Do Neoproterozoic (Moine) calc-silicate rocks represent metamorphosed tuffs?
A geochemical re-appraisal

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Running heads: LH: RICHARD A. BATCHELOR

RH: DO NEOPROTEROZOIC (MOINE) CALC-SILICATE ROCKS REPRESENT METAMORPHOSED TUFFS?

Suggest: CALC-SILICATE ROCKS

ABSTRACT: Following the identification of grey quartz–albite–chlorite–calcite–muscovite rocks in Meso- to Neo-proterozoic sequences in Scotland as metamorphosed tuffs of intermediate composition, it has been shown that this lithology will generate calc-silicate rocks at higher metamorphic grades. Both rock types occur as thin beds with sharp contacts with their host, occur as multiple beds in isolated suites, and share chemical compositions suggestive of volcanic sources with tholeiitic andesite affinities. The failure to recognise calc-silicate rocks as tuffs might explain the apparent scarcity of volcanogenic material through c. 220 million years of early Earth history in Scotland.

KEYWORDS: Calc-silicates, tuffs, intermediate magmatism, Moine

1 Calc-silicate rocks, which are metamorphic rocks composed mostly of plagioclase feldspar, amphibole,
2 garnet, quartz and occasionally epidote, are sporadically distributed throughout the Neoproterozoic
3 Moine Supergroup of Scotland. The Moine Supergroup comprises a thick sequence of sedimentary
4 rocks, deposited in fluvial (Bonsor & Prave 2008) and shallow marine environments between c. 950
5 Ma and 870 Ma (Mendum *et al.* 2009), intruded by some minor igneous intrusions, all of which were
6 subjected to regional metamorphism and deformation events (Strachan *et al.* 2010). The sediments
7 were derived from the denudation of the c.1000 Ma Grenville Orogen and deposited off the eastern
8 margin of Laurentia into a foreland basin. The value of calc-silicate rocks as indicators of metamorphic
9 grades was first established in Scotland by Kennedy (1949). Generally they occur as thin bands or
10 lenses, commonly less than 15cm thick, and have sharp upper and lower contacts with their host
11 metasediment. They are defined as containing less than 5% free carbonate minerals (Rosen *et al.*
12 2004). Calc-silicates from the Moine rocks of NW Scotland occur within psammites and semi-pelites,
13 and contain combinations of plagioclase feldspar, hornblende $\pm$ biotite, garnet, quartz, zoisite, and
14 minor calcite (Winchester 1972). The amount of zoisite is inversely proportional to the amount of
15 calcite, suggesting that the latter is consumed to create zoisite. Calcite is often preserved as inclusions
16 in garnet, implying it was present in the rock before garnet formed. Grain sizes generally vary from
17 0.1mm to 1mm.

18 A study of Moine calc-silicate rocks from the Morar area charted the mineralogical changes
19 which took place with increasing metamorphic grade (Tanner 1976). The lower grades are typified by
20 quartz, albitic plagioclase feldspar, garnet, biotite=hornblende and zoisite whereas at higher grades,
21 zoisite disappears and the plagioclase composition reaches bytownite and hornblende replaces biotite.
22 The garnet Alm70-60 - Gro30-40 is ubiquitous in the sequence. Further work on these rocks showed
23 that Na and K are lost from the calc-silicate during prograde metamorphism (Tanner & Miller 1980).

24 Epidote-bearing calc-silicates within the Moine Supergroup of Scotland were described by
25 Winchester (1975). These occurrences form bands and lenticles less than 10cm thick and occur within
26 the Morar and Loch Eil groups. While the bulk chemical composition is similar to the common zoisite-
27 garnet type, they differ in that garnet is absent and epidote takes the place of zoisite. Concentrations of
28 zirconium up to 766 ppm are reported, a value which is high for clastic sediments but normal for
29 igneous rocks with alkaline/intermediate compositions. Winchester's (1975) conclusion was that
30 epidote was a detrital mineral and the rock may have been related to an epidotic grit lithology, similar
31 to that in the Sleat Group (Torridonian) described by Stewart (2002). Some epidotic calc-silicates were
32 considered to have possibly originated from volcanic ash deposits (Winchester, pers. comm.).

33 Historically, references to putative tuffs in the Proterozoic of Scotland are scarce but four
34 examples (one of Lewisian and three of Moine ages) are quoted here and are presented to show that
35 volcanogenic rocks can masquerade as something different. One calc-silicate rock from the Scourian
36 complex of NW Scotland was described as a plagioclase-clinopyroxene-scapolite rock (Rollinson

1 1980). However, when the chemical composition was re-calculated on a volatile-free basis, the rock
2 became essentially a clinopyroxene-plagioclase rock (ie. a gabbro).. A study of hornblende rocks from
3 the Moine successions west of the Great Glen (Rock 1984) identified two samples whose chemical
4 composition suggested they were formed from contemporary volcanoclastic deposits. Two epidote
5 hornblende schists from the Moine Supergroup of Sutherland were considered to represent
6 penecontemporaneous volcanic ash deposits (Moorhouse & Moorhouse 1979). Garnetiferous
7 hornblende schists near to the contact of the Glenfinnan and Loch Eil groups. Moine Supergroup, were
8 thought to represent volcanic horizons (Peacock 1977).

9 This work was triggered by the identification of grey quartz - albite - chlorite - muscovite -
10 calcite rocks (cognate to altered variants named 'brown beds') in prehnite-pumpellyite to low
11 greenschist facies environments in the Dalradian Supergroup (Batchelor 2004a; 2004b) and in the
12 Torridonian Supergroup (Batchelor *et al.* 2008; Batchelor 2011) which were all interpreted as tuffs.
13 Circumstantial evidence from geochemical, mineralogical and field relationships led to the hypothesis
14 that these grey tuffs could convert to calc-silicate rocks under amphibolite facies metamorphism. Three
15 grey tuffs have CaO values of 9.8%, 10.5% and 16.1%. Values of CaO in 75 published analyses of
16 calc-silicates yielded a range of 3.0% to 21.6% CaO (Winchester 1972, 1975; Tanner 1976).

17 This study is based on experimental petrology and geochemical analysis of suites of Moine
18 calc-silicate rocks collected from the Northern Highlands of Scotland. Their geographical distribution
19 is shown in Figure 1 and their stratigraphical affiliations are shown below. The terminology for the
20 Moine Supergroup stratigraphy is based on Mendum *et al.* (2009).

22	GROUP	FORMATION	LOCALITY (Sample Numbers)
23	Loch Eil (c.860Ma)		
24			Cannich (CS/RB/50-56)
25	Glenfinnan	Glenfinnan Schists	
26			Ardalanish, Mull (CS/RB/34-40)
27			Uisken , Mull (CS/RB/44-49)
28		Lochailort Pelite	
29			
30	Morar (c.950Ma)	Upper Morar Psammite	Lochailort (CS/RB/18-24, TN/RB/69-73)
31		Morar Pelite	Mallaig CS/RB/1-6), Morar (TN/RB/77-86),
32			Arisaig (CS/RB/7-17)
33		Lower Morar Psammite	
34			
35			

36 **1. Sample descriptions**

1 **1.1. Mallaig**

2 A suite of six calc-silicate beds, not all contiguous in exposure, were sampled from roadside exposures
3 at Mallaighmor [NM 680 974]. Samples CS/RB/001-004 are situated on the west side of the road from
4 Mallaig. CS/RB/005, 006 were collected c. 60m downhill from the former samples, on the east side of
5 the road [NM 680 973]. Sample thicknesses vary from 10mm to 30mm. The host rocks are near-
6 vertical semi-pelites of the Morar Pelite Formation, Morar Group. The general mineral assemblage is
7 lamellar-twinning plagioclase feldspar, biotite (up to 2mm long) with abundant pleochroic haloes
8 (indicative of zircon), quartz (interlocking grains), poikilitic garnet, actinolite and rare zoisite, epidote
9 and titanite. Only one sample (CS/RB/006) contains free calcite.

10

11 **1.2. Morar**

12 A stratigraphically-coherent suite of calc-silicate beds (TN/RB/077–TN/RB/086) occurs at a roadside
13 cutting over a length of 53 m on the east side of the A830 road at [NM 674 914], 2km SSW of Morar
14 village. Samples vary in thickness from 20mm to 140mm. The host rocks belong to the Morar Pelite
15 Formation, Morar Group. One typical sample (TN/RB/083) displayed the following mineral
16 assemblage: lamellar-twinning plagioclase feldspar, biotite (up to 2mm long) containing pleochroic
17 haloes, quartz, zoisite, poikilitic garnet, calcite and hornblende. Grain size varies from 0.1 to 0.2mm.
18 This suite belongs to the Zone 1–Zone 2 transition of Kennedy (1949). Four samples (TN/RB/078, 080,
19 081, 082) contain a narrow zone, varying from 5mm to 50mm, of a brown crumbly material within the
20 boundaries of the calc-silicate rock, reminiscent of the Dalradian and Torridonian "brown beds"
21 (Batchelor *et al.* 2008) (Fig. 2). It would be consistent with the effect of sub-aerial weathering of a
22 residual calcite matrix, implying that all calcite was not consumed during the metamorphic
23 transformation of the original lithology.

24

25 **1.3. Arisaig**

26 A relatively recent road exposure on the A830 road 1.5km E of Arisaig [NM 674 860] provided the
27 opportunity to sample a continuous sequence of calc-silicate rocks CS/RB/007-017. Samples vary in
28 thickness from 20mm to 90mm. The mineral assemblages comprise lamellar-twinning plagioclase
29 feldspar, actinolite, biotite, quartz, calcite, poikilitic garnet, titanite and zoisite. Garnet often encloses
30 calcite.

31

32 **1.4. Lochailort**

33 A near-vertical suite of psammites and semi-pelites are well-exposed in a roadside cutting on the north
34 side of the A830 road, opposite its junction with the A861 road [NM 767 823]. These rocks form part
35 of the Upper Morar Psammite Formation, Morar Group (Johnstone & Mykura 1989; Mendum *et al.*
36 2009). Sample thicknesses vary from 12mm to 50mm. The mineralogy of this suite comprises

lamellar-twinning plagioclase feldspar showing variable degrees of sericitisation, biotite which has partly altered to chlorite, quartz and garnet associated with calcite. These rocks differ from the previous three suites in lacking amphibole, zoisite and epidote.

1.5. Mull – Ardalanish Bay

Calc-silicate rocks occur within semi-pelites of the Assapol Group, tentatively assigned to the Glenfinnan Group (mid-Moine Supergroup) by Holdsworth *et al.* (1987), at Ardalanish Bay, 3.5km south of Bunessan, Isle of Mull [NM 381 186]. Samples vary in thickness from 15mm to 70mm.

Samples were collected from west to east in the order CS/RB/034–040, and the succession here dips 50°NW. Sample CS/RB/040 from the east end of Ardalanish Bay yielded the following mineral assemblage: plagioclase feldspar (An_{40–80}), poikilitic garnet, quartz, interstitial zoisite, actinolite, titanite, calcite (residual inside garnet), subhedral zircon.

1.6. Mull – Uisken Bay

A sequence of psammites, which belong to the Assapol Group, tentatively assigned to the Glenfinnan Group by Holdsworth *et al.* (1987), is exposed around HWM [NM 392 188] in the middle of Uisken Bay. The general dip direction is 25°SE. Six calc-silicate rocks (CS/RB/044 to CS/RB/049) were collected - thicknesses varied from 20mm to 70mm over a horizontal distance of 13m. The general mineral assemblage comprises clinozoisite, poikilitic garnet (enclosing calcite), zoisite, chlorite, quartz, titanite and calcite. One sample (045) contains no feldspar, while another (048) contains plagioclase feldspar and biotite but no amphibole.

1.7. Cannich

A suite of seven calc-silicate rocks (CS/RB/050–056) were collected from a road cutting on the east side of the A831 road, 1km east of Cannich [NH 349 315]. These beds occur in psammites and semi-pelites, assigned to the Upper Glenfinnan Group - Lower Loch Eil Group by Mendum *et al.* (2009), and dip 45°SE. Thicknesses vary from 40mm to 150mm. Sample 053 contains abundant zoisite, quartz, biotite (with pleochroic haloes after zircon), garnet and titanite. No feldspar was identified implying it has been consumed in the formation of zoisite.

2. Experimental work

Two grey tuffs which occur in the Torridonian Supergroup (Batchelor 2005, 2011) comprise albite, chlorite, quartz, calcite and muscovite in prehnite–pumpellyite facies to low greenschist facies metamorphic environments. In order to test whether or not the grey tuffs could generate mineral assemblages similar to calc-silicates under high P/T conditions, their bulk chemical compositions were plotted on Eskola's ACF diagram, following Miyashiro (1994). The three variables were calculated on

1 an atom basis thus: $A = Al_2O_3 + Fe_2O_3 - Na_2O - K_2O$, $C = CaO - (3.3 \times P_2O_5)$, $F = FeO + MgO +$
2 MnO . The grey tuffs generated a mineral composition centred around vesuvianite (idocrase), with
3 sample TN/RB/026GY trending towards the wollastonite pole. On this basis experimental runs were
4 carried out at the Grant Institute, University of Edinburgh. The two tuff samples (TN/RB/026GY from
5 the Diabaig Formation and SK/RB/05GY from the Sleat Group) were run at 6kbar/600°C (amphibolite
6 facies) for 400 hours. Approximately 20mg of powder from each sample were sealed dry into welded
7 Pt capsules (length 1cm, diameter 3mm, wall thickness 0.1mm). Samples were placed in an internally-
8 heated gas vessel, brought to run pressure, and then heated to final run temperature over 15 minutes.
9 Argon was used as the pressure medium, and pO_2 was close to the Ni–NiO buffer at the relevant
10 temperatures. Samples were fast-quenched by cutting power to the vessels and subsequent cooling was
11 exponential, with an 80 % temperature drop in five minutes.

12 The products were examined by X-ray Diffraction (XRD) to ascertain their mineralogical
13 composition and the data were compared with the composition of the original material. The data are
14 presented in Table 2. The output from XRD was re-calculated using Rietveld software. This software
15 does not select minerals arbitrarily, so an estimate of likely phases has to be input manually. The main
16 points to note are that Ca-plagioclase increases, chlorite decreases, zoisite falls and grossular garnet
17 appears, the latter mineral being a key component of calc-silicate rocks. While not shown, amphibole
18 grows at the expense of chlorite.

19

20 **3. Geochemistry**

21 Geochemical data for calc-silicates are presented in Table 3. The range for SiO_2 is 47.4% to 76.8%,
22 with an average value of 63.9% (mean of 58). The first point to note is these new data (Averages 5 -
23 11) compare favourably with published data (Averages 1 - 4) and the grey tuffs as displayed in Fig. 3.
24 Also worthy of note is how the data for the host metasediments differ from the calc-silicate chemistry,
25 with the exception of Fe_2O_3/MgO . Values for Zr in the dataset reach 800ppm (Table 3). Some epidotic
26 calc-silicates from the Moine Supergroup (Winchester 1975) also have values of Zr considered high for
27 sedimentary rocks (400 - 700 ppm). These high levels of Zr were attributed by Winchester (*op. cit.*) to
28 the presence of heavy mineral bands.

29 Trace element data for each sampled area were averaged to generate a mean value for each
30 group in order to simplify the diagram (the number of samples are shown in parentheses). These mean
31 data were normalised to a host Moine metasediment (TN/RN/083A from Morar) together with three
32 Proterozoic tuffs (Batchelor 2004, 2005, 2011) (Fig. 4). The diagram suggests the calc-silicate rock
33 suites differ sufficiently from the metasediment to justify further investigation into their origin.

34 In order to discriminate between an igneous or a clastic origin, recourse was made to the use of
35 geochemical discrimination diagrams for amphibolites. Winchester (1984) was able to distinguish

1 between orthoamphibolites (igneous) and para-amphibolites (sedimentary) using TiO_2 vs Ni (Fig. 5a)
2 and Ni vs Zr/TiO_2 (Fig. 5b). The three grey tuffs and most of the Moine calc-silicates plot in the
3 igneous field.

4 In order to assess how coherent or otherwise are the compositions of the separate calc- silicate
5 rock assemblages, a Zr/Nb-Ti/Th plot was used (Fig. 6), where Zr/Nb reflects alkalinity and Ti/Th
6 reflects magmatic fractionation. These elements were selected by the author as an alternative to the
7 Zr/TiO_2 - Nb/Y discrimination diagram of Winchester & Floyd (1977) when it was reported that Y can
8 become mobile in altered rocks (Hill et al. 2000). Calc-silicate rocks compositions stretch across the dacite
9 - andesite - alkaine potassic fields. This is in keeping with the major element compositions which range
10 from 47% SiO_2 to 77% SiO_2 . This diagram helps to discriminate between the Mallaig, Morar and
11 Ardalanish (Mull) groups which form distinct domains. The Lochailort suite shows a bimodal
12 distribution with the five sample with higher Ti/Th (less evolved) representing the youngest five
13 samples in the sequence. Two of the five Uisken (Mull) samples (047, 048) overlap with Ardalanish
14 (Mull) sample 040, the oldest of that group, while Uisken 044 has an affinity with Mallaig/Morar
15 samples. The Arisaig group shows a wide scatter. The Morar set have a distinct alkaline affinity, with
16 three exceptions (078, 081, 080) which plot with the Mallaig set, a group which has a more calc-
17 alkaline nature. Ardalanish samples display a more transitional character. The dotted line, which
18 defines the oval ring in this diagram, represents the compositional field of Dalradian tuffs (Batchelor
19 2004a, 2004b) and Torridonian tuffs (Batchelor 2005, 2011).

20
21 A subset of samples from each group was analysed by ICP-MS for the Rare Earth Element
22 (REE) content and these data are presented in Table 4. A chondrite-normalised REE spider diagram
23 (Fig. 7) for all samples shows Light REE (LREE) enrichment for most samples and modest negative
24 Eu anomalies. The exceptions are the two Lochailort samples (CS/RB/019, 020) - the two lowermost
25 dotted lines - which uniquely display a positive Eu anomaly and a strong Heavy REE (HREE) depletion
26 relative to the rest of the samples. This latter feature could reflect an augmented concentration of
27 plagioclase, perhaps from a feldsparphyric source.

28 29 **4. Discussion**

30 The recent identification in Scottish Meso- to Neo-proterozoic rocks of a grey lithology comprising
31 albite, quartz, chlorite and calcite (with minor muscovite) as metamorphosed tuffs of an intermediate
32 composition (Batchelor *et al.* 2008; Batchelor 2011) led to the speculation that they could be the
33 precursors of calc-silicate rocks after higher grade metamorphism. Intriguingly, Kennedy (1949)
34 predicted this possibility when he surmised that quartz-albite-chlorite-calcite rocks in the Sleat Group
35 of the Torridonian Supergroup on the Isle of Skye could be precursors of Moine calc-silicate rocks, a
36 statement which simultaneously explained the origin of calc-silicate rocks but also implied an age

equivalence between Torridonian and Moine successions, an idea first controversially proposed by Ben Peach in Peach *et al.* (1907) but recently resurrected by Krabbendam *et al.* (2008).

Calc-silicate rock comprises plag + actin + gross gt + qtz $\pm$ cc ($\pm$ epid $\pm$ zo). Epidote and zoisite are intermediate phases. Metamorphic mineral pathways from low-grade (prehnite- pumpellyite) metamorphism of three protolith assemblages to (indicated $\gg$) amphibolite facies assemblages are listed here:

ANDESITE: alb + cc + musc + chl + qtz $\gg$ plag (olig) + actin + gt + qtz + musc

GREY TUFF: alb + qtz + chl + cc + musc $\gg$ plag + actin + qtz + gross gt + musc

PELITE: chl + musc + qtz $\pm$ alb $\pm$ cc $\gg$ andal $\pm$ cord + bi + qtz + alm gt + plag

Clearly andesite will generate a metamorphic assemblage similar to a grey tuff and calc- silicate rock, whereas a pelite will not. A lime-rich pelite (or marl) could generate a similar assemblage to andesite, depending on the relative amount of calcium and magnesium.

The similarities in bulk geochemical composition and field relationships between calc- silicates and the "grey beds" (tuffs) are suggestive of air-fall tuffs. The relatively high levels of plagioclase feldspar (20-30%) also support an igneous protolith. This pre-supposes that the metamorphic reaction would be essentially a closed system, although Na and K can be lost (Tanner & Miller 1980). The tholeiitic character of the calc-silicate samples described here is clear as in all cases $\text{Fe}_2\text{O}_3/\text{MgO} \gg 1$ (Fig. 2). The LREE enrichment (Fig 7) is also characteristic of continental tholeiitic sequences (Wilson 1989). This is consistent with magmatism within an extensional tectonic environment, an environment known to have existed off the eastern margin of Laurentia during late-Mesoproterozoic and early-Neoproterozoic times (Cawood *et al.* 2004). Though 100 Myr older, the Keenawan province is an example of a large flood tholeiitic basalt event c. 1.1 Ga (van Schmus *et al.* 1990). The lithologies range from tholeiitic basalt to weakly alkaline basalt through to Fe-andesites and rhyolites. This range of lithologies encompass the SiO_2 ranges mentioned earlier (average value 63.9%) which implies an intermediate igneous composition. The proposal that calc-silicate rocks originally formed as tuffs would imply an explosive regime fed by tholeiitic andesitic to dacitic magmas.

Extensional magmatism has been described within the Moine Supergroup of Scotland in which metagabbros and tholeiitic metadolerite dykes were emplaced in the Glenfinnan and Loch Eil groups. The metagabbros have been dated at 873 ± 6 Ma (Millar 1999). In general, andesitic tholeiites occur in continental flood basalt provinces and whose mineral composition is typically plagioclase feldspar $\pm$ clinopyroxene + quartz + FeTi oxides, with plagioclase occurring as phenocrysts and in the groundmass. The abundance of plagioclase feldspar explains the low value or total absence of a negative Eu anomaly.

Calc-silicate rocks have traditionally been described as metamorphosed marls or calcareous muds.

Based on the geochemical evidence presented, it is proposed that they should be considered as metamorphosed tuffs. The arguments to support this proposal are given below.

- * Arkoses, which contain high levels of feldspar are commonly coarse grained (1-5mm) proximal deposits, are unlikely to form thin fine-grained beds with sharp upper and lower contacts
- * Feldspar in metamorphosed clastic rocks tends to be fine-grained albite
- * Plagioclase feldspar is less common in clastic rocks than K-feldspar
- * Lamellar-twinning in plagioclase feldspar is an igneous characteristic
- * Feldspar concentrations in mudrocks are generally <5%, as opposed to 20 - 50% in the grey tuffs and calc-silicate rocks
- * Zr, Ti, Ni plots support an orthoamphibolite (igneous) affinity (Winchester 1984)
- * High concentrations of Zr (up to 800ppm) could be generated by alkaline trachytic magmas (Wilson 1989).
- * Isolated populations of thin beds which differ from their host is typical of tuffs which represent episodic phases of volcanism
- * If part of the Moine Supergroup (Upper Morar Psammite) had been deposited in braided river plains (Bonsor & Prave 2008), it is hard to conceive how a lime-rich marl could be formed and deposited in such an environment, except by invoking a marine or lagoon incursion on a regular basis and an equally rapid regression. In contrast an ash cloud could dump a layer of volcanic ash instantaneously.

Another key issue in this debate relates to the relative rarity of carbonate deposits in the Palaeo, Meso- and early Neo-proterozoic. Marbles are described in the Lewisian Loch Maree Group, in association with banded ironstones, and in the Lewisian inlier near Dornie. Carbonates are known in the Stoer Group, lower Torridonian Supergroup, but these are associated with algal mats and stromatolitic structures, while other deposits indicate that calcite pseudomorphed gypsum in what are described as evaporite lake deposits (Stewart 2002). Earlier reports of marbles in the Moine succession (Read *et al.* 1926) were later considered to be thrust slices and infolds of Lewisian basement (Holdsworth *et al.* 1994). No mention is made of carbonates in Moine sequences by Mendum *et al.* (2009). In other words, widespread carbonate precipitation was not a common feature of the Torridonian and Moine supergroups. Significant carbonate deposition doesn't appear until the early Dalradian, when the Ballachulish Limestone is deposited in the middle of the Appin Group. Age constraints on this are provided by a date of 806Ma for the Grampian Shear Zone (Noble *et al.* 1996) and the 720Ma-old Port Askaig Tillite (basal Argyll Group) (Condon & Prave 2000). These dates would suggest an age of c. 750Ma for the first significant limestone deposit in the Neoproterozoic, 120M years later than the youngest Moine rocks.

5. Conclusion

Consideration of field relationships, mineralogy and geochemistry suggest that calc-silicates could represent altered tuffs derived from tholeiitic sources of intermediate compositions erupted from extensional tectonic environments. Given the paucity of datable zircons, attention should be given to matching calc-silicate assemblages in terms of stratigraphy, relative thicknesses and abundance which would allow correlation of the barren Moine metasedimentary sequences of Scotland and contemporary deposits elsewhere. Unique REE signatures of calc-silicates rocks could be used to refine or even re-appraise existing ideas of Moine stratigraphy. This hypothesis could help to explain the apparent paucity of volcanic rocks over some 220 Myr of geological time during the Proterozoic when Torridonian and Moine rocks were being deposited in an active extensional basin.

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Figure Captions

Figure 1 Map of calc-silicate rock suites, with localities marked *. Moine groups adapted from Strachan *et al.* (2002). MG Morar Group, GG Grampian Group (with stippled ornament), LEG Loch Eil Group.

Figure 2 (a) Calc-silicate bed with crumbly brown interior band, Morar Group, Morar. Hammer head scale = 15cm. (b) "Brown Bed" alteration product at the periphery of the central grey bed (tuff), Sleat Group, Torridonian Supergroup, Isle of Skye.

Figure 3 Oxide ratios of data from published calc-silicate rocks and data from this work, Proterozoic tuffs and Moine metasediments.

Figure 4 Calc-silicate rock groups (mean of n samples) and Proterozoic tuffs, normalised to a host Moine metasediment (semi-pelite).

Figure 5 (a) Bivariate plot of TiO_2 vs. Ni for all calc-silicate rocks. Open triangles represent grey tuffs. Sedimentary-igneous boundary after Winchester (1984). (b) Bivariate plot of Ni vs Zr/TiO_2 for all calc-silicate rocks. Open triangles represent grey tuffs. Sedimentary-igneous boundary after Winchester (1984).

Figure 6 Bivariate plot of Zr/Nb vs. Ti/Th . Volcanic rock fields data from Wilson (1989). Superimposed (dotted oval) represents the field of Dalradian tuffs (Batchelor 2004a, 2004b) and Torridonian tuffs (Batchelor 2005, 2011).

Figure 7 Chondrite-normalised Rare Earth Elements for all calc-silicate rocks.

Table Captions

Table 1 Average values of major element oxides for calc-silicate rocks (published data and from this work), Neoproterozoic tuffs and Moine metasediments

Table 2 Mineralogical composition of experimental high P/T reaction products

Table 3 Geochemical data for a suite of calc-silicate rocks; a) Morar, b) Mallaig, c) Arisaig, d) Lochailort, e) Ardalanish Bay (Mull), f) Uisken Bay (Mull), g) Cannich

Table 4 Rare Earth Element concentrations for selected calc-silicate rocks

Table 1. Average values of major element oxide ratios for calc-silicate rocks, tuffs and metasediments.

	Average 1	Average 2	Average 3	Average 4	Average 5	Average 6
CaO/Al ₂ O ₃	0.65	0.71	0.60	0.55	0.40	0.85
CaO/MgO	8.62	10.46	5.06	8.51	5.50	13.40
CaO/TiO ₂	13.86	18.47	12.05	12.96	8.66	20.42
CaO/Fe ₂ O ₃	2.21	2.87	1.70	2.25	1.35	3.11
Fe ₂ O ₃ /MgO	3.90	3.64	2.98	3.79	4.06	4.31
TiO ₂ /MgO	0.62	0.57	0.42	0.66	0.64	0.66

	Average 7	Average 8	Average 9	Average 10	Average 11
CaO/Al ₂ O ₃	0.65	0.37	0.56	0.51	0.61
CaO/MgO	14.84	5.37	8.40	9.30	25.30
CaO/TiO ₂	18.78	17.06	14.50	12.40	24.70
CaO/Fe ₂ O ₃	3.80	3.35	2.20	2.10	4.40
Fe ₂ O ₃ /MgO	3.90	1.60	3.70	4.60	4.50
TiO ₂ /MgO	0.79	0.31	0.60	0.75	0.75

	GH/RB/112GY	SK/RB/05GY	TN/RB/026GY	Moine metasediments (3)
CaO/Al ₂ O ₃	0.89	0.97	1.92	0.23
CaO/MgO	12.20	10.17	24.75	1.72
CaO/TiO ₂	14.75	20.94	22.35	4.14
CaO/Fe ₂ O ₃	3.27	4.09	6.70	0.61
Fe ₂ O ₃ /MgO	3.73	2.49	3.69	2.81
TiO ₂ /MgO	0.83	0.49	1.11	0.42

Average 1: Epidotic calc-silicates (Winchester 1975)
 Average 2: Garnet-zoisite calc-silicates (Winchester 1972)
 Average 3: Calc-silicates from Fannich (Winchester 1972)
 Average 4: Calc-silicates (Tanner 1976)
 Average 5: Calc-silicates (this work), Mallaig (6)
 Average 6: Calc-silicates (this work), Morar (10)
 Average 7: Calc-silicates (this work), Arisaig (11)
 Average 8: Calc-silicates (this work), Lochailort (12)
 Average 9: Calc-silicates (this work), Ardalanish Bay, Mull (7)
 Average 10: Calc-silicates (this work), Uisken Bay, Mull (5)
 Average 11: Calc-silicates (this work), Cannich (6)

Table 2. Mineralogical composition of high P/T products

Sample locations:

TN/RB/026GY. Lower Diabaig, Highland Region. [NG 7925 6025], Diabaig Formation, Torridon Group.

SK/RB/05GY. 1 km east of Kyle of Lochalsh, Highland Region. [NG 7725 2725], Loch na Dal Formation, Sleat Group, Torridonian

%	TN/RB/026GY Grey Tuff	TN/RB/026GY Amphibolite facies
Quartz	32.6	28.7
Muscovite	-	0.7
Calcite	27.2	28.6
Albite	24.7	26.0
Anorthite	5.1	8.3
K-feldspars	2.5	4.0
Chlorite	5.3	1.0
Zoisite	0.8	0.4
Epidote	1.5	1.6
Almandine	0.4	0.3
Grossular	-	0.8
TOTAL	100.1	100.4

%	SK/RB/05GY Grey Tuff	SK/RB/05GY Amphibolite facies
Quartz	41.9	41.9
Muscovite	-	8.5
Calcite	18.9	16.4
Albite	15.5	13.5
Anorthite	4.8	5.2
K-feldspars	6.2	9.0
Chlorite	9.4	1.3
Zoisite	0.7	-
Epidote	1.6	0.8
Almandine	1.0	-
Grossular	-	1.8
TOTAL	100.0	98.4

Table 3a. Geochemical data for a suite of calc-silicate rocks from Morar.

%	TNRB077	TNRB078	TNRB079	TNRB080	TNRB081	TNRB082
SiO ₂	56.78	47.42	61.38	48.51	51.93	53.66
TiO ₂	0.62	0.72	0.65	0.63	0.68	0.63
Al ₂ O ₃	18.88	13.54	18.67	13.03	13.30	15.57
Fe ₂ O ₃	5.16	4.21	4.69	4.37	4.23	4.31
MnO	0.34	0.36	0.40	0.40	0.45	0.40
MgO	1.17	1.09	0.92	1.15	0.87	0.98
CaO	9.24	20.24	6.45	20.37	17.33	14.26
Na ₂ O	3.56	1.25	4.37	1.05	1.49	2.42
K ₂ O	1.05	0.15	0.85	0.17	0.41	0.65
P ₂ O ₅	0.45	0.35	0.58	0.24	0.45	0.46
LOI	1.8	10.3	0.4	10.6	8.5	5.9
TOTAL	99.05	99.59	99.36	100.56	99.61	99.21
ppm						
V	64	66	69	55	63	62
Cr	49	53	42	49	44	43
Ni	15	19	16	22	16	16
Rb	39	2	34	3	12	19
Sr	356	450	334	438	432	380
Y	35	35	42	31	49	36
Zr	133	504	162	238	448	203
Nb	14	18	21	12	16	18
Ba	182	43	158	47	124	102
La	42	71	38	49	70	44
Ce	90	148	78	105	143	92
Nd	40	71	38	48	66	40
Th	5	10	6	7	11	6
%	TNRB083	TNRB084	TNRB085	TNRB086	TNRB083A Metasediment	TNRB086A Metasediment
SiO ₂	60.99	58.50	53.66	61.96	61.30	59.76
TiO ₂	0.66	0.76	0.63	0.57	0.87	1.14
Al ₂ O ₃	15.33	17.03	16.91	14.60	16.11	16.93
Fe ₂ O ₃	3.58	4.68	3.88	3.59	6.12	7.38
MnO	0.30	0.35	0.43	0.36	0.07	0.04
MgO	0.98	0.93	0.82	0.96	2.13	2.68
CaO	10.46	10.69	13.32	10.37	2.97	4.62
Na ₂ O	2.20	2.42	2.87	2.48	2.54	3.56
K ₂ O	0.58	0.71	0.78	0.71	3.37	2.26
P ₂ O ₅	1.14	0.57	0.51	1.80	1.27	0.16
LOI	2.0	2.7	5.8	2.1	1.7	1.2
TOTAL	98.22	99.37	99.62	99.53	98.40	99.73
ppm						
V	79	74	66	81	121	
Cr	40	51	43	41	74	
Ni	17	18	17	16	30	
Rb	20	28	32	31	117	
Sr	341	387	366	324	291	
Y	52	46	41	62	50	
Zr	144	233	153	158	206	
Nb	21	32	22	22	16	
Ba	87	121	146	139	935	
La	49	50	34	51	66	
Ce	96	98	70	99	126	
Nd	46	47	31	52	61	
Th	8	8	4	8	10	

Table 3b. Geochemical data for a suite of calc-silicate rocks from Mallaig.

%	CSRB006	CSRB005	CSRB001	CSRB002	CSRB003	CSRB004
SiO ₂	65.00	60.33	60.16	63.98	58.14	62.03
TiO ₂	0.63	0.81	0.85	0.70	0.82	1.12
Al ₂ O ₃	15.00	18.53	18.59	17.61	18.80	16.83
Fe ₂ O ₃	2.80	5.51	5.69	5.39	6.36	5.71
MnO	0.24	0.34	0.33	0.32	0.34	0.31
MgO	0.80	1.40	1.32	1.24	1.58	1.38
CaO	8.73	7.13	6.91	4.50	8.38	7.11
Na ₂ O	2.39	3.45	3.60	4.48	2.94	2.66
K ₂ O	0.90	1.07	1.08	0.99	0.90	1.05
P ₂ O ₅	0.18	0.65	0.60	0.26	0.59	0.57
LOI	3.2	0.7	0.7	0.4	1.0	1.1
TOTAL	99.87	99.92	99.83	99.87	99.85	99.87
ppm						
V	51	70	68	56	95	77
Cr	34	47	47	40	54	54
Ni	10	19	21	19	24	19
Rb	39	47	47	46	33	54
Sr	379	425	407	440	389	372
Y	35	52	57	47	49	64
Zr	288	266	287	229	289	613
Nb	12	12	12	6	10	17
Ba	175	205	282	222	101	237
La	46	58	59	47	70	91
Ce	84	102	109	93	121	160
Nd	35	58	54	46	63	85
Th	9	9	11	10	10	20

Table 3c. Geochemical data for a suite of calc-silicate rocks from Arisaig.

%	CSRB007	CSRB008	CSRB009	CSRB010	CSRB011	CSRB012
SiO ₂	70.99	66.30	73.81	68.27	58.41	67.67
TiO ₂	0.33	0.46	0.24	0.19	0.86	0.26
Al ₂ O ₃	13.47	14.23	9.62	8.66	18.93	7.89
Fe ₂ O ₃	1.80	1.99	1.28	1.29	3.50	1.49
MnO	0.27	0.28	0.18	0.24	0.44	0.28
MgO	0.36	0.41	0.41	0.37	0.76	0.39
CaO	5.45	7.51	7.22	11.09	8.58	12.04
Na ₂ O	3.87	4.18	2.50	1.89	4.65	1.67
K ₂ O	0.79	0.64	0.43	0.34	0.89	0.31
P ₂ O ₅	0.27	0.54	0.15	0.14	0.75	0.18
LOI	2.3	3.3	4.0	7.4	2.1	7.7
TOTAL	99.90	99.84	99.84	99.88	99.87	99.88

ppm						
V	9	21	27	17	45	23
Cr	9	15	15	10	34	16
Ni	2	4	3	2	9	2
Rb	34	20	17	13	35	11
Sr	362	353	228	264	384	270
Y	25	20	22	15	40	22
Zr	156	221	114	104	306	154
Nb	8	14	6	5	23	5
Ba	262	158	138	71	231	71
La	15	22	18	18	35	32
Ce	36	47	36	38	70	60
Nd	5	14	17	11	30	28
Th	3	6	5	4	7	7

%	CSRB013	CSRB014	CSRB015	CSRB016	CSRB017
SiO ₂	67.70	59.91	60.53	58.60	62.56
TiO ₂	0.25	0.44	0.45	1.39	0.50
Al ₂ O ₃	15.25	12.66	18.01	17.74	18.07
Fe ₂ O ₃	2.08	3.27	2.48	4.28	3.20
MnO	0.31	0.38	0.30	0.35	0.30
MgO	0.63	1.05	0.59	1.02	0.81
CaO	7.29	12.39	11.39	10.17	7.97
Na ₂ O	3.60	1.57	2.51	2.87	3.77
K ₂ O	0.56	0.97	0.54	0.96	0.85
P ₂ O ₅	0.24	0.18	0.39	0.59	0.43
LOI	1.9	7.0	2.7	1.8	1.4
TOTAL	99.81	99.82	99.89	99.77	99.86

ppm					
V	26	46	44	78	42
Cr	13	24	27	48	28
Ni	3	11	5	13	10
Rb	23	36	16	36	31
Sr	235	249	367	398	383
Y	22	28	22	42	30
Zr	52	181	157	800	174
Nb	7	11	10	24	11
Ba	126	188	82	200	208
La	12	28	29	56	24
Ce	28	59	55	105	54
Nd	14	20	13	41	31
Th	3	7	5	15	6

Table 3d. Geochemical data for a suite of calc-silicate rocks from Lochailort.

%	CSRB019	CSRB020	TNRB073	TNRB072	CSRB018	CSRB023
SiO ₂	70.85	73.15	61.33	67.94	59.08	75.24
TiO ₂	0.15	0.20	0.74	0.24	0.46	0.15
Al ₂ O ₃	15.89	14.70	18.93	16.68	21.36	13.70
Fe ₂ O ₃	1.32	1.22	3.03	1.72	2.66	0.99
MnO	0.03	0.03	0.24	0.17	0.30	0.16
MgO	0.50	0.38	0.93	0.46	0.68	0.21
CaO	3.18	3.78	8.80	7.03	7.48	4.50
Na ₂ O	4.16	4.41	3.05	3.28	4.79	3.35
K ₂ O	2.63	0.74	0.85	0.84	1.23	0.49
P ₂ O ₅	0.15	0.21	0.25	0.31	0.77	0.38
LOI	0.9	1.0	1.7	1.2	1.0	0.6
TOTAL	99.76	99.82	99.85	99.87	99.81	99.77
ppm						
V	17	18	47	21	42	8
Cr	18	11	32	8	23	5
Ni	< 1	< 1	8	< 1	4	< 1
Rb	38	20	25	26	42	18
Sr	466	511	551	494	544	268
Y	9	8	16	9	24	15
Zr	53	80	271	59	134	50
Nb	2	3	11	3	13	7
Ba	1021	203	121	146	187	116
La	12	20	26	21	20	16
Ce	32	46	47	44	38	32
Nd	24	20	23	4	18	4
Th	1	2	5	2	3	2
%	TNRB071	TNRB070	TNRB069	CSRB021	CSRB022	CSRB024
SiO ₂	69.41	71.36	71.41	73.52	68.62	75.20
TiO ₂	0.38	0.24	0.57	0.14	0.40	0.40
Al ₂ O ₃	15.80	14.71	14.48	13.00	16.05	12.36
Fe ₂ O ₃	1.79	1.57	1.85	1.21	1.63	1.71
MnO	0.14	0.16	0.15	0.15	0.14	0.14
MgO	0.47	0.38	0.49	0.25	0.42	0.42
CaO	5.69	5.82	5.94	5.53	6.07	6.06
Na ₂ O	3.34	2.46	2.43	2.41	3.07	1.73
K ₂ O	0.81	1.14	0.90	1.54	1.74	0.65
P ₂ O ₅	0.40	0.46	0.25	0.44	0.26	0.17
LOI	1.6	1.6	1.4	1.6	1.4	1.0
TOTAL	99.83	99.9	99.87	99.79	99.8	99.84
ppm						
V	24	19	34	9	31	26
Cr	23	9	28	6	21	20
Ni	2	<1	<1	<1	<1	< 1
Rb	33	63	45	75	73	27
Sr	361	318	371	321	386	265
Y	20	17	20	14	20	16
Zr	147	71	308	53	161	176
Nb	9	10	14	5	15	11
Ba	119	124	286	168	278	122
La	31	21	45	16	31	46
Ce	57	44	85	33	61	84
Nd	23	20	31	4	23	28
Th	6	3	10	2	6	8

Table 3e. Geochemical data for a suite of calc-silicate rocks from Ardalanish Bay, Mull

%	CS/RB/034 CS/RB/038	CS/RB/035	CS/RB/036	CS/RB/037	CS/RB/037A Metasediment	
SiO ₂	63.51	64.99	64.73	62.93	65.12	65.44
TiO ₂	0.61	0.64	0.58	0.65	0.74	0.64
Al ₂ O ₃	16.89	15.91	16.11	17.12	16.34	15.64
Fe ₂ O ₃	3.77	4.17	2.69	4.28	5.12	4.53
MnO	0.12	0.08	0.09	0.14	0.04	0.11
MgO	0.80	1.14	1.03	1.13	1.85	1.36
CaO	9.07	6.85	9.74	8.33	3.79	6.10
Na ₂ O	1.02	1.69	0.80	0.92	3.74	1.74
K ₂ O	1.51	1.97	0.94	1.68	1.81	1.52
P ₂ O ₅	0.47	0.31	0.31	0.33	0.19	0.29
LOI	1.51	1.68	1.43	1.29	0.83	1.41
TOTAL	99.28	99.43	98.45	98.80	99.57	98.78
ppm						
V	90	91	102	88	80	86
Cr	30	34	30	34	44	37
Ni	8	16	11	13	21	14
Rb	74	90	45	86	90	73
Sr	344	336	358	335	372	275
Y	34	35	32	40	28	36
Zr	182	193	166	198	189	183
Nb	16	16	13	16	14	14
Ba	151	239	102	179	307	127
La	35	37	35	37	44	40
Ce	80	84	76	83	95	84
Nd	25	30	29	36	37	28
Th	8	9	7	8	8	10
%	CS/RB/039	CS/RB/040				
SiO ₂	63.45	61.22				
TiO ₂	0.64	0.58				
Al ₂ O ₃	16.36	14.63				
Fe ₂ O ₃	3.89	3.95				
MnO	0.13	0.12				
MgO	1.13	1.09				
CaO	10.96	11.65				
Na ₂ O	0.43	0.82				
K ₂ O	0.77	0.98				
P ₂ O ₅	0.27	1.59				
LOI	1.35	2.05				
TOTAL	99.38	98.68				
ppm						
V	84	85				
Cr	37	28				
Ni	12	10				
Rb	42	51				
Sr	383	383				
Y	34	38				
Zr	244	236				
Nb	15	16				
Ba	67	108				
La	41	40				
Ce	88	86				
Nd	34	27				
Th	9	9				

Table 3f. Geochemical data for a suite of calc-silicate rocks from Uisken Bay, Mull.

%	CS/RB/044	CS/RB/046	CS/RB/047	CS/RB/048	CS/RB/049
SiO ₂	67.23	76.67	63.11	70.49	76.80
TiO ₂	0.64	0.50	0.68	0.46	0.39
Al ₂ O ₃	13.39	10.73	16.52	13.68	10.57
Fe ₂ O ₃	3.26	2.93	4.85	3.24	2.40
MnO	0.13	0.05	0.15	0.08	0.06
MgO	0.69	0.55	0.98	0.79	0.63
CaO	10.66	4.27	7.94	5.44	5.22
Na ₂ O	0.20	1.64	1.25	1.49	0.36
K ₂ O	0.31	0.34	1.07	1.05	0.67
P ₂ O ₅	0.27	0.12	0.24	0.18	0.16
LOI	2.55	1.15	2.17	2.08	1.98
TOTAL	99.33	98.95	98.96	98.98	99.24
ppm					
V	70	54	87	67	50
Cr	30	24	38	22	23
Ni	7	6	20	7	3
Rb	16	18	55	45	28
Sr	306	285	313	230	159
Y	44	20	42	32	23
Zr	330	247	181	162	149
Nb	12	11	13	11	9
Ba	45	148	117	136	74
La	51	34	38	30	25
Ce	104	75	87	68	55
Nd	35	25	32	23	19
Th	10	8	10	7	6

Table 3g. Geochemical data for a suite of calc-silicate rocks from Cannich.

%	CS/RB/050	CS/RB/051	CS/RB/052	CS/RB/053	CS/RB/054	
	CS/RB/055					
SiO ₂	60.82	71.89	70.31	73.73	74.96	70.65
TiO ₂	0.14	0.32	0.42	0.27	0.27	0.60
Al ₂ O ₃	9.28	11.54	12.05	12.86	12.23	13.23
Fe ₂ O ₃	1.35	2.30	1.87	2.37	2.27	1.98
MnO	0.14	0.10	0.10	0.06	0.07	0.10
MgO	0.19	0.17	0.47	0.66	0.56	0.55
CaO	18.13	10.38	8.48	4.99	4.15	8.33
Na ₂ O	<0.05	0.14	1.38	2.16	2.77	1.30
K ₂ O	0.06	0.17	0.69	0.97	0.97	0.25
P ₂ O ₅	0.04	0.11	0.11	0.12	0.14	0.13
LOI	9.49	2.07	3.12	0.96	0.90	1.68
TOTAL	99.69	99.19	99.00	99.15	99.29	98.80
ppm						
V	16	34	29	17	29	42
Cr	8	13	16	12	12	20
Ni	2	2	2	3	3	3
Rb	9	14	62	59	57	15
Sr	223	193	195	124	164	147
Y	25	40	40	33	43	56
Zr	69	172	248	135	122	426
Nb	5	8	11	10	10	19
Ba	9	25	94	172	154	52
La	21	36	29	18	29	44
Ce	55	88	78	46	62	107
Nd	12	21	28	15	25	36
Th	3	6	7	3	4	9
%	CS/RB/056					
SiO ₂	70.97					
TiO ₂	0.18					
Al ₂ O ₃	12.04					
Fe ₂ O ₃	0.94					
MnO	0.08					
MgO	0.20					
CaO	8.58					
Na ₂ O	2.11					
K ₂ O	0.59					
P ₂ O ₅	0.07					
LOI	3.54					
TOTAL	99.30					
ppm						
V	13					
Cr	10					
Ni	3					
Rb	38					
Sr	206					
Y	28					
Zr	63					
Nb	7					
Ba	96					
La	21					
Ce	62					
Nd	12					
Th	3					

Table 4. Rare Earth Elements for selected calc-silicate rocks.

	Mallaig	Mallaig	Arisaig	Arisaig	Arisaig	Arisaig
	CS/RB/004	CS/RB/006	CS/RB/007	CS/RB/008	CS/RB/009	CS/RB/010
La	80.4	41.4	17.6	21.6	24.0	17.4
Ce	133	77	35	42	47	34
Pr	19.9	9.7	3.8	5.0	5.3	3.6
Nd	76	36	15	18	19	14
Sm	13.3	6.4	2.7	3.2	3.1	2.4
Eu	2.90	1.70	1.01	1.13	0.79	0.67
Gd	11.4	5.6	2.5	2.9	2.7	1.9
Tb	1.67	0.87	0.40	0.47	0.43	0.33
Dy	10.00	5.42	3.11	3.11	3.02	2.12
Ho	2.06	1.10	0.76	0.59	0.68	0.46
Er	5.95	3.47	2.70	1.93	2.33	1.56
Tm	0.87	0.51	0.46	0.30	0.39	0.26
Yb	5.83	3.50	3.65	1.93	3.04	1.89
Lu	0.87	0.52	0.56	0.33	0.48	0.27
ΣREE	357	193	89	102	112	81

	Arisaig	Arisaig	Arisaig	Arisaig	Arisaig	Arisaig
	CS/RB/011	CS/RB/012	CS/RB/013	CS/RB/014	CS/RB/015	CS/RB/016
La	31.7	26.7	11.8	25.3	24.1	46.5
Ce	62	53	23	50	44	93
Pr	7.7	5.6	2.9	6.0	5.6	11.4
Nd	30	20	10	23	22	42
Sm	5.7	3.7	2.2	4.5	4.0	7.9
Eu	1.74	0.82	0.71	0.96	1.42	2.15
Gd	4.8	3.0	2.1	3.6	3.5	6.8
Tb	0.83	0.50	0.40	0.57	0.51	1.04
Dy	5.64	3.01	2.69	3.76	3.33	6.49
Ho	1.23	0.64	0.64	0.86	0.68	1.36
Er	4.26	2.11	2.16	2.73	2.07	4.12
Tm	0.71	0.31	0.34	0.44	0.31	0.58
Yb	5.19	2.26	2.30	3.19	2.04	3.86
Lu	0.77	0.34	0.33	0.47	0.30	0.61
ΣREE	162	122	62	125	114	228

	Arisaig	Lochailort	Lochailort	Ardalanish Mull
	CS/RB/017	CS/RB/019	CS/RB/020	CS/RB/034
La	23.5	17.9	19.2	37.2
Ce	46	33	39	68
Pr	5.9	3.7	3.7	8.9
Nd	22	13	14	34
Sm	4.2	2.5	2.5	6.5
Eu	1.47	1.55	1.23	2.14
Gd	4.0	2.0	1.7	5.7
Tb	0.65	0.28	0.26	0.92
Dy	4.34	1.46	1.38	5.62
Ho	0.92	0.30	0.27	1.13
Er	2.86	0.77	0.82	3.23
Tm	0.42	0.10	0.12	0.46
Yb	2.96	0.71	0.88	3.14
Lu	0.45	0.11	0.12	0.47
ΣREE	120	77	85	177

Table 4. (continued)

	Ardalanish Mull	Uisken, Mull	Uisken, Mull	Cannich	Cannich
	CS/RB/040	CS/RB/044	CS/RB/049	CS/RB/051	CS/RB/055
La	37.4	47.1	24.1	33.4	43.9
Ce	70	86	46	73	97
Pr	9.1	10.7	6.0	7.9	11.5
Nd	35	40	22	29	44
Sm	6.4	7.7	4.5	5.9	9.3
Eu	1.58	2.25	1.23	1.54	1.86
Gd	5.8	7.0	3.8	6.0	9.0
Tb	0.91	1.10	0.62	0.96	1.47
Dy	5.66	7.02	4.01	6.23	9.23
Ho	1.20	1.47	0.78	1.30	1.86
Er	3.57	4.52	2.29	3.59	5.35
Tm	0.50	0.68	0.34	0.52	0.82
Yb	3.41	4.47	2.29	3.48	5.36
Lu	0.52	0.67	0.33	0.46	0.78
Σ REE	181	221	118	173	241

	Morar	Morar	Morar
	TN/RB/078	TN/RB/081	TN/RB/083
La	44.3	45.3	47.2
Ce	93	93	96
Pr	11.3	11.1	11.7
Nd	44	45	50
Sm	7.9	8.1	9.5
Eu	1.75	2.26	1.99
Gd	6.5	7.4	9.7
Tb	0.95	1.08	1.41
Dy	5.73	6.79	8.73
Ho	1.12	1.40	1.78
Er	3.29	4.17	5.13
Tm	0.48	0.60	0.74
Yb	3.25	4.27	5.31
Lu	0.52	0.67	0.84
Σ REE	225	231	250