted triangles = Glen Doe. r = Moine restite from Watt et al., (1996), filled circles at 75% SiO<sub>2</sub> = metasediment minimum melt from Patiño Douce and Harris (1998), asterisks at 45% SiO<sub>2</sub> = local mafic magma from Millar (1999). Moine = field for Moine metasediments = crosses. The “parent” field is drawn around the Glen Moriston samples.

Fig. 4. Multi-element chondrite-normalised normalised patterns for West Highland Granitic Gneiss and Moine metasediments for comparison. Note consistent large troughs at Ti, P, Sr and Nb and the close similarity of the Granite Gneiss with Moine metasediments.

Fig. 5. Chondrite-normalised REE plots for West Highland Granite Gneiss and Moine metasediments. Again, note the close similarity of all the patterns, including the Moine, with mild light REE enrichment, high heavy REE and significant negative Eu anomalies.

Fig. 6. Logarithmic, bivariate trace element plots showing the disposition of the West Highland Granitic Gneiss with respect to restite samples (Watt et al., 1996) and Moine, and hypothetical restite entrainment and crystal fractionation trends. Symbols as in Fig. 2.

Fig. 7.  $\epsilon\text{Nd}$  vs.  $^{87}\text{Sr}/^{86}\text{Sr}_i$ , annotated with  $\delta^{18}\text{O}$  (a) and  $\epsilon\text{Nd}$  vs.  $\epsilon\text{Hf}$  (b). Note separate

752 fields for individual Granitic Gneiss bodies, all distinct from that of Moine  
753 metasediments.  $\delta^{18}\text{O}$  ranges from normal metasedimentary values to locally rather  
754 low. The line through local MORB-dyke represents the range of Nd isotope  
755 compositions reported by Millar (1999).

756  
757 Fig. 8. Binary mixing models of mafic magma input. (a) Trace element mixing  
758 between MORB-like magma and Glen Moriston Granitic Gneiss end members - up  
759 to 40% admixture does not greatly disturb the shape of the trace element patterns.  
760 (b) Nd-Hf isotope mixing trajectory from potential Moine melt towards  
761 contemporary MORB-like magma.

762  
763 Fig. 9. Comparative multi-element chondrite-normalised plot, showing the West  
764 Highland Granitic Gneiss and the broadly-contemporaneous Vistas granite from the  
765 Scandinavian Caledonides. Data from Paulsson and Andreasson (2002).

**Petrogenesis of the Neoproterozoic West Highland Granitic Gneiss,  
Scottish Caledonides: cryptic mantle input to S-type granites?**

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7558 words including 51 references, with 9 figures and 2 tables.

**Abstract**

The Neoproterozoic (ca. 870 Ma) West Highland Granitic Gneiss, exposed in the Northern Highlands Terrane of Scotland, has elemental characteristics that are strikingly similar to those of the host Moine metasediments, which are thus consistent with an origin involving major Moine melting. Most of the constituent bodies have compositions significantly removed from minimum melts of pelites, and trace element constraints suggest variable but significant restite entrainment leading to less silicic bulk compositions with enhanced REE, Zr and Y. However, initial Nd and Hf isotope ratios are not coincident with contemporary Moine and imply a significant juvenile contribution. Close association with a regional suite of metabasites prompts consideration of mafic magma input, for which binary mixing models offer qualitative support. Quantitative difficulties with typical Moine metasediments are eased with radiogenic pelites or by partial melting of the mafic component. A possible alternative is currently unexposed Grenvillian felsic crust. Subsequent interaction of the granitic gneisses with meteoric water has significantly perturbed the oxygen and Sr isotope systems, the timing of which is equivocal but probably occurred during Caledonian events.

The elemental characteristics of the West Highland Granitic Gneiss show many similarities with Scandinavian (rift-related?) granites of the same age, but since their geochemistry is largely inherited from the protolith it would be unwise to pursue palaeotectonic attribution on this basis. However, the probable incorporation of significant mantle-derived mafic magma of MORB-like affinity is consistent with an extensional setting.

**KEYWORDS:** S-type granite, restite entrainment, mantle input, Neoproterozoic, Nd-Hf-Sr-O isotopes, petrogenesis.



## 1. Introduction-

Establishing the early history of polymetamorphic terrains is complex, as textural, mineralogical, geochemical and geochronological evidence may be modified or obliterated by later tectono-metamorphic events. Determining the tectonic setting of deformed granitic rocks may provide useful information. Granites may form as ‘anorogenic’ melts formed during rifting of continental crust; as calc-alkaline melts in a magmatic arc constructed along a continental margin; or as intracrustal melts formed during collisional thickening and/or extensional collapse of the orogen. Diagnostic criteria have been established for the recognition of past geodynamic setting, using detailed knowledge of structural relations, geochronology and geochemistry (e.g. Pearce et al., 1984). As well as providing age constraints, isotopes are often used to refine conclusions based on elemental work and elucidate petrogenetic processes. Interpretation becomes increasingly difficult as the degree of reworking increases, such that in many polymetamorphic terrains the tectonic setting of early, deformed granites is controversial. In this contribution, such techniques are used in an attempt to establish the petrogenesis and tectonic setting of an enigmatic suite of granitic gneisses exposed within the metasedimentary rocks of the early Neoproterozoic Moine Supergroup in northern Scotland (Fig. 1).

The Moine Supergroup of northern Scotland crops out between the Great Glen Fault and the Moine Thrust (Fig. 1). It was affected by Neoproterozoic ‘Knorydarian’ orogenic events at c. 820-790 Ma and c. 730 Ma (Rogers et al., 1998; Vance et al., 1998; Tanner and Evans, 2003; Cutts et al., 2010). This was followed during the Ordovician-Silurian by widespread reworking during Caledonian (s.l.) orogenic events that resulted from closure of the Iapetus Ocean (e.g. Soper and Hutton, 1984; Soper et al., 1992; Dewey and Strachan, 2003; Strachan et al., 2010). High-grade Caledonian metamorphism of the Moine Supergroup disturbed the geochronological record of Neoproterozoic events, the interpretation of which is not straightforward. The Moine Supergroup is intruded by felsic meta-igneous rocks known as the West Highland Granitic Gneiss (Johnstone, 1975). Members of the suite have yielded U-Pb zircon ages of c. 870 Ma (Friend et al., 1997; Rogers et al., 2001). Whether the granitic protolith was formed by crustal melting during an orogenic event (Barr et al., 1985; Friend et al., 1997) or extensional rifting and development of the Moine sedimentary basin(s) (Soper and Harris, 1997; Dalziel and Soper, 2001; Ryan and Soper, 2001) has implications for regional tectonic models for the Neoproterozoic evolution of this part of the North Atlantic region. This contribution documents a systematic geochemical and isotopic investigation of the West Highland Granitic Gneiss in an attempt to constrain the source(s) of the felsic melts and the palaeotectonic significance of this early magmatic event.

## 2. Geological background.

The Moine Supergroup comprises thick sequences of psammites and pelites, subdivided into the Morar, Glenfinnan and Loch Eil groups (Fig. 1; Holdsworth et al., 1994 and references therein). These are interfolded and intersliced with inliers of Archaean 'Lewisianoid' gneisses, which are thought to represent the basement on which the Moine rocks were deposited unconformably (Fig. 1; Holdsworth et al., 1994; Friend et al., 2008). Detrital zircons yield U-Pb ages mostly in the range 1800-1000 Ma, consistent with derivation from sources in eastern Laurentia (Friend et al., 2003; Cawood et al., 2007; Kirkland et al., 2008). The youngest detrital zircon grains in the Glenfinnan and Loch Eil groups yield ages of c. 900-920 Ma (Cawood et al., 2004; Cutts et al., 2010), providing an upper limit for deposition. Early metabasic intrusions within the Moine Supergroup display a tholeiitic chemistry, consistent with intrusion into thinned continental crust during extension and rifting (Moorhouse and Moorhouse, 1979; Winchester, 1984; Winchester and Floyd, 1983; Rock et al., 1985; Millar, 1999). Continental reconstructions for the early Neoproterozoic (Fig. 2) place the Moine basins either well within the Rodinia supercontinent (Dalziel and Soper, 2001) or much closer to its margin (Li et al., 2008), depending upon the location of Baltica relative to Greenland.

The West Highland Granitic Gneiss (Harry, 1953; Dalziel, 1966; Johnstone, 1975; Barr et al., 1985) comprises a number of separate intrusions, including those at Ardgour, Loch Arkaig, Fort Augustus, and Glen Moriston (Fig. 1). These intrusions mainly crop out close to the boundary between the Glenfinnan and Loch Eil groups (Fig. 1). East of Loch Quoich, granitic gneisses occur entirely within the Loch Eil Group. The granite suite is therefore discordant to the regional lithostratigraphy, although contacts with host Moine rocks are concordant at outcrop. While sharp at some localities, contacts between gneiss and metasedimentary country rock are apparently rapidly transitional at others, especially where the latter are migmatized. The gneiss is a coarsely-foliated, microcline-oligoclase-quartz granite with subordinate biotite and local hornblende and accessory garnet, sillimanite and ore. It carries abundant, sub-concordant quartzofeldspathic segregation pegmatites, bordered by biotite selvages. The granitic gneisses are compositionally and texturally relatively homogeneous, although the southern part of the Ardgour body includes a distinctive augen facies (Bailey and Maufe, 1916).

The granite gneiss suite has been interpreted as magmatic (Bailey and Maufe, 1916; Mercy, 1963), metasomatic (Harry, 1953; Dalziel, 1963; 1966), and as a tectonically-emplaced slice of pre-existing basement (Harris, in discussion of Winchester, 1974). Barr et al. (1985) interpreted the granitic protolith of the

gneisses to be a magmatic intrusion formed by anatexis of Moine rocks. This was consistent with chemical analyses of the gneisses, which have a restricted range of bulk composition with high SiO<sub>2</sub>, low Na<sub>2</sub>O/K<sub>2</sub>O and Fe<sub>2</sub>O<sub>3</sub>/FeO, an initial <sup>87</sup>Sr/<sup>86</sup>Sr ratio of 0.709, and are corundum normative. Other reasons which led Barr et al. (1985) to support a magmatic origin include: (1) the discordance of the suite with the regional lithostratigraphy; (2) the sharpness of contacts with host metasediments, although some are locally sheeted; (3) the presence of rare inclusions of psammite and hornblende schist, interpreted as xenoliths, and (4) the difficulties involved in converting a diverse series of metasediments into a uniform, homogeneous gneiss by metasomatism.

U-Pb (SIMS) dating of zircon needles and rims within the Ardgour granitic gneiss and its segregation pegmatites yielded an age of 873 ± 7 Ma (Friend et al., 1997). An age of 870 ± 30 Ma has also been obtained for formation of the granitic protolith of the Fort Augustus granitic gneiss (Rogers et al., 2001). A range of older Proterozoic ages, mainly between c.1800 Ma and c.1000 Ma, has been obtained from the cores of zircons in the granitic gneisses. These zircons were interpreted as detrital grains within the Moine sediments that melted to form the granitic gneiss protolith (Friend et al., 1997, 2003; Rogers et al., 2001). Metagabbros thought to have been intruded contemporaneously with the granitic gneiss in Glen Doe (Fig. 1) were intruded at 870 ± 6 Ma (U-Pb zircon, Millar, 1999).

### **3. Tectonic setting of the granitic gneiss suite.**

Barr et al. (1985) viewed the granitic gneiss intrusions as syn-orogenic and formed during regional migmatization, melting and early isoclinal folding of the Moine sediments. The absence of a thermal aureole adjacent to the granitic gneiss bodies implied to them that the country rocks were already at elevated temperatures when the granites were emplaced. Furthermore, they showed that the segregation pegmatites locally cross-cut the earliest gneissic fabric within the granitic gneisses which was therefore thought to have developed during this high-grade event.

The alternative view is that the granitic protolith of the gneiss was formed during crustal extension, development of the Moine basin(s), and emplacement of the regional metabasic suite that provided the heat source necessary to melt the Moine sediments. Millar (1999) and Dalziel and Soper (2001) argue that there is no evidence for any regional deformation or metamorphism of the Moine rocks, either prior to or during the emplacement of the protoliths of the granitic gneisses and the metabasic rocks, so both are pre-tectonic. Dalziel and Soper (2001) interpreted the zircons within the segregation pegmatites dated by Friend et al. (1997) to be xenocrysts inherited from the granitic protolith, and therefore considered that gneissification and melting to form the segregation pegmatites occurred much later

161 during the Caledonian orogeny.

162 In contrast to previous workers, Ryan and Soper (2001) envisaged that the  
163 protoliths of the granitic gneisses resulted not from the melting of the Moine  
164 sediments, but from anatexis of the basement rocks thought to have floored the  
165 Moine basin. They presented the results of mathematical modelling to show that  
166 emplacement of basaltic intrusions at depth could have provided sufficient heat to  
167 locally melt the underlying basement to produce granitic melts that migrated up  
168 through the sedimentary pile to their present locations. They suggested that the  
169 inferred basaltic intrusions are represented at a higher structural level within the  
170 Moine rocks by the regional metabasic suite. In view of the Archaean age of the  
171 basement inliers within the Moine Supergroup (Moorbath and Taylor, 1974; Friend  
172 et al., 2008), the absence of inherited zircons of this age within the granitic  
173 gneisses is surprising if they were produced by anatexis of the basement. However,  
174 Ryan and Soper (2001) account for this apparent inconsistency by suggesting that  
175 the basement source for the granite melts might in fact be Proterozoic.

#### 177 **4. Sampling and analytical techniques**

178 5-6 representative samples were collected from the largest granitic gneiss  
179 bodies at Ardgour, Loch Arkaig, Fort Augustus and Glen Moriston, supplemented  
180 by a smaller number of samples collected from Loch Quoich and Glen Doe. The  
181 samples were texturally relatively uniform with little variation in mineralogy. They  
182 were split, subsampled and crushed in a carbide shatterbox to pass 200# (<75 µm).  
183 Major elements and Ba, Sr, Y, Cr and Zr were determined by ICPAES at Oxford  
184 Brookes University by fusion dissolution followed by analysis against calibrations  
185 defined with international standard rock materials (SRMs). Accuracy and precision  
186 are estimated to be better than 1% relative standard deviation (rsd), on the basis of  
187 SRM analytical results and precision tests. Rare earth elements (REE) were also  
188 analysed by ICPAES, following fusion dissolution and cation-exchange  
189 preconcentration, at Oxford Brookes University. Natural SRMs were used to define  
190 the calibrations and monitor the quality of the data. Cr, Cu, Ga, Nb, Ni, Pb, Rb, Sr,  
191 Th, V, Y, Zn and Zr were analysed by XRF at Keele University and the British  
192 Geological Survey. Accuracy and precision of all the trace element analyses are  
193 better than 5% rsd, estimated as for the major element determinations.

194 Oxygen isotope analyses were performed using the laser fluorination  
195 method of Sharp (1990) as adapted for ClF<sub>3</sub> by Macaulay et al. (2000). Oxygen was  
196 released from c. 1mg samples following vacuum degassing, and converted to CO<sub>2</sub>  
197 by Pt-catalysed reaction with hot graphite. An in-line Hg-diffusion pump ensured  
198 rapid and quantitative transfer of O<sub>2</sub> to the conversion chamber and acted as a getter  
199 for residual halogen compounds. Isotope ratios were measured with an on-line VG  
200 PRISM III dual-inlet, triple-collector mass spectrometer. Data are reported in the

conventional  $\delta^{18}\text{O}\text{‰}$  notation relative to V-SMOW. Precision at  $1\sigma$  is  $\pm 0.2\text{‰}$  or better and NBS28 quartz gives  $9.6\text{‰}$ .

Nd and Sr for isotopic analysis were separated from whole-rock powders by standard cation exchange procedures following HF/HNO<sub>3</sub> dissolution. Isotopic analyses were performed at NIGL using a Finnigan-Mat automated thermal ionisation mass spectrometer. Determinations on standards covering the period during which the analyses were made are as follows: in-house Johnson and Mathey standard  $^{143}\text{Nd}/^{144}\text{Nd} = 0.511119 \pm 10$  ( $2\sigma$ ),  $n = 13$  (batch 1);  $0.511124 \pm 13$ ,  $n = 20$  (batch 2) and  $0.511113 \pm 9$ ,  $n = 16$  (batch 3); NBS 987  $^{87}\text{Sr}/^{86}\text{Sr} = 0.710217 \pm 24$  ( $2\sigma$ ),  $n = 10$  (batch 1);  $0.710222 \pm 18$ ,  $n = 20$  (batch 2) and  $0.710187 \pm 12$ ,  $n = 24$  (batch 3).  $^{143}\text{Nd}/^{144}\text{Nd}$  isotope ratios from are quoted relative to a value of  $0.511123$  for this standard (equivalent to  $0.511860$  for La Jolla).  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratios have been normalised to a value of  $0.710250$  for NBS987.

Hf was separated using a single LN-SPEC column procedure following the method of Munker et al. (2001). The Hf isotope composition was then analyzed at the NERC Isotope Geosciences Laboratories on a Nu-plasma HR multicollector plasma ionization mass spectrometer, using static multicollection. Correction for Lu and Yb interference on mass 176 was performed by standard reverse-mass-bias correction using empirically predetermined values for  $^{173}\text{Yb}/^{176}\text{Yb}$ .  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios were  $< 5 \times 10^{-6}$  and  $^{176}\text{Yb}/^{177}\text{Hf}$  ratios were  $< 2 \times 10^{-4}$  for all samples. Analyses of the JMC475 solution standard gave a value of  $0.282144 \pm 0.000008$  ( $2\sigma$ )  $n=14$ . One analysis of the BCR-2 rock standard analyzed with the samples gave a  $^{176}\text{Hf}/^{177}\text{Hf}$  value of  $0.282866 \pm 0.000006$  (2SE), after normalization to a value of  $0.282160$  for JMC475.

## 5. Results

The major element oxide abundances (Table 1) of the West Highland Granitic Gneiss are generally rather uniform, as befits the limited lithological range, with most samples falling between  $67.5 - 76.8$  wt% SiO<sub>2</sub>,  $0.13 - 1.6$  wt% MgO,  $0.9 - 3.3$  wt% CaO and  $3.5 - 5.7$  wt% K<sub>2</sub>O for example. However, those variations that do exist are systematic, as shown in the Harker diagrams (Fig. 3). Negative correlations with silica exist for TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MnO, MgO and P<sub>2</sub>O<sub>5</sub> (not shown), broadly convex-down with CaO and Na<sub>2</sub>O and broadly positive with K<sub>2</sub>O. There is a systematic arrangement of the various discrete granitic gneiss bodies, with Ardgour, Loch Arkaig and Fort Augustus consistently less silicic than Glen Moriston and Glen Doe – a roughly SW to NE trend. Data for local Moine metasediments, plus restite data from Watt et al. (1996) all lie to the silica-poor side of the granitic gneiss fields (Fig. 3). Trace elements (Table 1) are similarly coherent, as summarised by the chondrite-normalised plots (Figs. 4 and 5), and

bivariate plots (Fig. 6). All the granitic gneiss bodies show similar chondrite-normalised patterns characterised by relatively high trace element abundances overall, with a gentle increase from Yb at less than 50 times chondrite to Rb at several hundred times chondrite (Fig. 4). Superimposed upon this general increase towards the left (the most “incompatible”, with respect to mantle peridotite) are significant troughs at Ba, Nb, Sr, P and Ti, all of variable depth. The overall patterns are strikingly similar to those generated by Moine metasediments (Fig. 4). The REE group (Fig. 5) shows moderate light REE enrichment, variable negative Eu anomalies and relatively high but essentially flat heavy REEs. One sample from Glen Moriston lies significantly below the main group, with a large negative Eu anomaly. The Moine metasediments display a range of sub-parallel patterns of the same general shape, with mild light REE enrichment, negative Eu anomalies and relatively high but flat heavy REEs (Fig. 5), especially in pelitic samples. On average, the granitic gneisses have heavy REE (and Y) values closer to these than the more siliceous Moine samples. Within the bivariate trace element plots (Fig. 6), the systematic data disposition reappears, within well-defined arrays generally from Ardgour, Loch Arkaig and Fort Augustus to Glen Moriston and Glen Doe. Restite data, where available, fall to the trace-element-rich side of the granitic gneiss fields, and data for Moine pelites and semipelites vary but generally do not exceed those seen in the granitic gneisses.

The isotope data (Table 2) are summarised on plots of  $\epsilon\text{Nd}$  vs  $^{87}\text{Sr}/^{86}\text{Sr}_i$  annotated with  $\delta^{18}\text{O}$  values (Fig. 7a), and  $\epsilon\text{Nd}$  v  $\epsilon\text{Hf}$  (Fig. 7b). The granitic gneiss bodies define distinct fields whose  $\epsilon\text{Nd}$  varies from +2 to -5,  $\epsilon\text{Hf}$  from +4.7 to +13.6,  $^{87}\text{Sr}/^{86}\text{Sr}_i$  from 0.708 to 0.717, and  $\delta^{18}\text{O}$  from +3.0 to +7.8‰, all of which are considerable ranges. Also plotted on the diagrams are data for Moine metasediments (Millar, 1999 plus new Hf data), and local metabasic magmas (Millar, 1999 plus new Hf data). Available oxygen isotope data for Moine lithologies are sparse, but noted where available. They do not extend to the low values of some of the granitic gneiss samples.

## 6. Petrogenesis

There are many processes which might contribute to an explanation of the data. These include melting of local metasedimentary rocks with or without restite entrainment and crystal-liquid separation, melting of underlying basement rocks, introduction of juvenile mafic magmas, mixing of components from several such sources, subsequent metamorphism and alteration of elemental and isotopic characteristics, and so on. Many of these are considered below, starting with those most likely on geological grounds, with additions and modifications as required to explain as much of the data as possible.

#### 6.4.1. Primary petrogenetic controls:

Representative data for local Moine metasediments are available in Table 1. Pelites and semipelites are most likely to have melted, and have been plotted on Fig. 3. to indicate the potential Moine source. In all cases the granitic gneisses are displaced from the potential source – lower in MgO, Fe<sub>2</sub>O<sub>3</sub>, MnO, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and higher in Na<sub>2</sub>O, K<sub>2</sub>O and P<sub>2</sub>O<sub>5</sub>. This is expected for metasediment melting, as shown by experimental minimum melts derived from pelites under different melting conditions and, which plot closest to the compositions of the gneisses from Glen Moriston and Glen Doe (e.g. filled circles on Fig. 3 represent data from Patiño Douce and Harris, 1998, though note significantly higher Al<sub>2</sub>O<sub>3</sub>). However, it is clear from the ranges of the major element data that the other gneiss bodies cannot represent simple minimum melt compositions. Studies of migmatites have frequently suggested that biotite-rich selvages represent refractory material remaining after leucosome removal. Incomplete separation of melt from residue may modify melt compositions by “restite entrainment”. Watt et al. (1996) demonstrated that during Moine melting (albeit in the Kirtomy nappe now exposed near the north coast, and during the Caledonian orogeny) melanosomes had the assemblage quartz + plagioclase + k-feldspar + biotite + zircon + apatite + monazite + rutile, with SiO<sub>2</sub> as low as 35.99 wt%, K<sub>2</sub>O and MgO as high as 9.46 wt% and 6.86 wt% respectively, and Fe<sub>2</sub>O<sub>3</sub> up to 23.42 wt %. Two mafic restites (Watt et al., 1996) have been plotted on Fig. 3, from which it is apparent that the more mafic West Highland Granitic Gneiss bodies at Ardgour, Loch Arkaig and Fort Augustus may incorporate a small but significant excess of entrained palaeosome or biotitic restite – of the order of 20% (following the lever rule with the Glen Moriston and Glen Doe bodies as parental compositions).

The comparability of trace element abundances and ratios between the West Highland Granitic Gneiss and Moine pelites and semipelites is amply illustrated on the chondrite-normalised diagrams (Figs. 4 and 5). The closest comparisons are with the “restite-rich” Ardgour, Fort Augustus and Loch Arkaig bodies, with whose patterns the pelitic Moine is essentially identical, except for enhancement in P and depletion in Sr in the gneisses. The other gneiss bodies – Glen Moriston and Glen Doe – have systematically differing patterns with deeper troughs in Ba, Sr, P and Ti; lower Zr, Y and total REE contents and deeper negative Eu anomalies. One sample is particularly extreme, suggestive of minor feldspar (many of the gneisses carry K-feldspar augen), apatite, zircon and titaniferous accessory mineral fractionation. Bivariate, logarithmic trace element plots (Fig. 6a-f) against Zr may be used to constrain these possibilities. Zr is used since it is sensitive to both proposed processes – crystal fractionation and restite entrainment – and is available in the dataset of Watt et al. (1996). Data for Ce and Sm are also available for the restite (Watt et al., 1996), which then plot beyond the trace



element-rich Loch Arkaig, Ardgour and Fort Augustus bodies on Fig. 6a and b, consistent with restite entrainment as suggested above. Although qualitatively correct, simple mass balance suggests a significantly higher restite proportion than the major element data. The Ba and Sr plots (Fig. 6c, d) display marked inflections towards low abundances, consistent with zircon and feldspar removal from the most evolved samples from Glen Moriston and Glen Doe. Restite data are not available for these elements, nor for Th and Y, but it seems reasonable to suppose high concentrations of the latter in a zircon and monazite-bearing component (Watt et al., 1996, Fig. 6e, f).

Thus, the elemental evidence seems to be consistent with large-fraction melting of a Moine precursor. It might therefore be expected that the radiogenic isotopes in the gneisses reflect closely those of the Moine at the time of melting. However, there is good evidence for disruption of the Sr system as a result of late fluid activity, hinted at by the disparate  $^{87}\text{Sr}/^{86}\text{Sr}$  at similar  $^{143}\text{Nd}/^{144}\text{Nd}$  (Fig. 7a), and confirmed by correlations with abnormal  $\delta^{18}\text{O}$  and a variety of mobile elements. This will be dealt with in more detail later. First, the petrogenetic significance of the Nd and Hf isotope variations is addressed, since these are generally thought to be robust tracers of parental reservoirs. On the basis of the few data available for both Nd and Hf isotopes, Moine metasediments define a broad field from the characteristic negative  $\epsilon\text{Nd}$  and  $\epsilon\text{Hf}$  of Proterozoic continental crust to relatively radiogenic pelitic samples (Fig. 7b). A compilation of available Nd isotope data for the Moine (ILM unpublished) suggests that the former are dominant. The granitic gneisses from Loch Arkaig and Fort Augustus have small *positive*  $\epsilon\text{Nd}$  values, those for Ardgour and Glen Moriston are small and negative, while only those of Glen Doe in any way approach normal Moine values (Fig. 7b). All the granitic gneiss samples have positive  $\epsilon\text{Hf}$ . At first sight, this flatly contradicts the evidence presented above for a “normal” Moine source and requires something significantly more juvenile, and/or a completely different source. Other potential sources include Archaean to Proterozoic basement lying beneath the Moine Supergroup, and contemporaneous mafic magma.

The Lewisian basement is exposed to the west of the Moine Thrust, and is dominated by late Archaean (2.9-2.7 Ga) TTG-suite gneisses (at amphibolite or granulite facies) with minor mafic components. These show characteristic heavy REE depletion with variable positive Eu anomalies that result from amphibolite melting with minor garnet in the residue (e.g. Rollinson and Fowler, 1987), and are most unlikely to generate granites with high heavy REEs. Furthermore, the Nd isotope system of Lewisian gneisses would have evolved far away from the initial values of the West Highland Granitic Gneiss by 870 Ma (to ca. -15, Fig. 7b, based on data from Whitehouse et al., 1996), and Watkins et al. (2007) noted that the products of experimental melting of Lewisian gneisses are sodic granites and



granodiorites. Therefore, a Lewisian source can confidently be ruled out.

A Proterozoic basement source has been favoured by Ryan and Soper (2001). Unfortunately, exposures in Northern Scotland are small and may not be representative. Nevertheless, 1.8 Ga Rhinnian basement is exposed on Islay and Colonsay, and possibly extends to Inishtrahull off the coast of Northern Ireland (Muir et al., 1994). It is composed of deformed syenite and gabbro, with minor felsic and mafic intrusions. Geochemically, the major components (syenite and gabbro) show subduction-related characteristics (enrichment in light REE and other LILEs, relative depletion in HFSEs including large negative Nb anomalies on primitive-mantle-normalised multi-element plots, Muir et al., 1994). Nd isotope data (Muir et al., 1994) favour a juvenile source ( $\epsilon\text{Nd} = +0.6$  -  $+2.0$ ), and by 870 Ma these would have evolved to  $\epsilon\text{Nd} = -6$  to  $-9$  (Fig. 7b), which is also considerably more negative than the initial values of West Highland Granitic Gneiss, discussed above.

There has been much discussion in the literature concerning the extent of possible Grenvillian basement and/or events in Northern Scotland, but since very little is actually exposed (Storey et al., 2004), published elemental and Nd isotope data are conspicuous by their absence. The best that can be done is to seek representative data for juvenile Grenville crustal additions from elsewhere. Not surprisingly, these also appear to be various products of subduction-related magmatism. For example, Blein et al. (2003) documented the 1.4 Ga Bondy gneiss complex from the Central Metasedimentary Belt of the Grenville Province in some detail, assigning mafic granulites, intermediate gneisses and metatonalites to a mature island-arc setting, and equating minor quartzofeldspathic gneisses with back-arc high-silica rhyolites. The Nd isotope signature of such rocks (Blein et al., 2003), recalculated to 870 Ma, overlaps that of the West Highland Granitic Gneiss ( $\epsilon\text{Nd}_{870}$  for the mafic rocks =  $+1.3$  to  $+6.1$ , for the felsic rocks =  $-0.8$  to  $-2.7$ , Fig. 7b).

Broadly-contemporaneous mafic magmas have been identified within the Moine Supergroup (Millar, 1999), and although obvious field evidence for extensive mixing or dispersal within the granitic gneisses is absent, this may have been obscured by subsequent deformation, or the process could have occurred at a deeper structural level prior to migration of melts to their present locations. Significant volumes of contemporary mafic magma would also represent a sensible heat source for large-fraction melting. Major element data are consistent with limited admixture of mafic magma – the composition of which has been marked on Fig. 3 (data from Millar, 1999). Trace element data (Fig. 6) are less accommodating, but some combination of restite entrainment and magma mixing certainly would be possible. In more detail, binary mixing calculations (Fig. 8a) suggest that several tens of percent admixture of a MORB-like composition would

not appreciably affect trace element relative abundances, since most are dominated by the granitic end member. Nd-Hf isotope constraints generally support such interaction (Fig. 8b), but because of the relative Hf and Nd budgets of Moine and MORB, simple binary mixing would require large proportions of mafic magma (many tens of percent), that are difficult to reconcile with major element mass balance. If the melted Moine is of less usual isotopic composition, towards the high  $\epsilon_{\text{Nd}}\text{-}\epsilon_{\text{Hf}}$  (pelitic) part of the range, this problem reduces considerably. Alternatively, if the “mafic” isotopic contribution were in the form of a partial melt, a larger contribution of this silicic magma could remain within the elemental constraints. In either case, Hf isotope compositions remain excessive.

Further source region evidence is available from inherited zircons, which have been studied by Friend et al. (1997, 2003), and Rogers et al. (2001). These show a range of Proterozoic ages, but a complete absence of Archaean grains (Friend et al., 2003). The dominant peaks are at ca. 1400 and 1100 Ma, with very few analyses near 1800 Ma. These data are consistent with no source contributions from Lewisian or Rhinnian basement, but do allow a substantial Grenvillian (and older) component. On the other hand, they are also perfectly consistent with major Moine melting, since the inherited zircons from the West Highland Granitic Gneiss overlap detrital grains from the local Lochailort pelite (Friend et al., 2003).

In summary, major and trace element data are consistent with major Moine melting, with variations attributable to restite entrainment and minor fractionation. Nd-Hf isotope relationships require that any Moine component comes from isotopically unusual lithologies, and/or is mixed with a juvenile component. This likely derives from local mafic magmas, either directly or via partial melting, but recently-juvenile felsic material such as unexposed Grenvillian basement is another possibility. Such suggestions are not mutually exclusive, and attest to the well-known complexities of intracrustal granite petrogenesis.

## 6.2. Secondary petrogenetic processes

Stable isotopes are powerful indicators of fluid movements in the Earth’s crust, and much is known about normal ranges within igneous, sedimentary and metamorphic rocks. Moine metasediments have typical  $\delta^{18}\text{O}$  values between +8.0 and +10.2‰ (Table 2, and MBF unpublished data). Therefore, the low extreme of the range of values for the West Highland Granitic gneiss samples (+7.7 to +3.0‰) is surprising and requires explanation. During anhydrous melting, the oxygen isotope signature is little changed, since mineral-melt fractionation factors are small at high temperature. However, most crustal melts form under hydrous conditions, when stable isotope systematics may be considerably modified, sometimes generating low  $\delta^{18}\text{O}$  magmas (see review by Taylor, 1990). On the other hand, similar low  $\delta^{18}\text{O}$  values in high-grade regional metamorphic rocks elsewhere have

also been attributed to deep penetration of surface-derived water (e.g. Miller and Cartwright, 1997). It is therefore possible that variations in  $\delta^{18}\text{O}$  may be the result of melting or later fluid involvement (or both). Correlations between  $\delta^{18}\text{O}$ , elements and the other isotope systems were sought in order to investigate these possibilities. Rb,  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\text{K}_2\text{O}$  generally increase with falling  $\delta^{18}\text{O}$ , whereas elemental Sr, CaO and  $\text{Na}_2\text{O}$  generally decrease *within* gneiss bodies. These observations are consistent with alteration of feldspar, commonly the most susceptible mineral to O isotope exchange in hydrothermal systems. The fluid responsible likely had high Rb/Sr and probably also high  $^{87}\text{Sr}/^{86}\text{Sr}$ , in accord with the suggestion of Millar (1999) in relation to local metabasite alteration.

## 7. Palaeotectonic affinities and correlations

The palaeotectonic setting of the West Highland Granitic Gneiss is controversial (Barr et al., 1985; Friend et al., 1997; Soper and Harris, 1997; Millar, 1999; Dalziel and Soper, 2001; Ryan and Soper, 2001). Paulsson and Andreasson (2002) have discussed possible correlations of Neoproterozoic bimodal basic – granitoid magmatism within the Scandinavian, Scottish and Siberian Caledonides, with respect to attempted rifting of Rodinia at c. 845 Ma. They drew specific comparison between the West Highland Granitic Gneiss and the Vistas Granite of the Seve Nappe Complex, northern Sweden, whose petrogenesis was ascribed to an S-type origin yet plotting in the field of within-plate granites on the discrimination diagrams of Pearce et al. (1984). The chemical data presented above allow this proposed correlation to be tested further. Figure 9 (a,b) shows chondrite-normalised multi-element patterns for the Vistas Granite (data from Paulsson and Andreasson, 2002) for comparison with those of the West Highland Granitic Gneiss. The similarity is striking, at first sight strengthening the proposed correlation between these broadly contemporaneous anatectic granites.

However, it is clear from this study that the main control on the chemistry of the gneiss suite is that of the protolith. Similar conclusions have been reached for anatectic granites elsewhere. For example, Brown and D'Lemos (1991) related the calc-alkaline signature of Cadomian (late Neoproterozoic) granites from the French Armorican massif directly to the geochemistry of their source Brioverian sediments. Therefore, it is unwise to ascribe any particular palaeotectonic setting on the basis of granitic gneiss geochemistry. However, the likely incorporation of significant volumes of MORB-like mafic magma is consistent with contemporaneous crustal extension (as concluded by Millar, 1999).

## 8. Conclusions

The present study illustrates many of the complexities inherent in the constraint of petrogenesis and tectonic setting of deformed and metamorphosed

granites in orogenic belts. The weight of elemental evidence suggests derivation of the West Highland Granitic Gneiss by anatexis of Moine metasediments, with restite entrainment, mixing of magmas from different sources and minor crystal fractionation to explain the range of elemental data. The Nd and Hf isotope system record the significant contribution of isotopically more-juvenile materials, and the Sr and O isotope systems were altered as a result of late fluid percolation. Since elemental chemistry is inherited largely from the protolith, it cannot be diagnostic of a later tectonic setting. Nevertheless, the involvement of significant volumes of local mafic magma with MORB-like chemistry is consistent with crustal extension.

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Peter Cawood, Jim Connelly, Ian Dalziel, Clark Friend, Staci Loewy, Graeme Rogers, Paul Ryan and Jack Soper are all thanked for numerous discussions concerning the origin of the West Highland Granitic Gneiss. Kathryn Goodenough and an anonymous reviewer provided thorough and very helpful comments on the submitted manuscript.

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Figure Captions-

Fig. 1. Geological sketch map of the Northern Highland Terrane (NHT), northern Scotland, showing the distribution of West Highland Granitic Gneiss. GGF = Great Glen Fault, SBT = Sgurr Beag Thrust, MTZ = Moine Thrust Zone. Agg = Ardgour Granitic Gneiss, FAgg = Fort Augustus Granitic Gneiss, GM = Glen Moriston, GD = Glen Doe, LA = Loch Arkaig, LQ = Loch Quoich. S = Strontian, G = Glenfinnan, LS = Loch Sunart.

Fig. 2. Schematic reconstructions of Laurentia, Baltica and Amazonia at c. 1000 Ma, following amalgamation of Rodinia and Grenville and Sveconorwegian (SN) orogenesis: (a) after Dalziel and Soper (2001), and (b) after Cawood et al., (2010). M, Moine Supergroup. Other abbreviations: Hb, Hebridean foreland; T, Torridon Group; YS, Yell Sound Group; K, Krummedal succession; Sw, NW Svalbard; Sc, Central Svalbard; Se, Eastern Svalbard; Sa, Sværholt Succession; So, Sorøy Succession.

Fig. 3. Harker diagrams presenting West Highland Granitic Gneiss major element data. Circles = Ardgour, triangles = Loch Arkaig, diamonds = Loch Quoich, squares = Fort Augustus, pluses = Glen Moriston, inverted triangles = Glen Doe. r = Moine restite from Watt et al., (1996), filled circles at 75% SiO<sub>2</sub> = metasediment minimum melt from Patiño Douce and Harris (1998), asterisks at 45% SiO<sub>2</sub> = local mafic magma from Millar (1999). Moine = field for Moine metasediments = crosses. The “parent” field is drawn around the Glen Moriston samples.

Fig. 4. Multi-element chondrite-normalised normalised patterns for West Highland Granitic Gneiss and Moine metasediments for comparison. Note consistent large troughs at Ti, P, Sr and Nb and the close similarity of the Granite Gneiss with Moine metasediments.

Fig. 5. Chondrite-normalised REE plots for West Highland Granite Gneiss and Moine metasediments. Again, note the close similarity of all the patterns, including the Moine, with mild light REE enrichment, high heavy REE and significant negative Eu anomalies.

Fig. 6. Logarithmic, bivariate trace element plots showing the disposition of the West Highland Granitic Gneiss with respect to restite samples (Watt et al., 1996) and Moine, and hypothetical restite entrainment and crystal fractionation trends. Symbols as in Fig. 2.

Fig. 7. εNd vs. <sup>87</sup>Sr/<sup>86</sup>Sr<sub>i</sub>, annotated with δ<sup>18</sup>O (a) and εNd vs. εHf (b). Note separate

fields for individual Granitic Gneiss bodies, all distinct from that of Moine metasediments.  $\delta^{18}\text{O}$  ranges from normal metasedimentary values to locally rather low. The line through local MORB-dyke represents the range of Nd isotope compositions reported by Millar (1999).

Fig. 8. Binary mixing models of mafic magma input. (a) Trace element mixing between MORB-like magma and Glen Moriston Granitic Gneiss end members - up to 40% admixture does not greatly disturb the shape of the trace element patterns. (b) Nd-Hf isotope mixing trajectory from potential Moine melt towards contemporary MORB-like magma.

Fig. 9. Comparative multi-element chondrite-normalised plot, showing the West Highland Granitic Gneiss and the broadly-contemporaneous Vistas granite from the Scandinavian Caledonides. Data from Paulsson and Andreasson (2002).

Figure 1

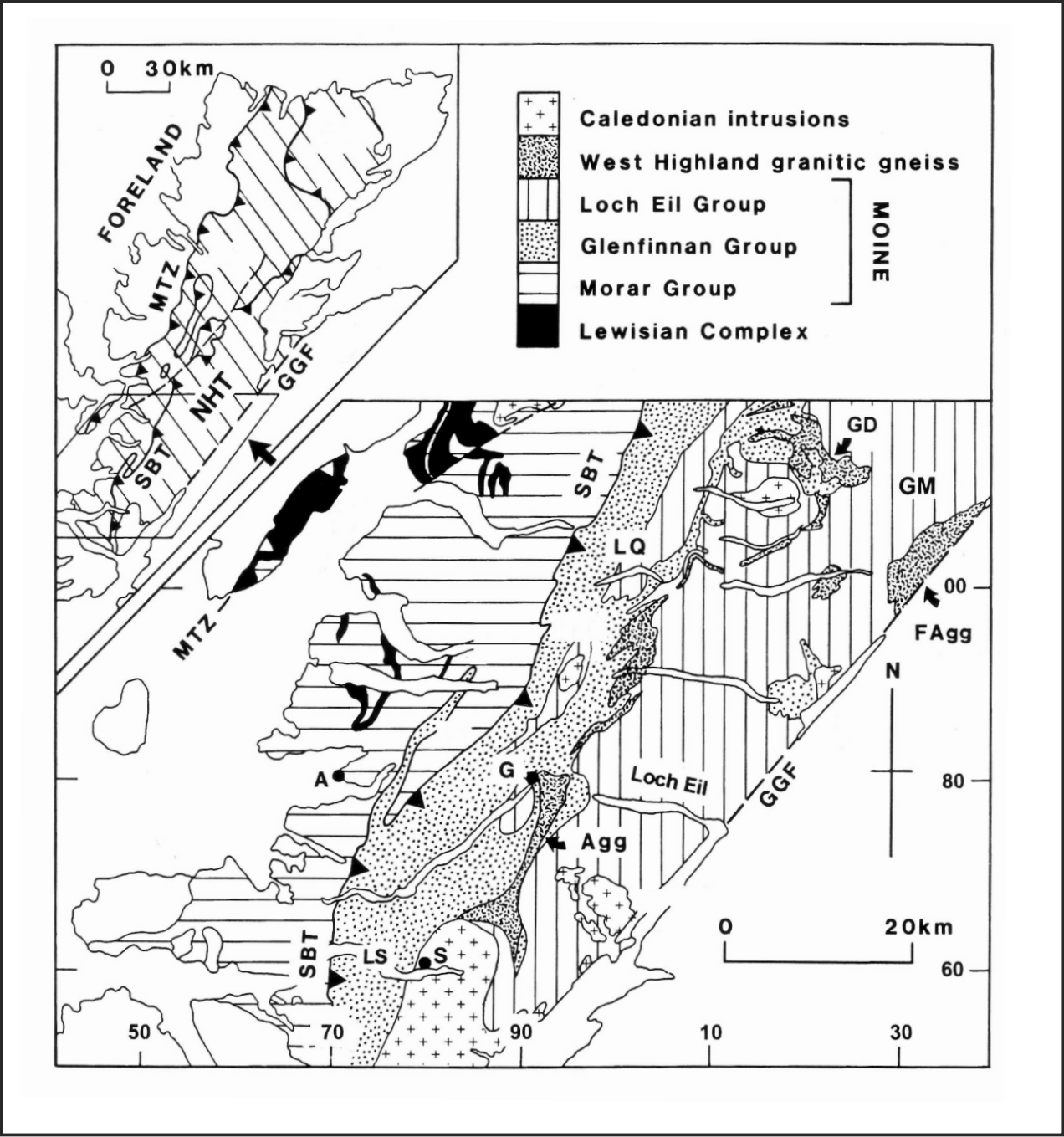


Figure 1

Figure 2

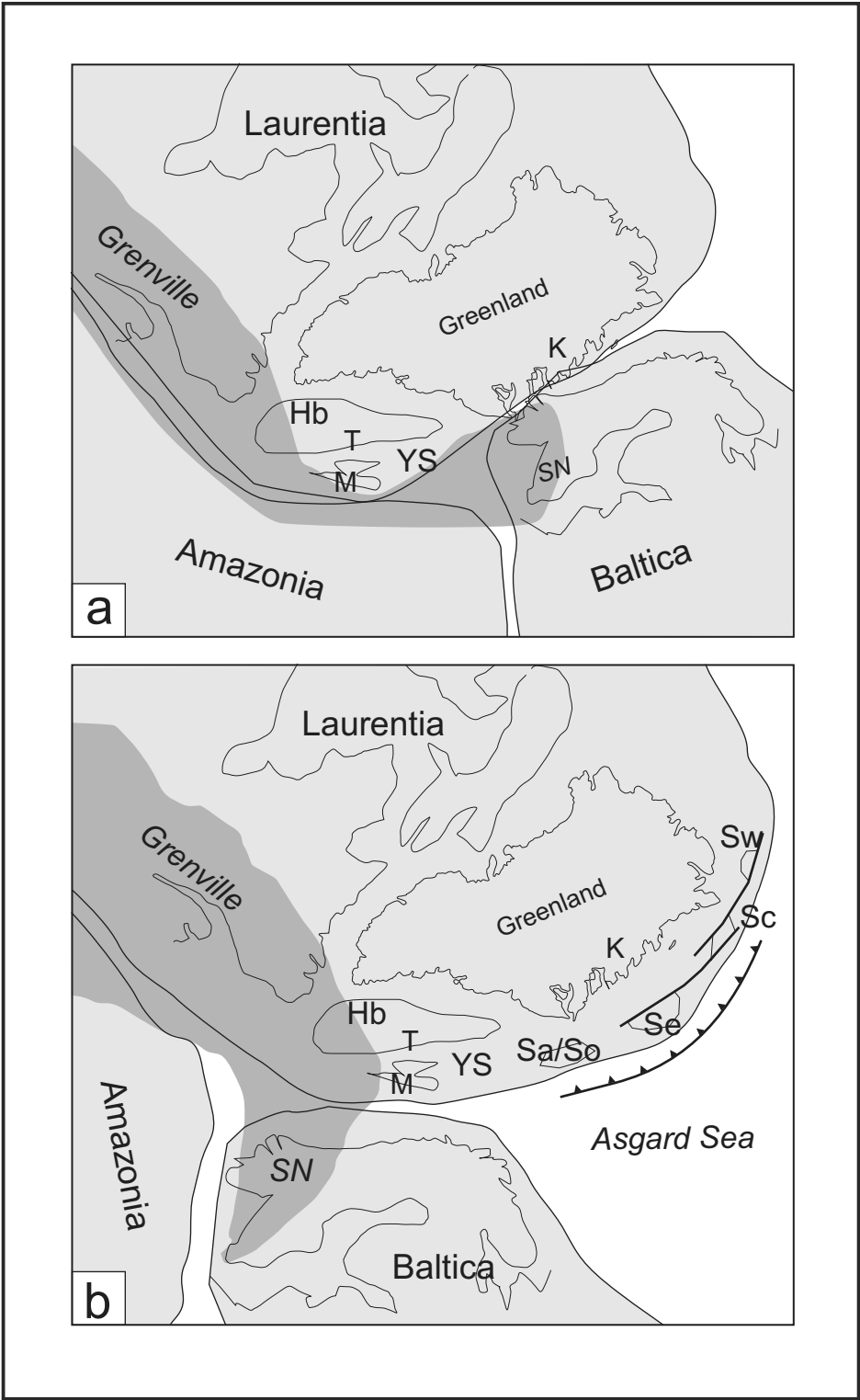


Figure 2

Figure 3

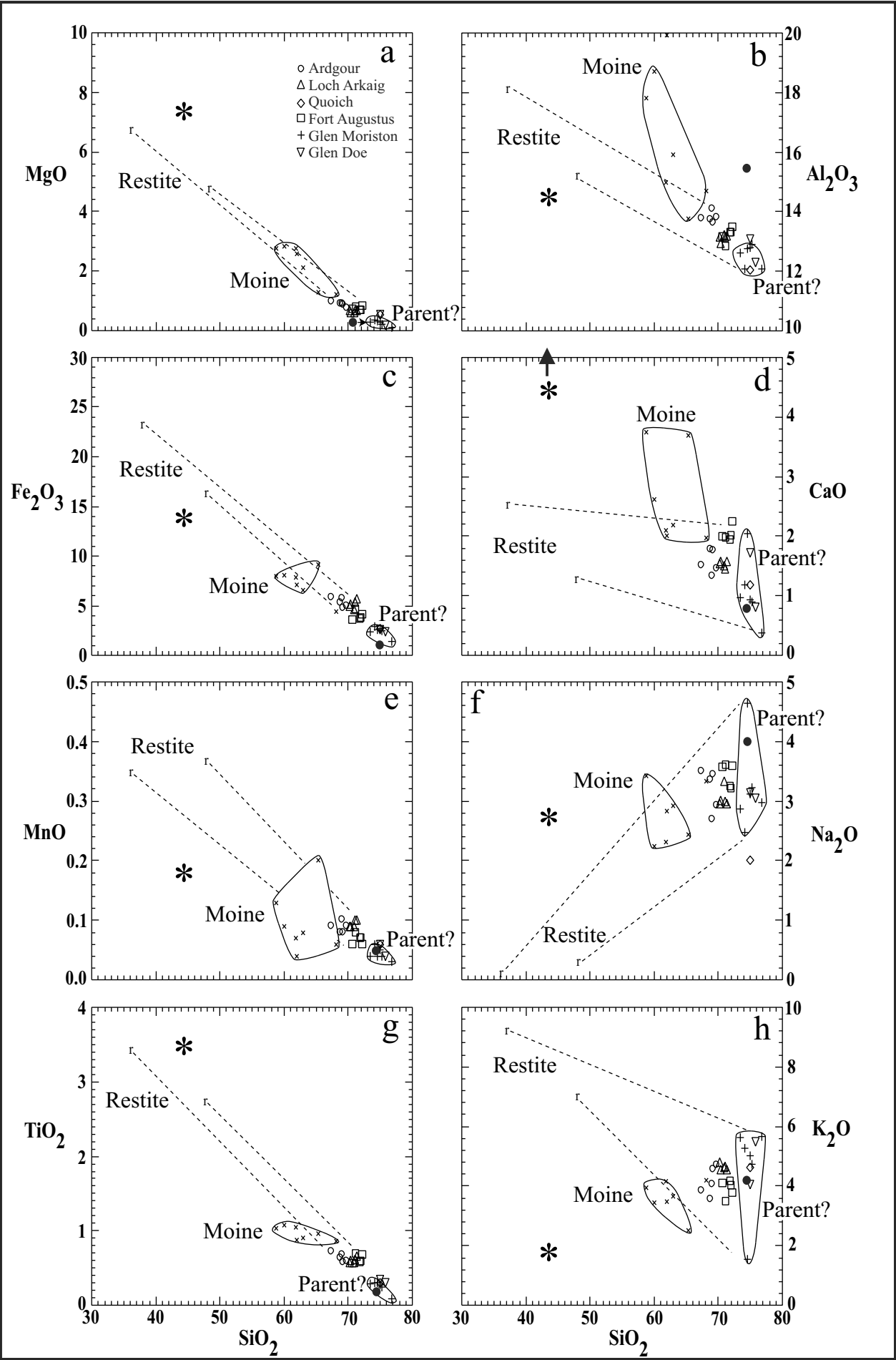


Figure 3

Figure 4

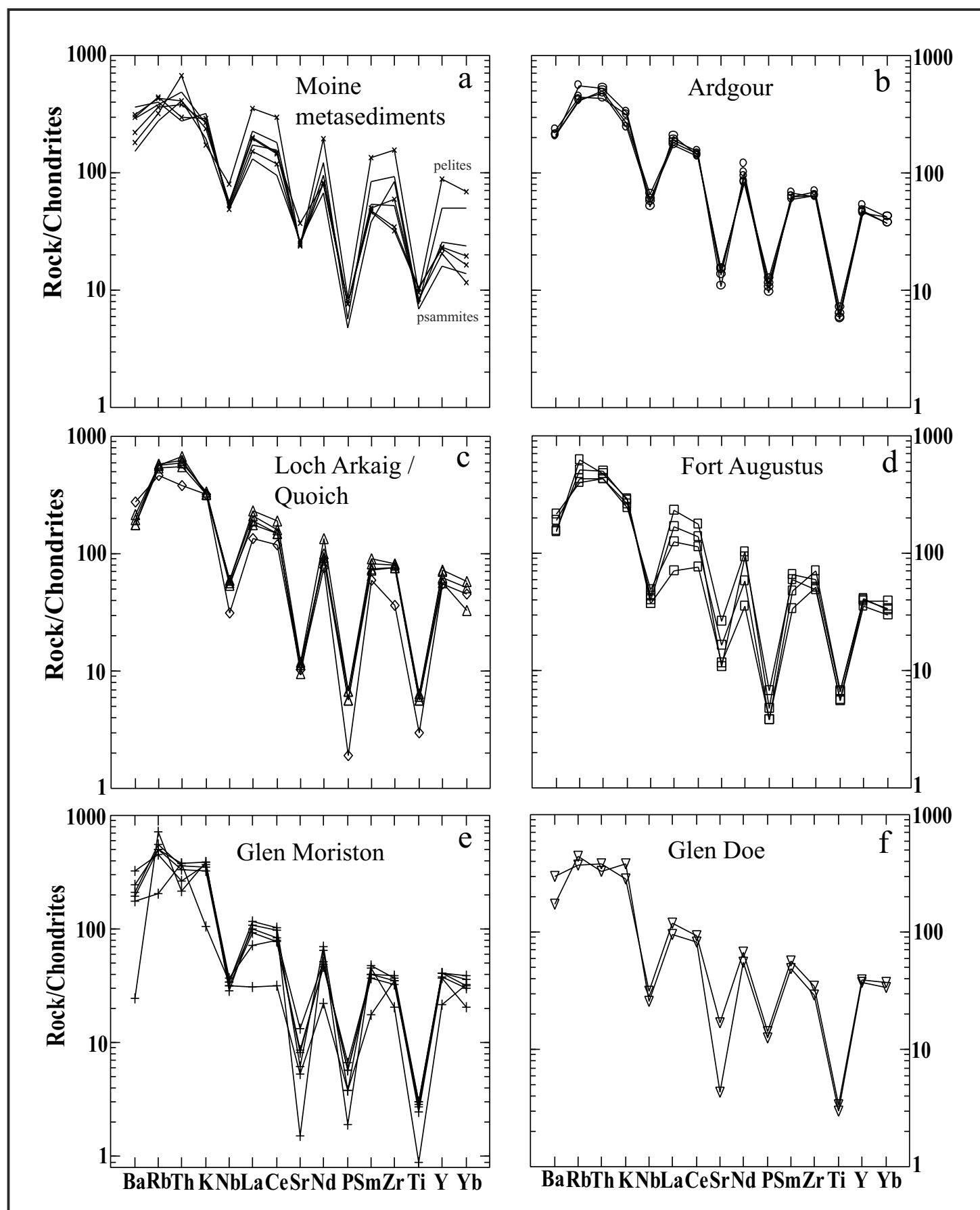


Figure 4

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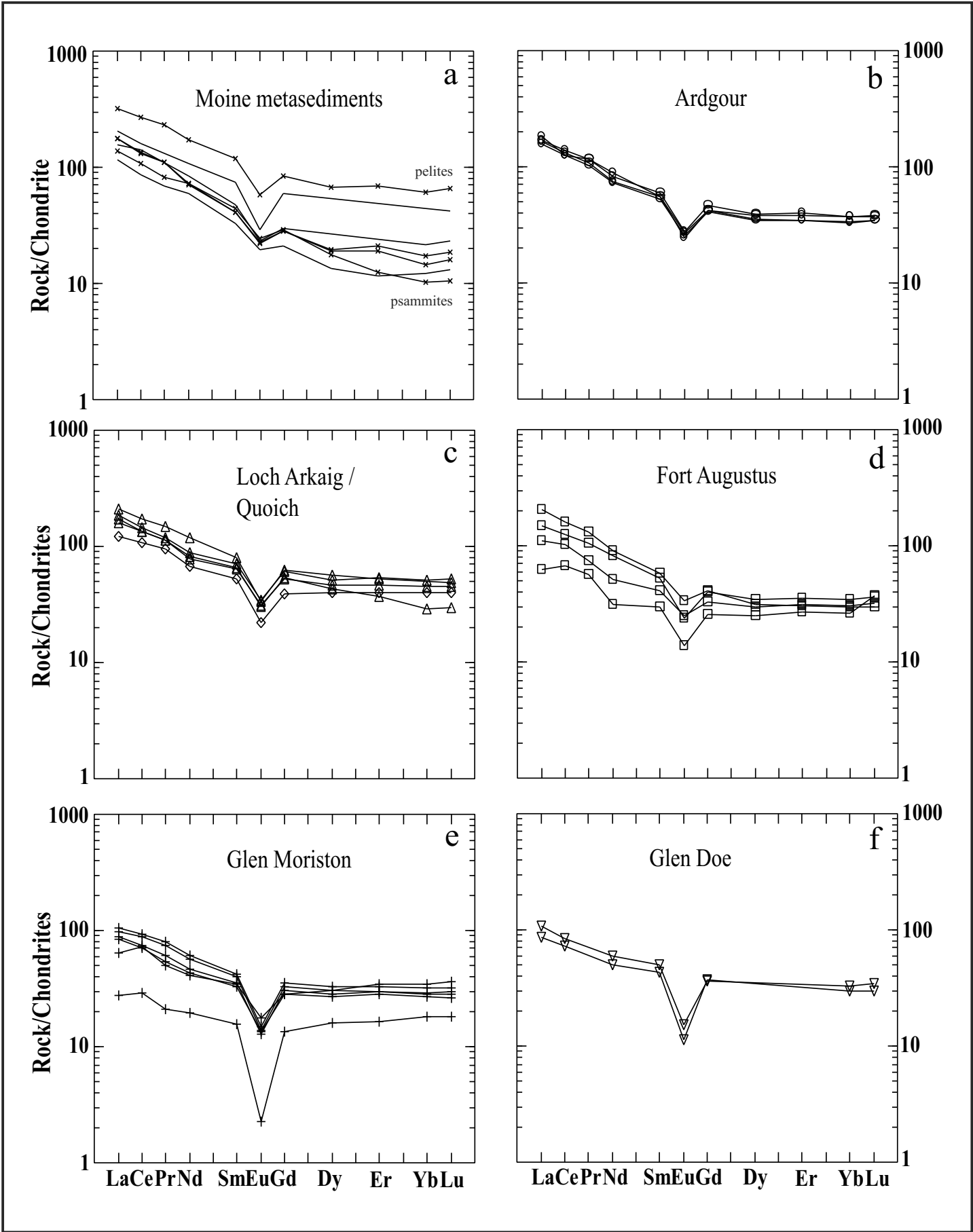


Figure 5



Figure 6

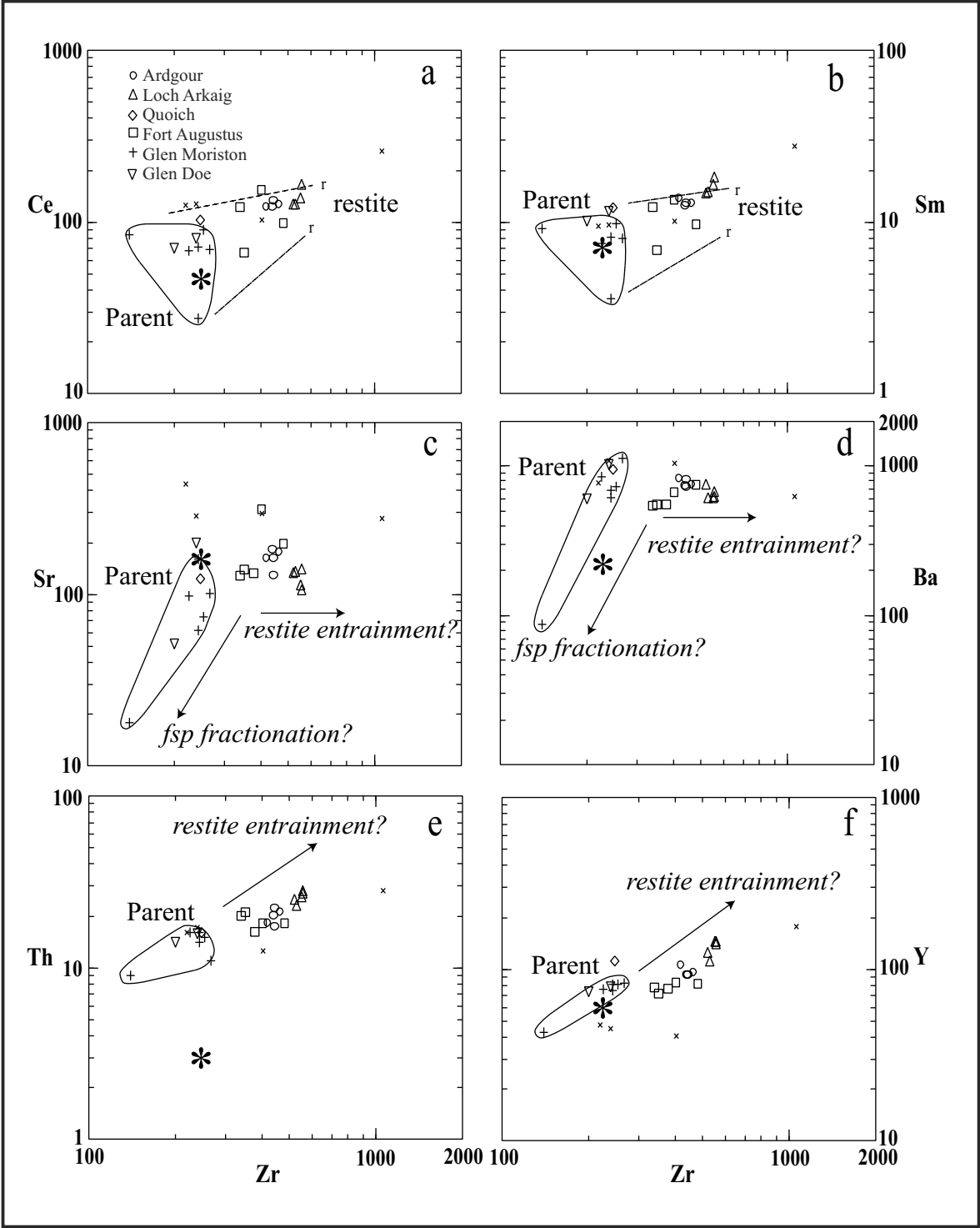


Figure 6

Figure 7

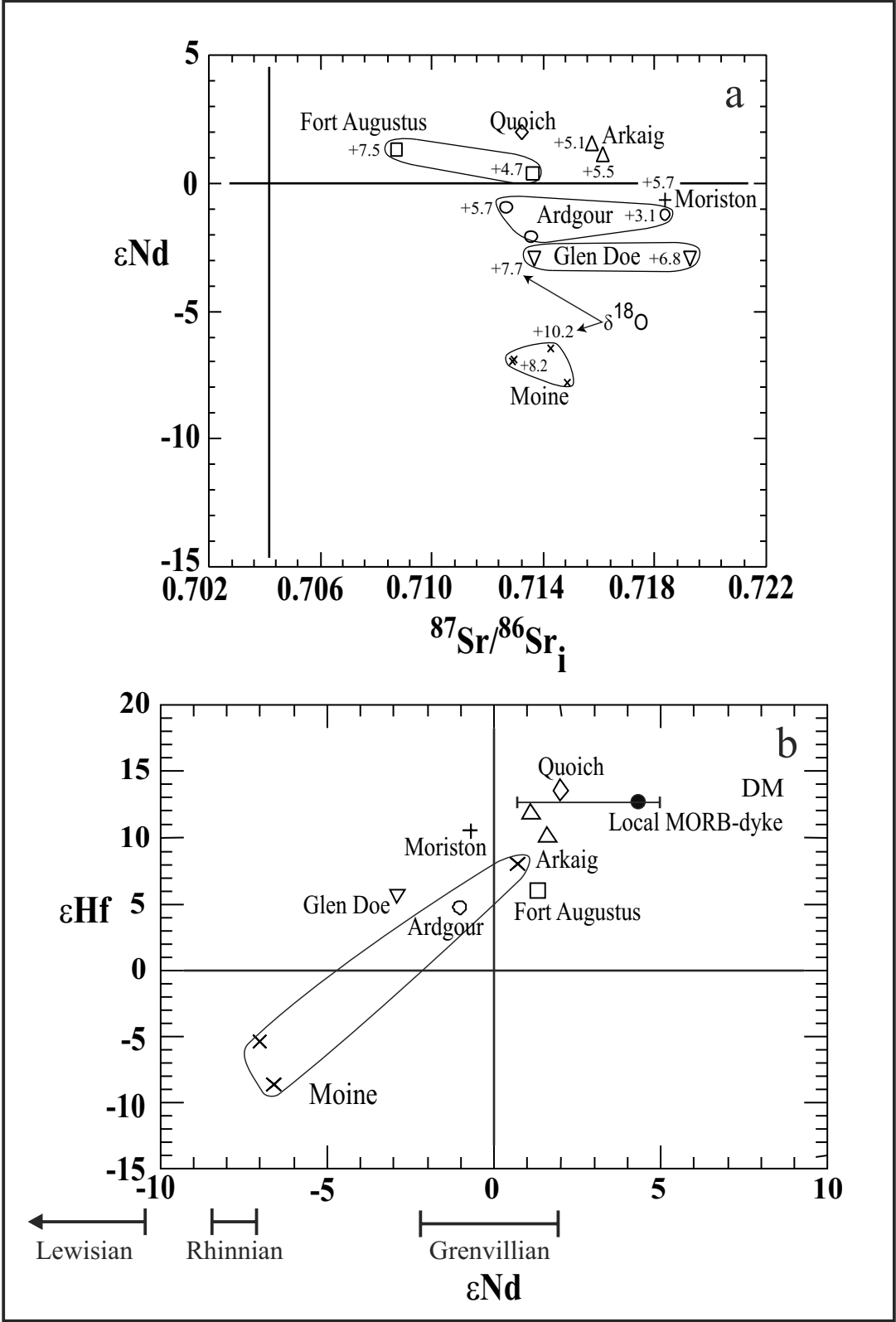


Figure 7

Figure 8

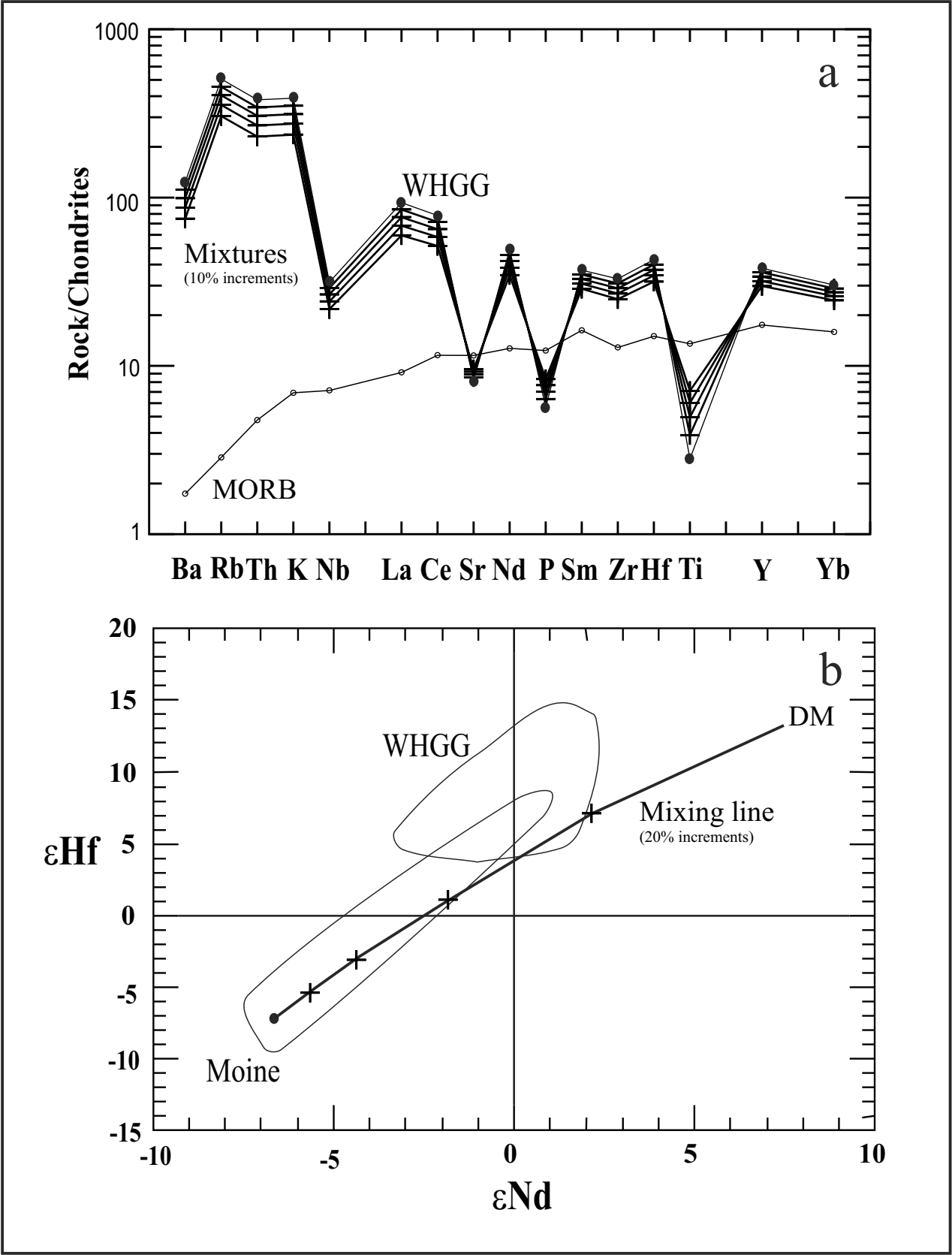


Figure 8

Figure 9

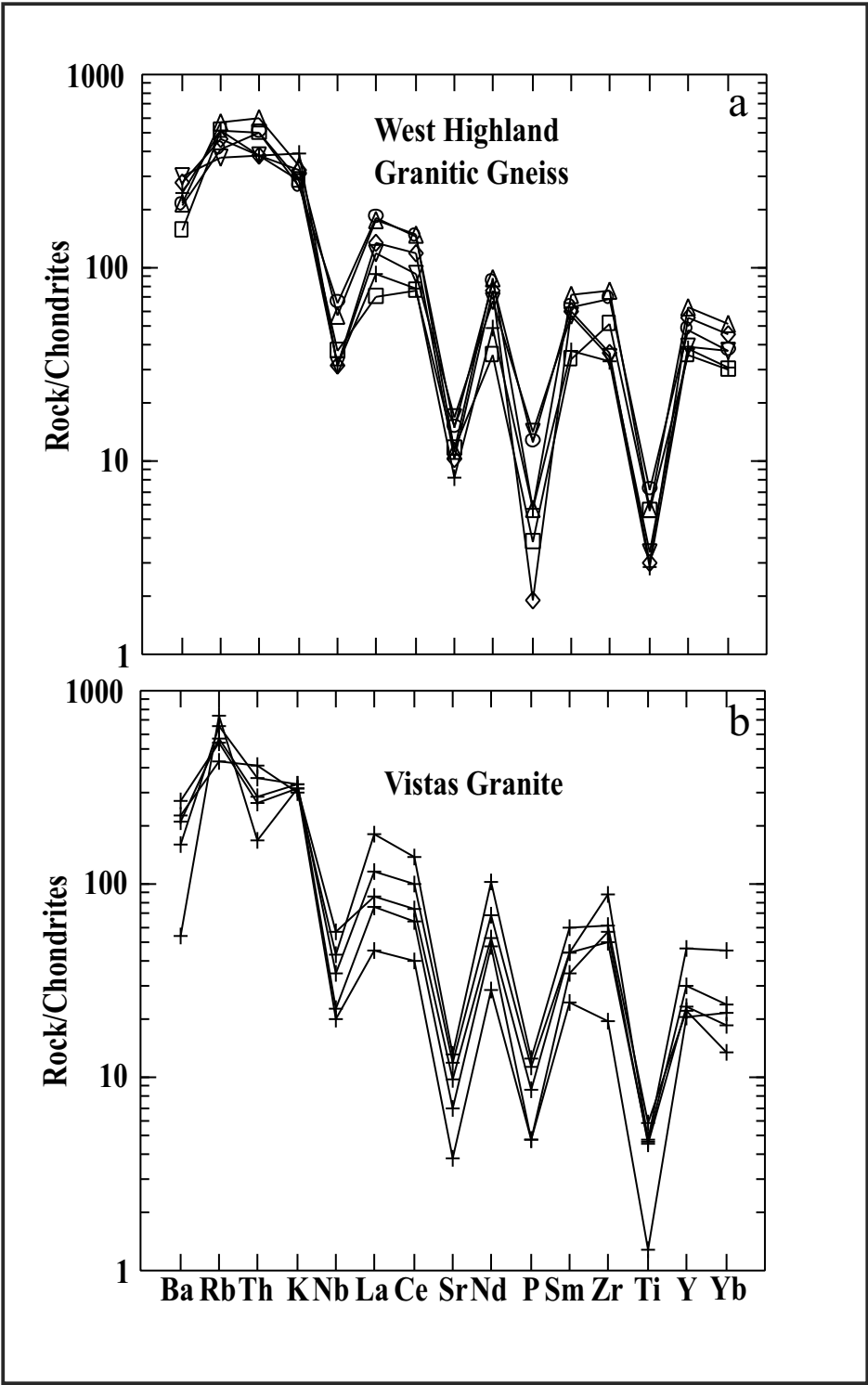


Figure 9

Table 1  
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	Ardgour					Fort Augustus					Glen Moriston						Loch Arkaig					Glen Doe		Quoich	Moine metasediments							
Sample	AG A	AG B	AG 3	AG 4	AG 5	FA A	FA B	FA 3	FA 4	FA 5	GM A	GM B	GM C	GM 4	GM 5	GM 6	LA 1	LA 2	LA 3	LA 4	LA 5	D24	D48	Q21	IM49	S40	Q3	GD3	MJ019	Q12	IM32	
SiO <sub>2</sub>	69.10	69.80	69.19	67.50	68.85	71.90	72.00	72.13	70.58	71.16	75.20	75.00	76.80	73.49	74.62	74.10	70.33	71.29	70.96	70.23	71.09	75.00	75.80	74.96	58.73	60.06	65.39	68.15	70.39	78.56	81.45	
TiO <sub>2</sub>	0.67	0.59	0.58	0.72	0.64	0.57	0.59	0.67	0.56	0.69	0.25	0.28	0.09	0.29	0.31	0.31	0.61	0.66	0.58	0.57	0.62	0.34	0.30	0.30	1.04	1.07	0.96	0.86	0.81	0.37	0.45	
Al <sub>2</sub> O <sub>3</sub>	14.10	13.80	13.62	13.76	13.74	13.30	13.30	13.49	13.14	12.85	12.9	12.80	12.10	12.62	12.78	12.08	12.95	13.20	13.24	13.17	13.17	13.1	12.3	12.05	17.82	18.69	13.75	14.69	13.65	10.69	8.57	
Fe <sub>2</sub> O <sub>3</sub>	5.73	4.93	4.73	5.85	5.26	3.71	3.80	4.15	3.61	4.62	2.53	2.73	1.47	2.37	2.61	2.96	5.21	5.69	4.65	4.95	5.39	2.63	2.39	2.72	7.95	8.13	9.17	4.38	5.73	2.33	2.01	
MnO	0.10	0.09	0.08	0.09	0.08	0.07	0.07	0.06	0.06	0.08	0.04	0.05	0.03	0.04	0.04	0.06	0.09	0.10	0.09	0.09	0.10	0.06	0.04	0.06	0.13	0.09	0.20	0.06	0.11	0.03	0.04	
MgO	0.89	0.75	0.86	0.96	0.89	0.68	0.70	0.84	0.73	0.80	0.23	0.28	0.13	0.30	0.34	0.36	0.61	0.67	0.61	0.68	0.68	0.55	0.20	0.55	2.77	2.84	1.29	1.21	1.55	0.77	0.55	
CaO	1.32	1.46	1.75	1.50	1.77	1.94	2.00	2.24	1.99	1.98	0.90	0.94	0.38	0.97	2.04	1.18	1.58	1.57	1.50	1.55	1.46	1.73	0.81	1.19	3.75	2.62	3.69	1.97	1.66	0.98	0.87	
Na <sub>2</sub> O	2.69	2.92	3.44	3.49	3.35	3.24	3.21	3.59	3.57	3.60	3.22	3.12	2.98	2.86	4.64	2.48	3.02	2.95	3.33	2.95	3.00	3.13	3.04	2.01	3.43	2.24	2.43	3.33	2.56	1.89	1.62	
K <sub>2</sub> O	4.04	4.71	4.55	3.83	3.56	4.15	4.03	3.75	4.09	3.48	4.73	5.02	5.66	5.63	1.53	5.28	4.54	4.57	4.63	4.80	4.65	4.07	5.47	4.64	3.93	3.46	2.52	4.21	2.81	3.46	1.86	
P <sub>2</sub> O <sub>5</sub>	0.13	0.11	0.10	0.13	0.12	0.07	0.07	0.05	0.04	0.04	0.04	0.04	0.02	0.06	0.06	0.07	0.06	0.07	0.07	0.06	0.06	0.15	0.13	0.02	0.08	0.08	0.09	0.08	0.08	0.02	0.02	
LOI	0.82	1.34	0.89	0.41	0.28	0.01	0.52	0.43	0.33	0.20	0.24	0.24	1.00	0.34	0.26	0.12	0.24	0.20	0.30	0.53	0.41	0.02	0.14	1.36	0.33	0.64	0.15	0.46	1.06	0.17	2.35	
Total	99.59	100.50	99.79	98.24	98.54	99.64	100.29	101.40	98.70	99.50	100.28	100.50	99.19	98.97	99.23	99.00	99.24	100.97	99.96	99.58	100.63	100.96	100.62	99.86	99.96	99.92	99.64	99.40	98.86	99.27	99.79	
Ba	809	721	816	743	731	537	545	664	551	750	690	736	87	852	615	1126	623	675	611	752	618	1030	600	956	775	1098	632	1039	532	1232	1059	
Rb	159	194	153	145	147	217	204	150	179	141	176	194	252	177	71	158	212	200	189	197	201	130	155	163	126	149	112	153	96	100	84	
Sr	161	128	160	174	180	127	131	311	138	194	62	74	18	97	159	101	106	141	135	133	113	198	51	122	435	285	278	296	292	211	177	
Y	91	91	105	95	92	78	76	83	71	81	75	82	43	76	81	83	145	140	112	126	144	79	74	111	47	45	178	41	51	3	19	
Zr	444	443	423	467	438	338	377	403	350	482	242	253	139	225	242	265	554	556	527	521	553	239	200	246	219	238	1059	405	360	221	223	
Nb	21	20	18	23	21	14	15	15	13	17	11	12	10	11	12	13	20	21	19	20	21	11	9	11	19	20	28	17	18	4	6	
Th	17	22	18	21	20	20	16	18	21	18	14	15	9	16	16	11	27	28	23	25	26	15.8	13.9	16	16	17	28	12.6	17	2	5	
Pb	26	26	31	26	31	22	20	18	23	20	30	26	23	33	18	28	23	23	25	31	29	-	-	33	30	30	20	-	-	22	18	
Ga	20	20	19	20	19	16	16	19	16	17	19	17	19	16	17	18	20	22	20	22	23	-	-	20	24	23	25	-	-	10	9	
Zn	95	85	82	107	93	57	58	59	55	68	52	51	49	46	48	67	96	107	85	96	101	-	-	53	103	125	145	-	-	17	14	
Cu	16	18	9	11	13	8	6	4	13	5	3	5	2	7	12	3	9	7	24	12	10	-	-	12	32	26	33	-	-	7	9	
Ni	5	4	1	6	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4	2	3	34	39	14	24	25	4	4	
V	47	46	44	53	43	45	39	57	47	48	12	12	4	16	16	8	31	36	25	35	34	-	-	13	114	120	69	62	54	33	40	
Cr	20	19	23	18	20	19	18	19	20	19	14	16	19	17	14	14	15	11	15	9	9	1	1	11	56	67	8	39	44	29	26	
La	-	62.2	66.6	60.01	57.2	54.9	-	75.2	22.93	40.8	10.1	38.8	35.9	30.6	32.6	23.8	-	76.4	63.1	58.5	68.3	39.27	31.34	44.43	64.5	65.1	117.1	50.4	57.0	12.0	25.2	
Ce	-	132	121	125	120	120	-	153	65.2	97.2	27.6	89.8	83.6	67.7	71.7	69.5	-	166	128	128	139	80.54	70.15	102.7	125	128	260	103	135	33.6	64.0	
Pr	-	15.8	15.9	14.8	13.9	14.5	-	18.0	7.78	10.3	2.87	11.0	10.3	7.30	8.31	6.8	-	20.6	15.4	15.5	16.4	-	-	13.2	15.0	15.3	32.0	11.2	-	4.04	7.12	
Nd	-	63.5	58.8	53.3	51.2	58.6	-	65.0	22.5	36.5	13.9	43.8	40.6	31.0	32.7	29.2	-	85.0	58.0	55.5	63.2	42.02	35.22	47.8	50.4	51.5	124	51.8	60.0	10.9	21.2	
Sm	-	12.8	13.6	12.8	12.2	12.0	-	13.4	6.82	9.57	3.57	9.82	9.15	7.51	8.11	8.07	-	18.3	15.1	14.7	16.5	11.59	10.01	12.0	9.49	9.6	27.4	10.1	11.0	1.92	4.00	
Eu	-	2.10	2.39	2.32	2.23	2.05	-	2.93	1.21	2.17	0.20	1.31	1.21	1.17	1.13	1.53	-	2.92	2.68	2.75	3.00	1.34	0.98	1.93	1.98	1.93	5.09	2.10	2.00	0.63	0.85	
Gd	-	12.9	14.2	13.0	12.5	12.4	-	12.5	7.86	10.1	4.15	10.8	10.1	8.76	9.38	8.61	-	19.0	16.5	16.1	18.7	11.13	11.39	11.9	8.68	8.77	25.6	8.97	9.20	2.17	4.22	
Dy	-	14.4	14.9	13.4	13.2	13.1	-	12.0	9.59	11.4	6.17	12.4	11.5	10.2	10.8	11.6	-	21.6	16.5	17.6	19.5	-	-	15.1	7.46	7.25	25.5	6.76	-	1.14	3.14	
Er	-	9.38	9.89	8.70	8.69	8.77	-	7.62	6.65	7.80	4.14	8.13	7.43	7.13	7.40	8.65	-	13.2	9.16	11.7	13.3	-	-	10.0	5.18	4.73	17.2	3.09	-	-	2.59	
Yb	-	9.16	9.18	8.22	8.27	8.62	-	7.30	6.52	7.50	4.54	7.87	7.19	6.65	7.07	8.57	-	-	7.24	11.2	12.7	8.21	7.34	10.0	4.31	3.63	15.1	2.58	5.30	0.45	1.74	
Lu	-	1.42	1.44	1.30	1.30	1.37	-	1.14	1.41	1.23	0.687	1.23	1.14	0.997	1.07	1.37	-	1.85	1.13	1.73	2.02	1.30	1.14	1.53	0.71	0.61	2.50	0.40	0.89	-	0.32	

**Table One.** Major and trace element analyses of West Highland Granitic Gneisses and representative Moine metasediments. Major element oxides in weight percent, trace elements as parts per million.

Table 2  
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	Ardgour			Fort Augustus		Glen Moriston		Loch Arkaig		Glen Doe		Quoich	Moine metasediments				
Sample	AGG-B	AGG3	Mo46d	FAGG3	FAG-A	GMG-C	GMGG-4	LAGG5	LA2	D24	D48	Q21	S40	IM32	IM49	Q12	Q3
Rb	194	153	-	150	217	252	177	201	200	130	144	163	149	84	126	100	112
Sr	128	160	-	311	127	18	97	113	141	198	49	122	285	177	435	211	278
<sup>87</sup> Rb/ <sup>86</sup> Sr	4.4124	2.7771	2.2000	1.3979	4.9754	43.1474	5.3180	5.1818	4.1272	1.8594	8.5864	3.8853	1.5161	1.3762	0.8393	1.3744	1.1680
<sup>87</sup> Sr/ <sup>86</sup> Sr	0.771494	0.746067	0.74	0.725593	0.773469	1.374442	0.782332	0.778089	0.765805	0.73605	0.822522	0.759985	0.731192	0.731000	0.722982	0.731575	0.727529
<sup>87</sup> Sr/ <sup>86</sup> Sr <sub>i</sub>	0.718421	0.712665	0.713538	0.708778	0.713625	0.855459	0.718366	0.715761	0.716162	0.713685	0.719243	0.713251	0.712956	0.714447	0.712886	0.715043	0.713481
Sm	15.321	16.533	16.360	11.905	12.608	4.636	9.766	20.269	22.077	11.590	10.010	13.705	11.335	4.509	10.286	1.661	33.632
Nd	67.225	73.948	74.080	50.847	55.494	14.401	38.898	87.029	91.509	42.020	35.220	54.189	61.055	23.145	54.919	9.293	152.6
<sup>147</sup> Sm/ <sup>144</sup> Nd	0.13777	0.13515	0.13350	0.14154	0.13734	0.19462	0.15177	0.14079	0.14585	0.16674	0.17181	0.15289	0.11222	0.11776	0.11321	0.10804	0.13321
<sup>143</sup> Nd/ <sup>144</sup> Nd	0.512246	0.512247	0.512179	0.512398	0.512329	0.512653	0.512356	0.512411	0.512415	0.512322	0.512351	0.512498	0.511818	0.511863	0.511820	0.511746	0.512318
ε Nd	-1.3	-1.0	-2.2	1.3	0.4	0.5	-0.7	1.6	1.1	-2.9	-2.9	2.0	-6.9	-6.6	-7.0	-7.9	0.6
Lu	-	1.44	-	1.14	-	-	0.997	2.02	1.85	-	1.14	1.53	-	0.35	0.75	-	2.50
Hf	-	15.00	-	14.50	-	-	8.55	22.50	23.40	-	6.31	10.90	-	7.04	7.39	-	38.50
<sup>176</sup> Lu/ <sup>177</sup> Hf	-	0.01361	-	0.01114	-	-	0.01653	0.01273	0.01121	-	0.02561	0.01990	-	0.00705	0.01438	-	0.00920
<sup>176</sup> Hf/ <sup>177</sup> Hf	-	0.282582	-	0.282579	-	-	0.282796	0.282720	0.282745	-	0.282809	0.282938	-	0.282101	0.282310	-	0.282615
ε Hf	-	4.7	-	6.0	-	-	10.5	10.1	11.8	-	5.7	13.6	-	-8.6	-5.4	-	8.4
δ <sup>18</sup> O	3.1	5.7	-	7.5	4.7	5.3	5.7	5.1	5.5	7.7	6.8	-	-	10.1	8.2	-	-

Table Two. Sr, Nd, Hf and O isotope data for the West Highland Granitic Gneiss and Moine metasediments.