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Application of major- and trace-element geochemistry to refine U-Pb zircon, and Sm/Nd or Lu/Hf sampling targets for geochronology of HP and UHP eclogites, Western Gneiss Region, Norway

Kurt Hollocher,[1,*] Peter Robinson,[2] M.P. Terry,[3] and Emily Walsh[4]

[1]Department of Geology, Union College, Schenectady, New York 12308, U.S.A.
[2]Geological Survey of Norway, N-7491, Trondheim, Norway
[3]Department of Geology and Geological Engineering, South Dakota School of Mines and Technology, Rapid City, South Dakota 57701, U.S.A.
[4]Department of Geology, Cornell College, Mount Vernon, Iowa 52314, U.S.A.

Abstract

The geochemistry of kyanite and orthopyroxene eclogites (7 samples) indicate that they are gabbroic cumulates. Incompatible trace elements in these rocks occur at low concentrations compared to regionally associated eclogites that are compositionally similar to basaltic magmas (11 samples). Eclogites with cumulate protoliths commonly contain <10 ppm Zr, <1.2 ppm Sm, and <0.2 ppm Lu, compared to generally >100 ppm Zr, >4 ppm Sm, and >0.4 ppm Lu for basaltic eclogites. Because of low Zr concentrations, igneous and metamorphic zircons are rare or absent in these eclogites. Samarium and Lu concentrations are also low in the kyanite and orthopyroxene eclogites, but they have parent/daughter Sm/Nd ratios of 0.23–0.51 and Lu/Hf ratios of 0.22–0.60, higher than most associated basaltic eclogites at 0.22–0.38 and 0.11–0.18, respectively. These results suggest that kyanite and orthopyroxene eclogites are poor targets for zircon geochronologic work, but are good targets for Sm/Nd and Lu/Hf mineral/whole rock geochronology because of their high parent/daughter ratios.

Keywords: Norway, kyanite eclogite, geochronology, zircon, gabbro, cumulate, orthopyroxene eclogite, samarium-neodymium, lutetium-hafnium

Introduction

The Scandinavian Caledonides are a complex Silurian-Lower Devonian (Scandian) orogenic belt representing the multi-stage closing of part of the Iapetus Ocean (e.g., Roberts and Gee 1985). The Western Gneiss Region, Norway, is an enormous window eroded through Scandian thrust sheets, in which Proterozoic Baltican basement rocks and deep synclinal remnants of the thrust sheets are exposed (Fig. 1; Robinson 1995). Although extensive zircon geochronologic work has been carried out on eclogites in the Western Gneiss Region and related areas (e.g., Essex and Gromet 2000; Tucker et al. 2004; Krogh et al. 2004; Hacker and Gans 2005; Root et al. 2005), few high-precision ages (2σ errors of 1 to 2 Ma) have been obtained.

Kyanite eclogites are particularly attractive targets for geochronologic work because their low variance metamorphic assemblages allow more-precise determination of metamorphic conditions (Terry et al. 2000; Ravna et al. 2004). Precise geochronology, combined with good constraints on metamorphic conditions, can yield metamorphic pressure-temperature-time paths that are valuable for understanding Caledonide tectonics (e.g., Mørk et al. 1988; Gromet et al. 1996; Hacker and Gans 2005; Walsh et al. 2007). Although some kyanite eclogites have yielded zircons and have been successfully dated (e.g., Root et al. 2004; McClelland et al. 2006), an outstanding problem is that kyanite eclogites generally yield few or no zircons, and those present are very small. Why should this be?

Major- and trace-element analyses of selected Norwegian eclogite whole rocks, from deeply folded synclinal remnants of Scandian thrust sheets in the coastal part of the Western Gneiss Region (Fig. 1), explain this difficulty. The new geochemical data give insight as to which isotopic systems in addition to U-Pb zircon are most appropriate for dating different types of eclogites, and how to recognize them. This issue is important for efficient application of field and analytical efforts to understand the history of high-pressure (HP) and ultrahigh-pressure (UHP) eclogite metamorphism and tectonic evolution of the Scandinavian Caledonide mountain chain.

Kyanite eclogites and zircon: Western gneiss region

Kyanite eclogites have proven to be useful for thermobarometry, and phase relations have made it possible to estimate UHP metamorphic conditions of, for example, 820 °C and 34–39 kbar for the pristine core of a body discovered on Fjørtoft (Terry et al. 2000; Robinson et al. 2003; Ravna et al. 2004). The garnets in this body contain polycrystalline pseudomorphs after platy crystals of coesite. In addition, the omphacite in this rock contains apparently exsolved needles of quartz and hornblende. This is evidence of a possible Ca-eskola vacancy substitution (Gasparik and Lindsley 1980) combined with OH^- substitution (Terry et al. 2000, 2003; Terry and Robinson 2001) that could

* E-mail: hollochk@union.edu

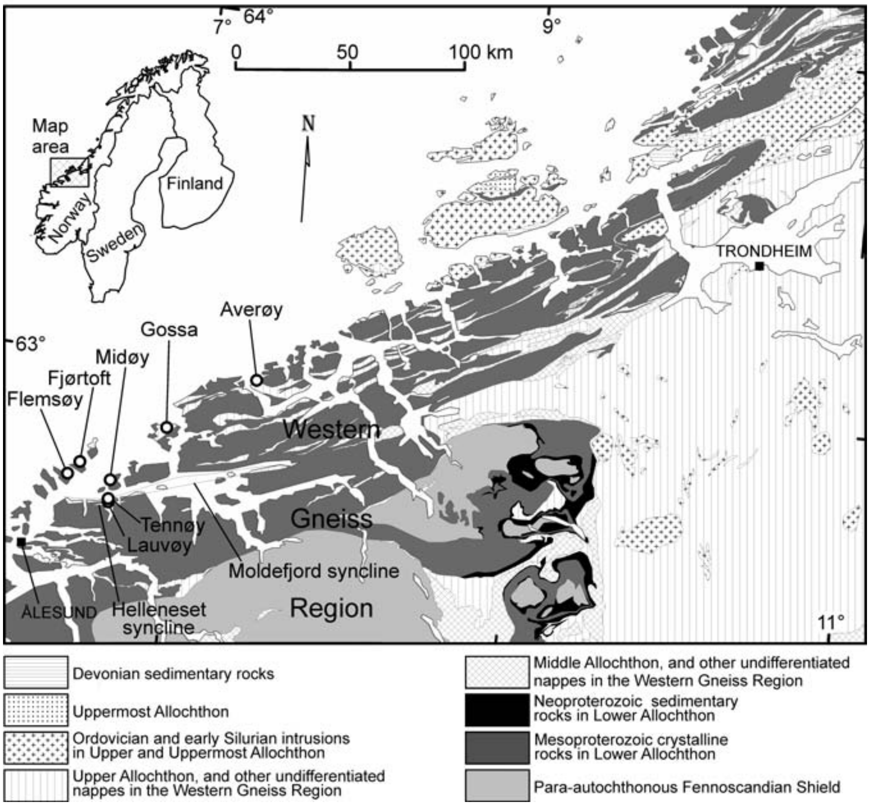

Figure 1. Geologic map of the northern part of the Western Gneiss Region, Norway. Sample locations are shown as open circles. Modified after Figures 1 and 2 in Tucker et al. (2004).

Table 1. Analytical data on eclogites in the Sætra and Blåhø Nappes

	Cumulate compositions									
Location	Gossa Island					Fjørtoft	Flemsøy	Midøy	Averøy	
Sample	205	206	207	208	209	32	1294YK	190	223	224
Nappe	Blåhø	Blåhø	Blåhø	Blåhø	Blåhø	Blåhø	Blåhø	Blåhø	Blåhø	Blåhø
Eclogite type	Orthopyroxene	Kyanite	Kyanite	Kyanite	Kyanite	Kyanite	Kyanite	Basaltic	Basaltic	Basaltic
Partial major element analyses, wt%, and molar ratios × 100										
SiO_2	48.41	45.88	48.93	47.32	49.45	47.27	44.22	47.90	47.75	47.22
FeO_{total}	11.72	6.36	5.13	5.89	4.90	5.22	7.56	13.84	10.07	8.87
MgO	20.92	13.48	10.15	11.84	10.72	11.67	8.37	6.49	8.79	10.21
CaO	7.38	12.56	15.33	14.91	16.93	14.91	14.20	8.29	11.76	12.39
Na_2O	0.20	1.15	2.23	1.13	1.83	0.84	1.00	2.87	2.83	2.83
P_2O_5	0.15	0.01	0.01	0.01	0.01	0.01	0.01	0.46	0.19	0.08
$Mg/(Mg + Fe_{total})$	76	79	78	78	80	80	66	46	61	67
Ca/(Ca + Na)	95	86	79	88	84	91	89	61	70	71
CIPW norms, vol%, major normative components only										
Plagioclase	31.1	63.9	56.1	59.2	49.7	59.6	70.6	59.2	51.9	51.5
Clinopyroxene	8.6	9.7	28.1	21.6	36.8	19.2	8.0	7.4	23.1	21.7
Orthopyroxene	44.1	2.4	–	2.4	–	4.1	–	6.7	–	–
Olivine	14.1	22.7	11.8	15.9	9.7	14.5	17.2	14.5	15.0	16.8
Total	97.9	98.7	96.0	99.1	96.2	97.4	95.8	87.8	90.0	90.0
Plagioclase An%	93	83	71	81	73	86	89	52	55	66
Trace elements, parts per million by weight										
Zr	35	1.9	4.7	3.1	6.9	4.8	11.0	138	155	53
La	0.67	0.17	0.24	0.20	0.81	1.97	2.06	22.5	7.0	1.8
Nd	2.7	0.6	1.1	0.7	2.2	3.3	5.5	29	13	7
Sm	1.19	0.23	0.53	0.36	1.02	0.76	1.55	6.35	4.08	2.59
Lu	0.22	0.05	0.09	0.08	0.14	0.06	0.17	0.51	0.41	0.33
Hf	0.98	0.08	0.22	0.13	0.31	0.18	0.53	3.53	3.80	1.80
Th	0.071	0.003	0.007	0.006	0.099	0.245	0.15	1.96	0.79	0.09
Sm/Nd	0.44	0.42	0.48	0.51	0.47	0.23	0.28	0.22	0.31	0.38
Lu/Hf	0.22	0.59	0.41	0.60	0.44	0.31	0.32	0.14	0.11	0.18
Trapped liquid %	32%	1%	4%	3%	30%	18%	26%	–	–	–

also be an indicator of UHP conditions (Liou et al. 1998; but see Page et al. 2005).

Based on the mineralogy of this rock, Terry et al. (2000) stated: "A striking feature of this sample compared with any other eclogites [then known in the region] is the high pyrope and grossular contents of garnet, low jadeite content and high [Mg/(Mg+Fe_t)] ratio of the omphacite, and the abundances of quartz, zoisite and kyanite. A most likely protolith for this eclogite was a magmatically primitive igneous cumulate rock dominated by Ca-plagioclase and Mg-rich pyroxene" (p. 1644). About the same time, Terry and Robinson located other kyanite eclogites on Flemsøya and Gossa, as well as a coarse orthopyroxene eclogite associated with the kyanite eclogites on Gossa.

In 1997, Tom Krogh initiated a program of U-Pb zircon-baddeleyite geochronology on eclogites and gabbros studied in detail by Terry and Robinson. Despite the hard work obtaining adequate amounts of zircon from some eclogites, results are reported in Krogh et al. (2004). Successfully dated rocks include the Averøy eclogite in the Blåhø Nappe (eclogite facies metamorphism at 415 ± 2 Ma, amphibolite facies overprint at ~410 Ma; Krogh et al. 2004; data shown in detail in Robinson et al. 2003). Our samples 223 and 224 come from different locations in this same body (Table 1). Unfortunately, the UHP eclogite on Fjørtoft yielded no zircon. More recently, Brad Hacker and Andrew Kylander-Clark began a program to date eclogite metamorphism in Norway using Sm/Nd and Lu/Hf, and Robinson suggested the Fjørtoft eclogite as a likely candidate. All this geochronological effort on eclogites is necessary because precise geochronology is key to understanding Scandian tectonic processes in the region.

TABLE 1.—*EXTENDED*

Basaltic compositions							
Tennøy						Lauvøy	
60	61	63	64	65	66	67	69
Sætra	Sætra	Sætra	Sætra	Sætra	Sætra	Sætra	Sætra
Basaltic	Basaltic	Basaltic	Basaltic	Basaltic	Basaltic	Basaltic	Basaltic
51.09	50.32	50.92	50.78	49.58	51.10	50.99	51.01
16.05	12.73	12.34	12.63	11.86	12.45	12.01	12.41
4.66	6.58	6.71	6.51	7.45	6.56	6.88	6.36
8.93	10.65	10.60	10.86	11.36	10.69	10.74	10.38
2.16	2.45	2.69	2.57	2.59	2.20	2.55	2.59
0.32	0.19	0.15	0.18	0.16	0.16	0.17	0.22
34	48	49	48	53	48	51	48
70	71	69	70	71	73	70	69
47.1	53.1	53.8	53.3	54.3	51.3	54.1	52.8
15.2	19.7	20.8	21.2	22.4	19.7	19.9	19.7
22.7	17.8	17.3	18.0	8.4	21.4	19.6	20.3
–	2.6	2.4	1.9	9.0	–	1.1	0.0
85.0	93.2	94.3	94.3	94.0	92.3	94.7	92.9
54	54	50	52	53	57	53	51
222	142	136	140	104	141	134	157
15.3	9.9	9.3	8.5	7.0	9.2	9.4	12.6
25	16	15	14	12	15	15	18
7.35	4.80	4.52	4.37	3.72	4.58	4.49	5.22
0.82	0.59	0.53	0.54	0.44	0.54	0.57	0.62
5.97	3.81	3.64	3.80	2.79	3.81	3.56	4.20
1.75	0.84	0.98	1.02	0.58	1.03	1.05	1.28
0.29	0.30	0.30	0.31	0.30	0.30	0.31	0.29
0.14	0.16	0.14	0.14	0.16	0.14	0.16	0.15
–	–	–	–	–	–	–	–

SAMPLES AND ANALYSES

Most of the samples reported here were collected in 2004 as part of an extensive sampling program for metamorphosed igneous rocks in various nappes in the area between Trondheim and Ålesund (Fig. 1). The dominant collection targets were amphibolites and gabbros, but a variety of eclogites, including kyanite- and orthopyroxene-bearing varieties, from the Blåhø and Sætra Nappes were also collected. We use the term orthopyroxene eclogite rather than garnet websterite (e.g., Carswell et al. 1985, 1990) because garnet + omphacite is ~70% in this rock, consistent with the definition of eclogite (Carswell 1990), and normative plagioclase is 31% (Table 1), indicative of gabbroic rather than ultramafic parentage. Major-element analyses of all samples were performed by ICP-OES at Acme Laboratory (Vancouver, Canada). Trace-element analyses were performed by Hollocher by HF pressure vessel dissolution and ICP-MS at Union College. Partial data are shown in Table 1; detailed results will be reported elsewhere.

RESULTS

The analyzed rocks were divided into probable cumulate or basaltic varieties based on bimodal distributions of several compositional characteristics (see Abstract). The distinction between these two varieties is indicated by differences in FeO (averages: 6.7 cumulate vs. 12.3 wt% basaltic), MgO (12.5 vs. 7.0 wt%), Mg/(Mg + Fe_{total}) molar ratio (77 vs. 50%), normative plagioclase composition (An_{82} vs. An_{54}), normative plagioclase + clinopyroxene + orthopyroxene + olivine (representing likely cumulus phases; 97.3 vs. 91.7%), and incompatible element concentrations (e.g., Zr, 10 vs. 138 ppm). Using CIPW volume norms as a proxy for low pressure igneous modes (Table 1), the orthopyroxene eclogite (sample 205) apparently had an olivine norite protolith, and the kyanite eclogites had olivine gabbro protoliths. The eclogites with basaltic compositions are compositionally similar to other regionally available mafic rocks in Scandian nappes, as indicated by 56 Blåhø Nappe and 67 Sætra Nappe amphibolites of basaltic composition collected from the same part of the Western Gneiss Region (to be reported elsewhere).

Figure 2 shows REE patterns for the 18 eclogites reported here. Both cumulate and basaltic types have a range of REE pattern shapes, from LREE-enriched to LREE-depleted. In all cases, however, eclogites identified as being of cumulate origin have lower MREE and HREE concentrations than any of the basaltic eclogites. The Gossa kyanite eclogites are all LREE-depleted with pattern maxima (excluding Eu) in the MREE's. This pattern shape suggests that REE concentrations in these rocks are dominated by cumulus augite. In basalt magmas, augite has a REE partition coefficient maximum in the MREE, and generally has much higher partition coefficients for the REE than plagioclase, orthopyroxene, and olivine (e.g., partition coefficients of Wood and Blundy 1997; Norman et al. 2005). The Fjørtoft kyanite eclogite is LREE-enriched, but all normalized REE values are <10 like the Gossa kyanite eclogites. Simple fractional crystallization modeling (not shown, partition coefficients of Hollocher 1993) indicates that model gabbroic cumulates have REE patterns sub-parallel to their parental liquids (exclusive of Eu). The LREE-enriched (Fjørtoft, sample 32) and LREE-depleted (Gossa kyanite eclogites) REE patterns of cumulate eclogites in Figure 2 were therefore derived, respectively, from LREE-enriched and -depleted parent magmas. Five of the six kyanite eclogites have positive Eu anomalies, not found in the basaltic eclogites, indicative of considerable cumulus plagioclase.

The Gossa orthopyroxene eclogite is LREE-depleted but has

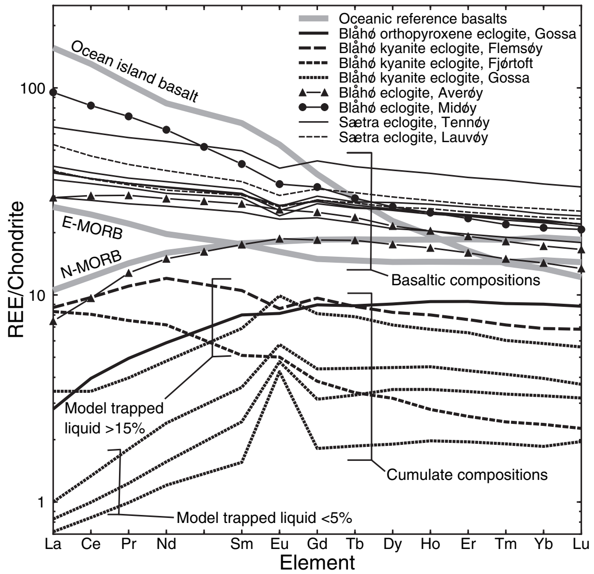

FIGURE 2. Chondrite-normalized REE patterns eclogites, including kyanite (6) and orthopyroxene (1) eclogites having igneous cumulate protoliths, and more common eclogites of basaltic composition (11). Reference lines for oceanic basalt are from Sun and McDonough (1989). Chondrite-normalizing factors are from McDonough and Sun (1995).

higher REE concentrations than most of the kyanite eclogites (Fig. 2). It is MgO-rich (20.9%) but relatively poor in CaO and Na_2O. This suggests the possibility that its high MgO content was derived from Ca-Mg exchange during high-temperature hydrothermal alteration with sea water (e.g., Humphris and Thompson 1978; Mottl and Holland 1978). Figure 3a shows, however, that this and the other cumulate eclogites are compositionally similar to common gabbroic rocks and does not plot at low Ca/(Al-Na-K) ratios as would be expected from hydrothermal sea water alteration.

If our interpretation for the cumulate origin of the kyanite and orthopyroxene eclogites is correct, then it is of interest to estimate the original proportion of trapped interstitial liquid. A highly incompatible (e.g., Pearce and Parkinson 1993), relatively immobile (e.g., Becker et al. 2000) element such as Th should occur almost entirely in the trapped liquid component of a cumulate. We find that, within a factor of two, Th concentrations in Blåhø and Sætra Nappe amphibolites of basalt composition (134 samples, including eclogites, to be reported elsewhere) can be estimated by the empirical relationship:

$$\mathrm{Th}_{\mathrm{amphibolite}} \approx 0.15\left(\frac{\mathrm{La_n}}{\mathrm{Sm_n}}\right)^2_{\mathrm{amphibolite}} + 0.58\left(\frac{\mathrm{La_n}}{\mathrm{Sm_n}}\right)_{\mathrm{amphibolite}} . \qquad (1)$$

Because model REE patterns for gabbroic cumulates (not shown) are sub-parallel to their parent magmas, we can use the La_n/Sm_n ratios in the cumulate eclogites to estimate Th concentrations in liquids parental to them. The percentage of trapped liquid in the cumulates can therefore be approximated:

$$\text{Percent trapped Liquid} \approx 100 * \frac{\mathrm{Th}_{\mathrm{eclogite}}}{\left(0.15\left(\frac{\mathrm{La_n}}{\mathrm{Sm_n}}\right)^2_{\mathrm{eclogite}} + 0.58\left(\frac{\mathrm{La_n}}{\mathrm{Sm_n}}\right)_{\mathrm{eclogite}}\right)} . \qquad (2)$$

This results in model trapped liquid ranging from 1% in sample 206 to 32% in sample 205, a range from adcumulates to orthocumulates (Table 1; e.g., Philpotts 1990, p. 247).

PERTINENCE TO GEOCHRONOLOGIC WORK

The low content of Zr (Fig. 3b) and other incompatible elements in the kyanite eclogites is consistent with cumulate origin. A mafic igneous rock with low Zr may not reach zircon saturation even under metamorphic conditions. This explains the lack of zircon in the Fjørtoft kyanite eclogite, discussed above (4.8 ppm Zr), and why zircon is difficult to find in kyanite eclogites generally. Note that mafic plutonic rock reference compositions (Fig. 2b) tend to have lower Zr concentrations than volcanic rocks, suggesting that some of the plutonic rocks are cumulates. Our kyanite eclogites overlap these plutonic rocks and extend to even lower Zr concentrations. The basaltic eclogites have roughly an order of magnitude more Zr and so are more likely to contain metamorphic zircon.

Figure 3c shows Sm concentrations and Sm/Nd ratios that are of interest for Sm/Nd geochronologic work (e.g., garnet-whole rock). Among the reference data set, plutonic rocks generally plot at low Sm concentrations and high Sm/Nd ratios compared to volcanic rocks, again probably representing a considerable proportion of cumulate rocks. Gossa kyanite eclogites and the orthopyroxene eclogite have lower Sm concentrations (0.23–1.02 ppm) than do the basaltic eclogites (3.7–7.4 ppm), but the Gossa eclogites have higher Sm/Nd ratios (0.42–0.51) than do the basaltic eclogites (0.22–0.38). Like Figure 3b, the kyanite eclogites plot in a region dominated by the plutonic rock reference set. The Flemsøy, and particularly the Fjørtoft, eclogites have both low Sm concentrations and low Sm/Nd ratios, and so represent somewhat more difficult candidates for Sm/Nd dating than do the other kyanite eclogites. High-precision geochronologic work is easiest if rocks have both high REE abundances and high Sm/Nd (parent/daughter) ratios.

Figure 3d shows Lu concentrations and Lu/Hf ratios of our samples, of interest for Lu/Hf geochronology. The plutonic rock reference set tends to plot at low Lu concentrations and high Lu/Hf ratios, relative to the volcanics, and to overlap the Gossa kyanite and orthopyroxene eclogites. The analyzed basaltic eclogites have Lu concentrations of 0.33–0.82 ppm, compared to 0.05–0.14 for the kyanite eclogites, and Lu/Hf ratios of 0.11–0.18 and 0.31–0.60, respectively. The Lu/Hf system therefore resembles the Sm/Nd system in that the kyanite eclogites have comparatively low Lu concentrations but high parent/daughter ratios.

Mafic kyanite eclogites in the Norwegian Western Gneiss Region appear to be plagioclase-rich gabbroic cumulates, with low concentrations of REE, Zr, and other incompatible elements compared to eclogites of basaltic composition. Our one orthopyroxene eclogite, interpreted to be a noritic cumulate, has intermediate trace element concentrations probably in part

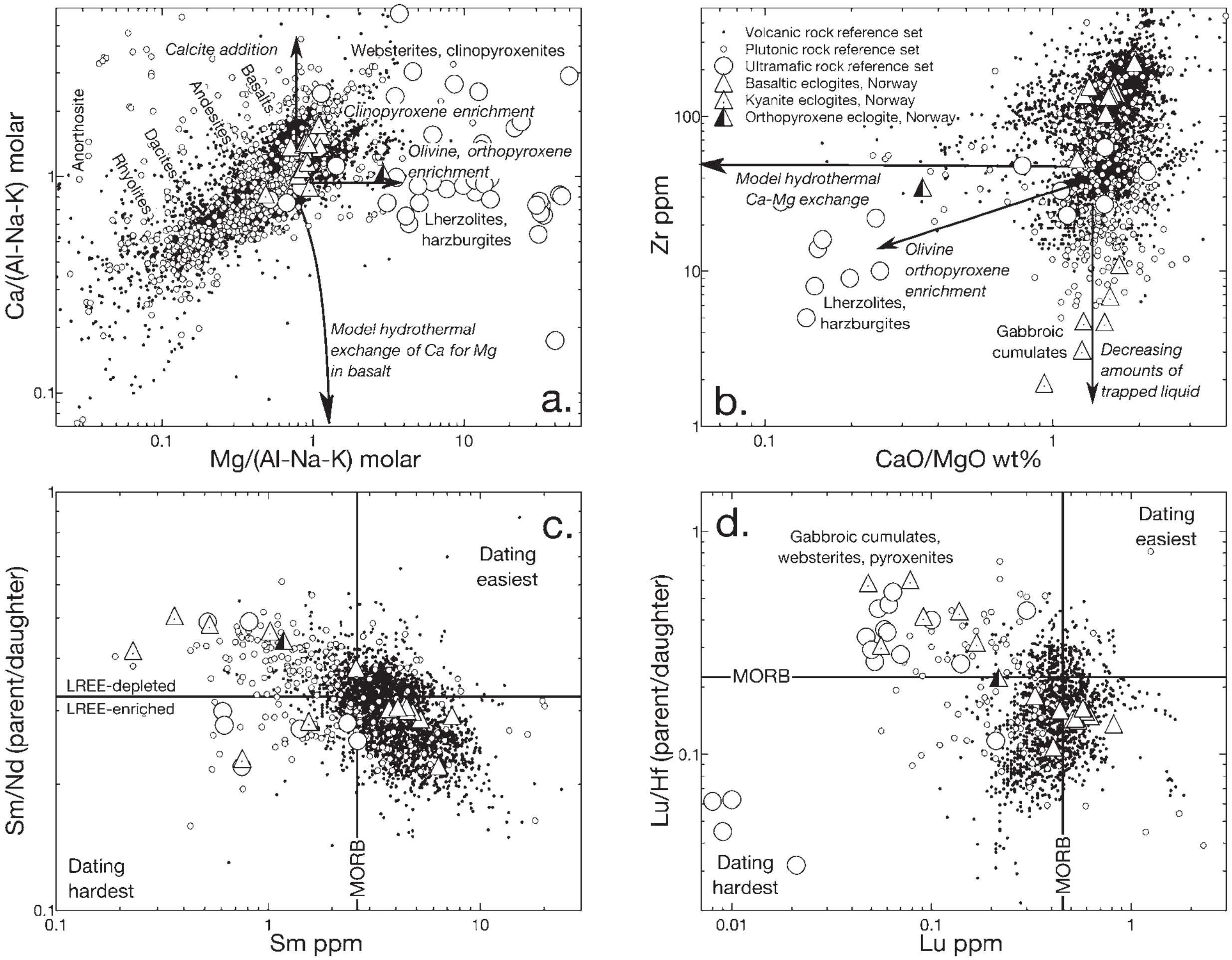

FIGURE 3. Major- and trace-element ratios of Norwegian eclogites (triangles) compared to a reference set. (**a**) Molar Ca/(Al-Na-K) vs. Mg/(Al-Na-K) ratios, illustrating the range of igneous rocks and some chemical alteration vectors. (**b**) Zirconium vs. CaO/MgO ratio, Zr being of concern for U-Pb zircon dating. (**c**) Sm/Nd ratio vs. Sm, of concern for Sm/Nd geochronology. (**d**) Lu/Hf ratio vs. Lu, of concern for Lu/Hf geochronology. The reference set includes 10 139 volcanic, 894 plutonic, and 49 ultramafic rocks from the GEOROC (http://georoc.mpch-mainz.gwdg.de/georoc/) and PETDB (http://www.petdb.org/) public compositional databases (see Lehnert et al. 2000, and references therein). These samples were selected from all major ocean ridges, from the Andes, Cascades, New Britain-Bismarck, and Mariana arcs, and from the Deccan, Columbia River, and North Atlantic flood basalt provinces. Plotted data passed a filter algorithm to exclude alkaline and altered rocks, those with total volatiles (H_2O, CO_2, F, Cl, S, LOI) >2%, a sum of the ten major oxides outside a 97–102% range after conversion of all iron to FeO, and SiO_2 outside the range of 45–78% (**a**), or 45–54% (**b**, **c**, and **d**).

as a result of a considerable original trapped liquid component. Kyanite and orthopyroxene eclogites are apparently derived from mafic cumulates and tend to have very low Zr concentrations. They therefore are poor candidates for zircon dating applications. In contrast, though these eclogites have low overall REE concentrations, their parent/daughter ratios for the Sm/Nd and Lu/Hf systems are generally higher than for most basaltic rocks. Mineralogy that can be determined in the field is therefore a useful guide to trace-element chemistry. It is our hope that this information will help with the efficient selection of eclogites suitable for particular geochronologic studies.

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