RESEARCH ARTICLE

Geochemistry and palaeogeographical setting of greenstone units on Frosta peninsula, Nord-Trøndelag, Central Norwegian Caledonides

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Volcanic and high-level intrusive rocks of the Støren Nappe exposed on the west coast of Frosta peninsula occur in two, distinct, magmatic units; the bimodal *Fånes complex* and the metabasaltic *Granheim greenstone*. North of Småland, the former unit is stratigraphically overlain by a conglomerate (Helsingplassen conglomerate) comprising clasts of Fånes rocks. Felsite clasts in this conglomerate are indistinguishable petrographically and geochemically from felsites occurring in thick sheets in the Fånes complex. South of Småland, the pillowed Granheim greenstone is unconformably overlain by the Huva conglomerate, composed largely of clasts derived from the greenstone, and in turn overlain by limestones and calcareous phyllites (Risset limestone) of Katian (Late Caradocian) age. The Granheim-Huva-Risset succession can be followed westwards onto the island of Tautra.

Geochemically, the greenstones in the Fånes and Granheim units, although both showing broadly oceanic basalt compositions, are distinctly different. The greenstones of the Fånes complex have LREE-depleted, chondrite-normalised patterns, whereas the Granheim greenstones have relatively flat REE patterns and generally higher REE contents. Both are depleted in Ta, falling in the arc basalt field on the Th–Hf–Ta diagram, but have distinct MORB-normalised Ta/La ratios. This would imply that extrusion of the original basaltic flows is likely to have occurred in a subduction-related, arc environment. The felsites in the Fånes complex have highly evolved rhyolitic compositions and plot across the boundary between ocean-ridge and volcanic-arc granites on trace element discrimination diagrams. They have LREE-enriched, chondrite-normalised patterns with marked negative Eu anomalies that resemble the REE pattern in the Fagervika trondhjemite from the Bymarka ophiolite. By analogy with Fagervika, we suggest that the bimodal Fånes complex rocks were generated in a primitive island-arc setting on recently formed oceanic crust. Zircons from a felsite sheet have yielded a U–Pb age of 488 ± 5 Ma (see accompanying paper). This Tremadocian age for the Fånes complex is similar to ages reported from fragmented ophiolites and felsic rocks of primitive arc affinity in other parts of the Trondheim Region.

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Introduction

In the Caledonides of central Norway, assemblages of mostly mafic, metavolcanic to high-level intrusive rocks occur widely in the Upper Allochthon in a series of nappes or thrust sheets known collectively as the Köli Nappes. Geochemical studies have shown that many of these magmatic units, traditionally called 'greenstones' in Scandinavia, are tholeiitic metabasalts, in places with associated, subordinate felsic rock types ranging from plagiogranite sheets and dykes to rhyodacite flows (Loeschke 1976, Halls et al. 1977, Lutro 1979, Grenne and Roberts 1980, Grenne and Lagerblad 1985, Roberts and Tucker 1998, Roberts and Stephens 2000, Roberts et al. 2002). Furthermore, some of the magmatic assemblages include sheeted mafic dykes, gabbros and even ultramafic cumulates, and are representative of fragmented and dismembered ophiolites (Gale and Roberts 1974, Grenne et al. 1980, Prestvik 1980, Furnes et al. 1985, 1988, Heim et al. 1987, Slagstad 1998, 2003, Roberts et al. 2002, Nilsson et al. 2005), some of which involve components of primitive arcs.

Initial deformation and metamorphism of these ophiolite fragments or immature arc rocks is generally tied to their obduction in Early Ordovician time prior to uplift, erosion and accumulation of Mid Arenig and younger volcanosedimentary successions in arc-related marginal basins (Roberts et al. 1984, 2002, Grenne and Lagerblad 1985). Application of U–Pb isotopic dating techniques, targeting zircons in felsic rocks, has greatly aided our understanding of the actual ages of these dismembered ophiolites or greenstone units. In the Trondheim Region of central Norway, the few, mafic to bimodal, magmatic assemblages so far dated fall in the age range from Late Cambrian (Furongian) to earliest Ordovician (Tremadocian), circa 495 to 480 Ma (Dunning 1987, Bjerkgård and Bjørlykke 1994, Roberts and Tucker 1998, Roberts et al. 2002).

Several other greenstone complexes in the Köli Nappes of this region have been studied geochemically, e.g., on Ytterøya, Inderøya and near Levanger and Steinkjer, but the results of these studies have yet to be published. Comparable magmatic units occur on the Frosta peninsula, in central Trondheimsfjord, part of which was the subject of an informal NGU report (Roberts 1982). In this contribution, we document the results of geological and geochemical studies of these rocks on Frosta. In a companion short paper, U–Pb zircon age data are presented from a felsic body within a greenstone complex, and from cobbles of felsite in a stratigraphically overlying conglomerate (Gromet and Roberts 2010).

Geological setting

The rocks of the Frosta peninsula comprise mostly middle greenschist-facies sedimentary successions of the Støren Nappe, one of several, oceanic, Köli Nappes in this part of the Norwegian Caledonides (Figure 1, inset map). The Støren Nappe is perhaps better known from the Hovin-Hølonda area southwest of Trondheim where the lower parts of the sedimentary succession contain a diverse fauna of Mid Arenig to Llanvirn age and largely Laurentian affinity (Bergström 1979, 1997, Bruton and Bockelie 1980, Ryan et al. 1980, Spjeldnæs 1985, Neuman and Bruton 1989). Higher up in the succession, faunas of Caradoc–Ashgill age are typically more cosmopolitan in character (Neuman et al. 1997), attesting to a diminished provinciality as the Iapetus Ocean contracted through Ordovician time.

In the Frosta area, poorly preserved body fossils—fragments of gastropods, stromatoporoids and corals—had been recorded from a limestone on Tautra (Spjeldnæs 1985), indicative of a Late Caradocian (Early Katian) age for that formation. More recently, pelagic, Early-Mid Katian conodonts have been recovered from the correlative Risset limestone on the mainland of the Frosta peninsula (Tolmacheva and Roberts 2007). Apart from these occurrences, trace fossil assemblages, notably the *Nereites* ichnocoenosis, have been recorded from different parts of the peninsula (Roberts 1969, 1984, Uchman et al. 2005). This particular ichnofacies is indicative of basin-plain and outer fan to fan-fringe sediments, and corroborates the interpretation of depositional environments made earlier for these dominantly turbiditic, siliciclastic rocks with interspersed submarine-channel and fan conglomerates (Roberts 1969, Pedersen 1981, Strømmen 1983). Sedimentological studies have indicated a bipolar provenance for the sediments, with volcanic arc and shelf material feeding into the elongate basin from a northwestern source (present-day coordinates) whereas largely continent–derived debris entered from the southeast (Pedersen 1981, Roberts et al. 1984).

Geology of the Småland area

Two different successions, each consisting of an oceanic igneous basement and a sedimentary cover sequence, occur, respectively, to the north and to the south of Småland on the west coast of Frosta peninsula (Figure 1). To the north of Småland, a bimodal sequence consisting mainly of mafic volcanites (greenstones) and shallow felsic intrusions (felsites) occurs in the Breivika area and extends inland and northwards to Fånesbukta (Figure 1). Directly northeast of Breivika, the rocks of this bimodal unit are in inferred tectonic contact with a thin wedge-shaped slice of higher grade, garnetiferous mica schists and minor amphibolite, quartzite and marble (Figure 1), but reappear just to the northeast and extend up to Fånes. For convenience of description we refer to this bimodal unit as the *Fånes complex*, with occasional reference to the mafic rocks as the Fånes greenstones. In the Breivika area, the bimodal Fånes rocks dip to the northeast but along strike they pass through the vertical to eventually dip eastwards southeast of Fånes. To the south and southeast, the Fånes

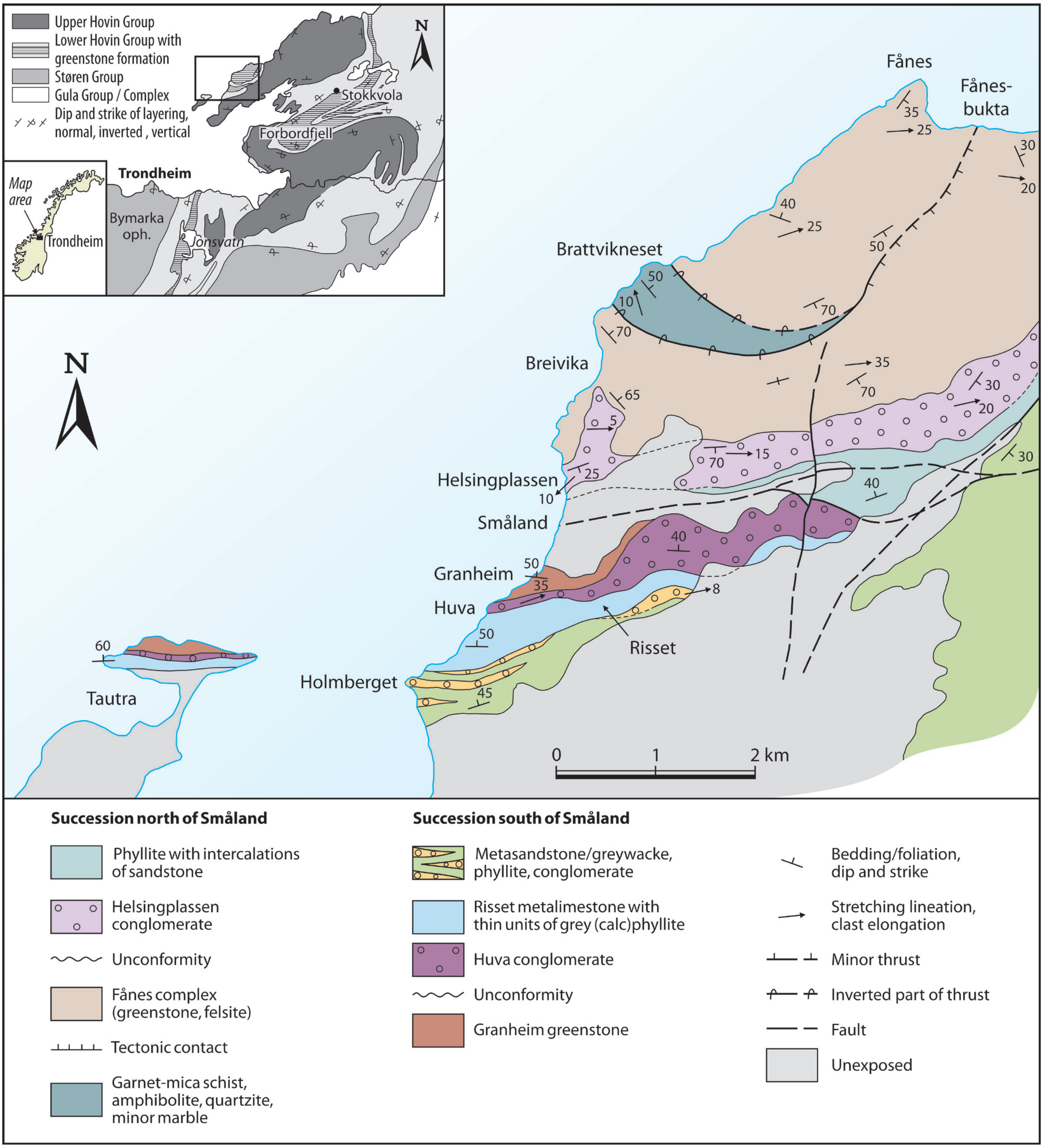

Figure 1. Simplified geological map of the southwestern part of Frosta peninsula and Tautra island.

greenstones are overlain unconformably by a polymict conglomerate containing abundant pebbles mainly of felsite and greenstone in a green-grey, silty phyllite matrix. This conglomerate is here named the *Helsingplassen conglomerate* from the locality on the coast where it is best exposed. The conglomerate is strongly deformed with highly elongate stretched pebbles up to 0.5 m in length, and with long axes trending ENE–WSW to NE–SW. Some of the clasts show an internal weak foliation at a high angle to the clast elongation, a fabric evidently acquired before sedimentation. Inland, the Helsingplassen conglomerate contains layers of green-grey sandstone with sporadic pebbles and is overlain by a thinly bedded succession of phyllite and metasandstone.

To the south of Småland, a c. 150–200 m-thick succession of metabasaltic greenstones, including pillow lavas, crops out along the coast at Granheim, and a little farther south is in contact with a deformed conglomerate—the *Huva conglomerate* of Strømmen (1983)—containing pebbles mainly of greenstone with subordinate felsite. We refer to these metabasaltic rocks as the *Granheim greenstone*. Stretched pebbles in the Huva conglomerate are up to 20 cm in length and clast long-axis lineations trend ENE–WSW. The Granheim greenstone succession dips generally to the north at c. 50° such that the conglomerate lies structurally beneath. In its coastal exposure, the Huva conglomerate is no more than 20 m thick and displays a southward fining of clast material. To the south, it is in contact with a c. 250 m-thick sequence of both pure and impure metalimestones (the Risset limestone of Tolmacheva and Roberts 2007) with thin intercalations of black phyllite. The limestone formation passes structurally down section into either a polymict conglomerate or a metagreywacke and phyllite succession. The conglomerate contains clasts mainly of metaigneous rocks and limestone, with several large, subangular, limestone clasts up to 40 cm across. Other conglomerates are exposed on the coast at Holmberget (Figure 1). These turbiditic sandstones and submarine-fan conglomerates are generally assigned to the Upper Hovin Group (Vogt 1945), locally called the Ekne Group (Kiær 1932), whereas the Granheim, Huva and Risset formations are considered to be part of the Lower Hovin Group (Roberts 1985).

The structurally highest part of the succession south of Småland, comprising the massive and pillowed Granheim greenstone, the Huva conglomerate and the Risset limestone, is also exposed on the northern part of the island of Tautra to the west (Figure 1).

Stratigraphic way-up of the successions

In coastal parts of the map area between Holmberget and beyond Brattvikneset, both the Granheim and the Fånes magmatic units, and their sedimentary cover successions, dip to the north but appear to be structurally inverted. One of the aims of this paper is to show that the magmatic units and the clasts of such rocks in the adjacent conglomerates are petrographically and geochemically similar. In addition, pillow lava shapes both at Granheim (Figure 2) and on Tautra show that the volcanites young to the south and are thus stratigraphically and structurally inverted. This is contrary to Strømmen (1983) who interpreted the volcano-sedimentary succession between Småland and Holmberget as right way up and younging to the north, putting the Granheim greenstone at the stratigraphic top of the sequence. She based this interpretation on alleged sedimentary structures in the succession south of the Huva conglomerate, such as water-escape features and inferred channelling; however, re-examination suggests a tectonic rather than sedimentary origin for some of these structures. In this same part of the area, the abundant large clasts of limestone in the conglomerate structurally below the Risset limestone also points in favour of a structural inversion of the succession.

On Tautra, some of the shelly fossils have been reported to be in growth position (Spjeldnes 1983), suggesting that the succession youngs to the north, but again the evidence for this is not convincing. In our view, the compositional similarity between the magmatic rocks and the pebbles in the conglomerates is strong evidence that the latter are derived by erosion of the former, and that the conglomerates, at Huva and Helsingplassen, unconformably overlie the two magmatic complexes. This agrees with general relationships in other parts of the Trøndelag region where polymict or greenstone conglomerates (e.g., Venna, Stokkvola, Steinkjer and Lille Fundsjø conglomerates) directly overlie metabasaltic or bimodal magmatic successions as, for example, at Forbordfjell (Figure 1, inset), c. 10 km southeast of Frosta (Roberts 1975, Grenne and Roberts 1980).

Petrography of the igneous rocks

The greenstones are massive to foliated mafic rocks (in the latter case traditionally called greenschists) consisting largely of microcrystalline albitic plagioclase, stilpnomelane, actinolite, epidote and biotite with secondary quartz, carbonate, titanite and iron oxides. The felsites are also massive to foliated rocks and range from fine grained and commonly porphyritic to medium grained with granoblastic textures. The coarser grained rocks are characterised by myrmekite intergrowths of quartz and feldspar. Quartz occurs mostly in irregular masses comprising several grains with undulose extinction and serrated grain boundaries. Albite phenocrysts are commonly subhedral, generally occurring in clusters of grains, and variably altered (sericitised). Altered (chloritised) biotites are associated with the feldspars. The matrix is mostly granular quartz with epidote, generally in clusters of small grains. Titanite and secondary iron oxides occur in irregular patches and as veins. The pebbles in the Helsingplassen conglomerate show the same variety of textures as the in situ felsites, but are generally slightly more altered and veined, and with secondary quartz and calcite.

Geochemistry

Analytical procedures

Major and trace elements of the greenstone and felsite samples were measured by XRF on fused glass beads and pressed powder pellets, respectively, at the Geological Survey of Norway, Trondheim, using common international standards for calibration. Six greenstone samples and three greenstone pebbles were analysed by Instrumental Neutron Activation for rare earth elements (REE) and the elements Hf, Ta, Th and U at the Department of Physico-Chemical Geology, University of Leuven, Bel-

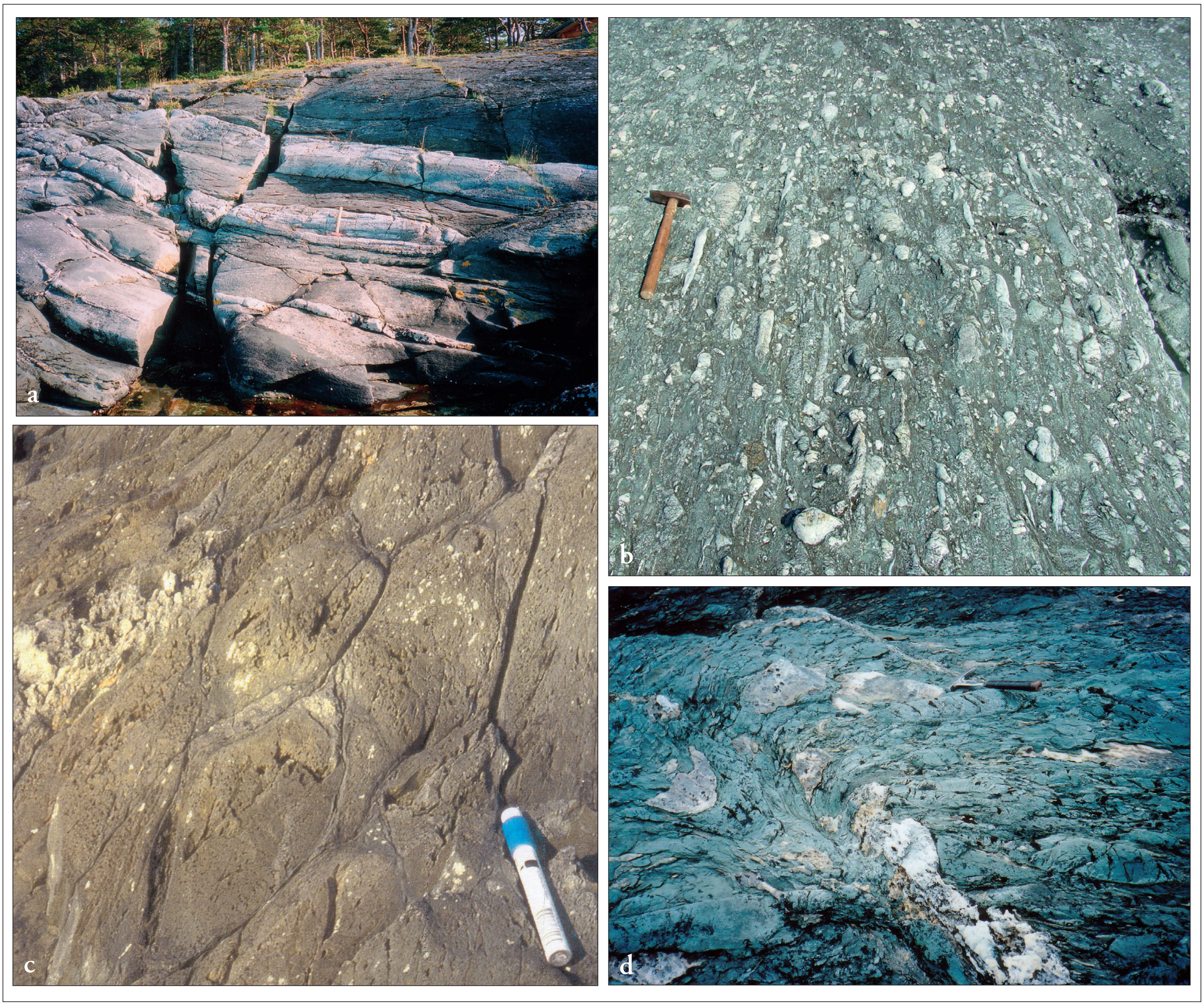

Figure 2. Field photographs. (a) Fånes complex. Concordant felsite layers (light coloured) in greenstone. The hammer is 35 cm long. Coastal exposure, Breivika. (b) Helsingplassen conglomerate with abundant elongate light-coloured felsite clasts. The darker clasts are mostly greenstone with minor gabbro. The hammer is 40 cm long. Coastal exposure at Helsingplassen. (c) Pillow lavas from the Granheim greenstones just north of the contact with the Huva conglomerate. The lavas dip steeply to the north (left), but the pillow shapes, with cuspate bases and rounded tops, show younging to the south (right). The marker pen is 15 cm long. (d) Huva conglomerate. Elongate greenstone clasts, some with transverse fractures. The light areas are folded quartz-calcite veins. The hammer is 30 cm long. Coastal exposure at Huva.

gium (analyst Jan Hertogen). REE data plus Hf, Ta, Th and U analyses were also acquired for the eight samples of felsic rocks, by laser ablation ICP–MS analysis at the Geological Survey of Norway; and at the same time three additional samples of greenstone were analysed for the same elements for comparison with the other analyses.

Major and trace element geochemistry

Greenstones

In a preliminary, unpublished geochemical study of 31 greenstones from the area depicted in Figure 1, Roberts (1982) referred to these mafic volcanic rocks collectively as the 'Frosta greenstones'. Eleven of these samples were from the Granheim greenstone and 5 of pebbles taken from the Huva conglomerate. The remaining 15 samples were taken north of Småland from the Fånes complex. The full analytical data for these 31 samples are available as an Excel file, upon request. Strømmen (1983) also reported 9 major and trace element analyses from the greenstones south of Småland and 3 analyses of greenstone clasts from the Huva conglomerate.

The mafic volcanic rocks are mostly metabasalts, possibly extending into the field of more evolved basaltic andesites, and show a range of SiO_2 contents from 45.92 to 54.35%. Both Strømmen and Roberts concluded that the 'Frosta greenstones' are predominantly tholeiitic ocean-floor basalts, based on trace element discrimination diagrams, with one or two samples showing trends toward island-arc and within-plate composi-

Table 1. Major and trace element analyses of greenstones and felsites. Greenstones: FR1 and FR10 from the Fånes complex, FR26 from the Granheim greenstone. Felsites: F5–F7 in situ; F8–F12 clasts from the Helsingplassen conglomerate.

Sample no	FR1	FR10	FR26	F5	F6	F7	F8	F9	F10	F11	F12
Easting	**589650**	**588050**	**584050**	5845500	584510	584510	584250	584250	584250	584250	584250
Northing	**7056000**	**7057100**	**7052350**	7054150	7053950	7053950	7053600	7053600	7053600	7053600	7053600
SiO_2	48.74	44.1	47.5	75.03	78.87	77.79	76.81	76.35	77.16	77.05	78.57
Al_2O_3	15.1	14.8	13.7	13.36	12.22	12.04	11.53	11.65	10.92	10.81	11.96
Fe_2O_3	13.3	13.1	12.7	2.4	1.26	1.73	2.14	1.27	1.72	1.68	0.76
TiO_2	1.87	1.4	1.81	0.34	0.15	0.19	0.2	0.15	0.15	0.14	0.15
MgO	6.23	5.21	6.99	0.47	0.19	0.12	0.12	0.09	0.24	0.22	<0.01
CaO	8.58	11.4	9.13	1.37	0.38	1.33	3.46	2.85	3.27	3.17	1.39
Na_2O	3.88	3.58	3.5	5.96	6.38	5.97	4.52	5.46	4.64	4.72	6.01
K_2O	0.08	0.08	0.11	0.24	0.09	0.05	0.08	0.07	0.06	0.06	0.06
MnO	0.12	0.17	0.18	0.04	0.02	0.02	0.02	0.02	0.03	0.03	<0.01
P_2O_5	0.15	0.12	0.19	0.06	0.02	0.02	0.03	0.02	0.02	0.03	0.02
LOI	2.22	4.17	2.72	0.49	0.35	0.33	0.62	1.24	1.23	1.22	0.32
Total	100.27	98.13	98.53	99.76	99.93	99.59	99.53	99.17	99.44	99.13	99.24
Y	41	23	28	186	141	152	161	146	126	126	258
Zr	103	56	79	50	20	59	55	58	44	42	37
Nb	1.4	0.8	2.7	4.3	3	7.1	4.6	4	3.9	3.8	4.6
La	5.6	2.5	5.4	16	14	18	11	21	14	13	15
Ce	16	8.1	15	36	33	50	32	55	39	35	45
Pr	2.5	1.4	2.2	4.3	3.1	5.9	4.1	5.7	4.3	3.8	4.6
Nd	15	8.9	12	20	13	27	20	26	19	17	20
Sm	4.6	3.3	4.1	5.3	2.9	7.5	6.2	6.8	5.5	4.7	5
Eu	1.8	1.2	1.6	0.9	0.5	1	1.1	1.1	0.9	0.8	0.9
Gd	5.3	3.7	4.6	5.2	2.7	7.3	6.5	6.6	5.2	4.6	4.4
Tb	0.9	0.8	0.9	0.9	0.5	1.3	1.2	1.2	1	0.9	0.8
Dy	6.3	4.8	5.6	6.5	3.1	9.2	8	8	6.5	6.1	5.2
Ho	1.5	0.9	1.1	1.6	0.8	2.1	1.9	2	1.5	1.5	1.3
Er	4.1	2.7	3.2	5	2.1	6.3	5.8	5.6	4.5	4.5	4.1
Tm	0.7	0.4	0.5	0.8	0.4	1	0.9	0.9	0.8	0.8	0.7
Yb	4	2.7	2.9	5.5	2.4	6.7	6.1	5.7	5.1	5.2	4.4
Lu	0.56	0.4	0.43	0.86	0.38	0.98	0.87	0.81	0.72	0.67	0.65
Hf	2.5	1.9	2.5	5.3	4.3	4.9	4.7	4.4	3.7	3.8	6.4
Ta	<0.1	<0.1	0.2	0.3	0.3	0.4	0.3	0.4	0.3	0.3	0.4
Tb	0.3	0.3	0.5	3.7	1.8	2.8	2.5	3	2.3	2.1	3.4
U	<0.3	<0.3	0.3	1.3	1	1.4	1.2	1.4	1.1	1.1	1.6

Coordinates apply to UTM Zone 32, WGS84.

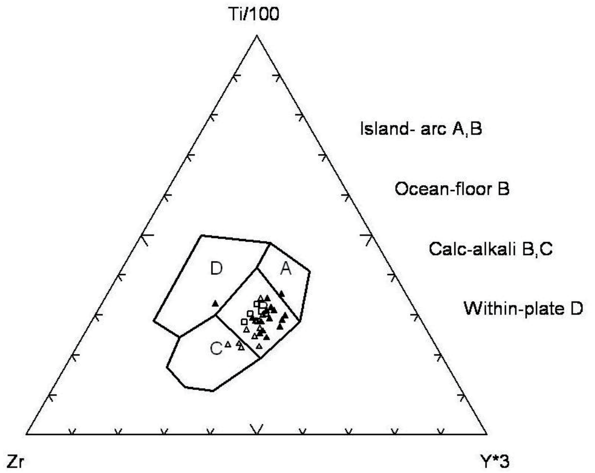

Figure 3. Ti-Zr-Y plot (Pearce and Cann 1973). Fånes greenstones: filled triangles; Granheim greenstones: open triangles; clasts in the Huva conglomerate: open squares.

tions (Figure 3), and Roberts (1982) compared them to the geochemically similar middle member of the Forbordfjell greenstones (Grenne and Roberts 1980). It was also noted that the greenstone pebbles in the Huva conglomerate are compositionally similar to the structurally overlying (Granheim) greenstone. In our present study, we have also reanalysed three of the original greenstones sampled by Roberts (1982), FR1, FR10 and FR26, with the addition of rare earth element analyses (Table 1).

Felsites

New analyses of 3 felsite samples from the Fånes complex and 5 samples of clasts extracted from the Helsingplassen conglomerate are incorporated in this study (Table 2). The felsites have high SiO_2 contents (the 3 in situ samples, F5–F7, include those with the highest (78.87%) and lowest (75.03%) values), relatively low Al_2O_3 and Fe_2O_3 and very low MgO contents. Variable CaO is partly due to secondary calcite veining, especially notable in the pebbles from the conglomerate (F8–F12). Geochemically, the felsites have typical trondhjemitic compositions, plotting in the Ab corner of the normative Ab–An–Or triangular plot (Barker 1979). Normative 'Q' is about 40% and normative 'Ab' about 50%. On an alkali-silica volcanic rock classification diagram they plot at the high SiO_2 end of the rhyolite field (Le Bas et al. 1986). However, it is possible that the silica and alkali contents have been altered by low-grade metamorphism and metasomatism. On stable trace-element, tectonic environment, discrimination diagrams they plot across the boundary between the ocean ridge granite (ORG) and volcanic arc granite (VAG) fields (Figure 4).

Table 2. Rare earth elements and Hf, Ta, Th and U contents (ppm) of greenstones from the Fånes complex (FR3, FR8, FR 13), the Granheim greenstones (FR16, FR20, FR21) and clasts from the Huva conglomerate (PEB2, PEB4, PEB5).

Sample	FR-3	FR-8	FR-13	FR-16	FR-20	FR21	FR/PEB-2	FR/PEB-4	FR/PEB-5
Easting	589250	588250	586250	584300	584150	584150	584000	584000	584000
Northing	7056050	7056200	7054700	7052600	7052550	7052550	7052350	7052350	7052350
La	4.8	2.24	2.8	4.5	6.2	5.9	6.9	7.5	7.7
Ce	15.8	7.6	8.7	13.3	18.2	16.7	18.7	20.3	19.8
Nd	14.3	8.8	8.5	10.6	13.6	12.8	15.5	15.8	14.6
Sm	4.71	3.28	3.05	3.32	3.96	3.88	4.66	4.5	4.49
Eu	1.65	1.32	1.25	1.13	1.38	1.24	1.71	1.65	1.85
Gd						4.7	5.8		
Tb	1.18	0.88	0.84	0.75	1.04	0.87	1.05	1	1.02
Yb	4.82	3.36	3.2	3.02	4	3.59	3.46	3.19	3.1
Lu	0.81	0.58	0.43	0.52	0.55	0.63	0.56	0.51	0.42
Hf	3.27	2	1.96	2.84	3.41	3.36	2.95	0.3	0.25
Ta	0.15	0.04	0.06	0.21	0.24	0.22	0.25	0.3	0.25
Th	0.6	0.39	<0.2	0.6	0.87	0.75	0.39	0.76	0.57
U	0.17	<0.15	<0.15	0.21	0.2	0.2	0.34	0.39	0.22

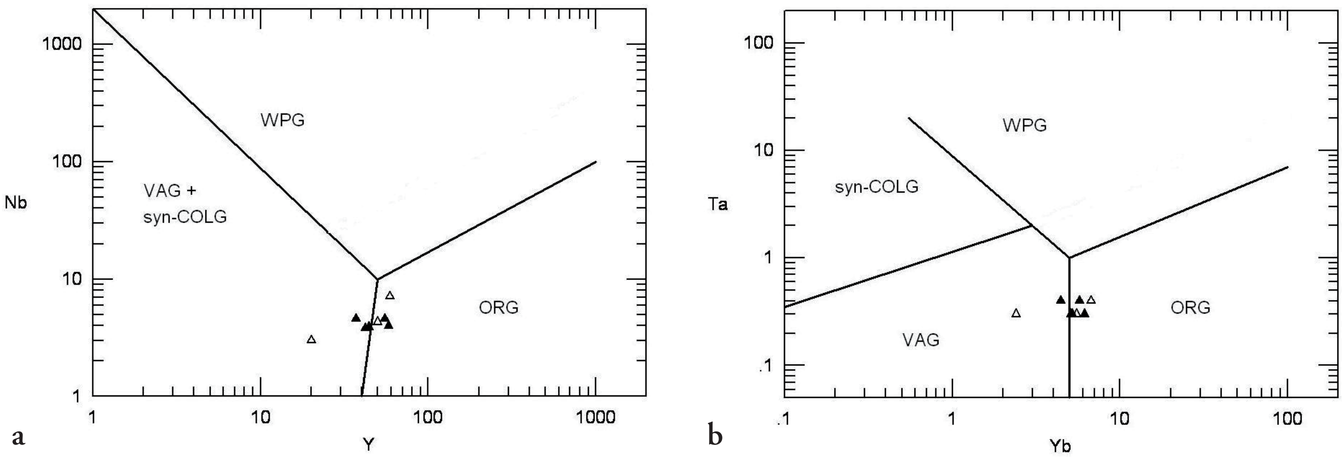

Figure 4. (a) Nb–Y and (b) Ta–Yb tectonic environment discrimination diagrams for granitic rocks (Pearce et al. 1984). Open symbols – in situ felsites, closed symbols – conglomerate clasts. ORG, Ocean ridge granite, VAG, volcanic arc granite, WPG, within-plate granite, syn-COLG, syn-collision granite.

Rare earth element geochemistry

Previously unpublished REE and Hf, Ta, Th and U analyses of six samples of greenstones (3 from the Fånes and 3 from the Granheim) and three samples of greenstone pebbles from the Huva conglomerate are shown in Table 2. On chondrite-normalised plots the greenstones have flat to light rare earth (LREE) depleted patterns (Figure 5). The Fånes complex greenstones, some of which are interbedded with the felsites, have mainly LREE-depleted patterns, whereas the Granheim greenstones have flat patterns, as do the pebbles from the overlying Huva conglomerate. According to Sun and McDonough (1989), depleted and flat REE patterns correspond broadly to N-type and E-type MORBs, respectively.

Rare earth element and Hf, Ta, Th and U analyses of the 8 felsites (3 in situ samples from the Fånes complex and 5 pebbles from the Helsingplassen conglomerate) are shown in Table 1. They have similar chondrite-normalised REE patterns with enrichment in the LREEs and marked negative Eu anomalies (Figure 6). The heavy rare earth elements (HREE) show a flat pattern. Compared to the Fånes greenstones they are enriched in the REEs, except for Eu, most markedly in the LREEs and less so in the HREEs. One of the in situ felsite samples (F6) has markedly lower contents of the intermediate and heavy REEs than the others, although the general pattern is similar; the reason for this disparity, however, is not clear.

Th, Hf and Ta analytical data

Both the Fånes and the Granheim greenstones have moderate (Granheim) to large (Fånes), negative Ta anomalies which point towards a subduction-related arc setting (Pearce 1982).

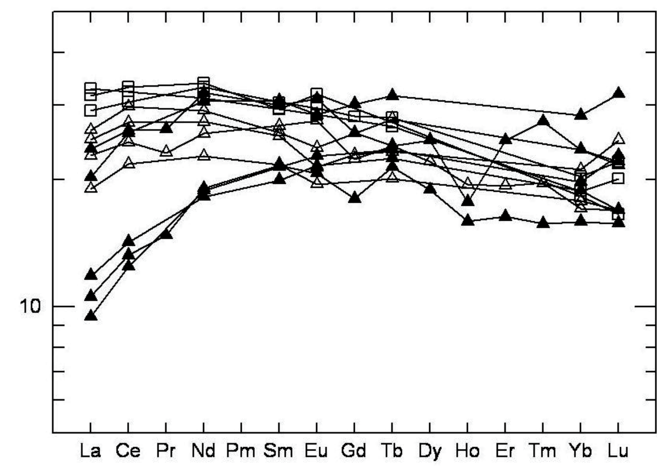

Figure 5. Chondrite-normalised REE plot of the analysed greenstone samples (normalisation values after Sun and McDonough 1989). Fånes greenstones: filled triangles; Granheim greenstones: open triangles; clasts in the Huva conglomerate: open squares.

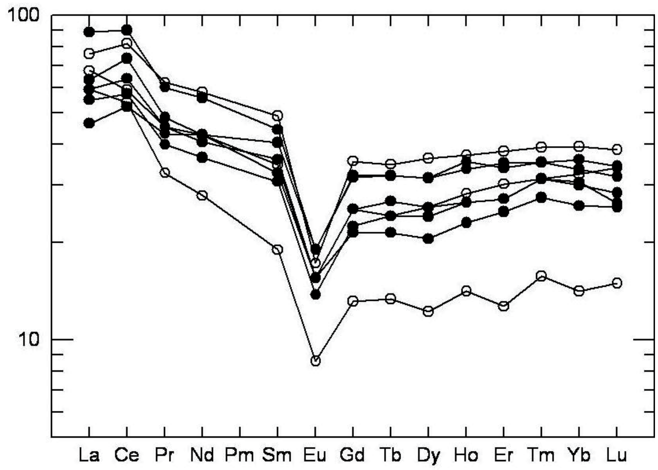

Figure 6. Chondrite-normalised REE plot of the analysed felsites (normalisation values after Sun and McDonough 1989). In situ felsites (open symbols) and clasts from the Helsingplassen conglomerate (closed symbols).

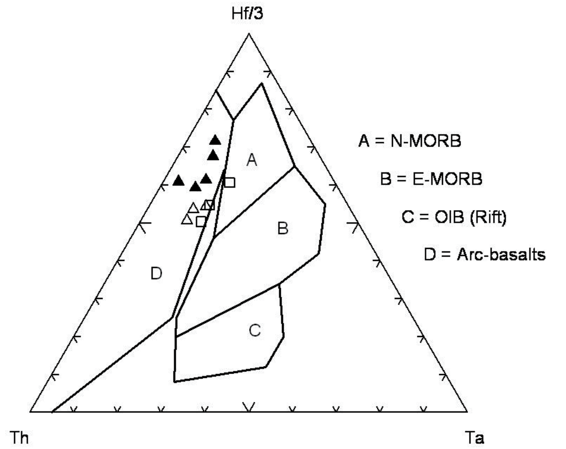

Figure 7. Th–Hf–Ta plot (Wood 1980). Fånes greenstones: filled triangles; Granheim greenstones: open triangles; clasts in the Huva conglomerate: open squares

Furthermore, the Fånes greenstones have MORB-normalised Ta/La ratios of <0.6 (range 0.34–0.59), whereas such ratios for the Granheim greenstones are >0.7 (range 0.70–0.88). On the Th–Hf–Ta plot of Wood (1980), the two greenstones plot separately, but both are located in the field of arc-related basalts (Figure 7). There is, thus, good reason, in this particular case, to dismiss the interpretation of Sun and McDonough (1989) which is based solely on REE patterns.

Discussion

Presentation of the geochemical data has pointed to a measure of uncertainty or ambiguity in interpreting the extrusive setting of these mafic volcanites. As noted above, from REE patterns alone, LREE depletion in the greenstones of the Fånes complex would traditionally favour an N-MORB origin (Sun and McDonough 1989), whereas the flat pattern of the Granheim greenstones might signify their generation as E-type MORB lavas. The felsite component of the Fånes complex, on the other hand, points to a transitional ocean floor to island arc affinity. On a Ti–Zr–Y plot (Figure 3) (Pearce and Cann 1973), both greenstones fall in the ocean floor field, yet in the Th–Hf–Ta diagram of Wood (1980) (Figure 6) they are clearly located in the field for island-arc tholeiites. As the Fånes complex is bimodal, with the felsites indicating arc involvement, then a subduction-related, primitive arc setting appears to be more likely than a non-arc scenario, moreso as the greenstones show large, negative Ta anomalies.

In comparing our geochemical data with those of other extrusive magmatic complexes in the central Trøndelag region, it is natural to look first at the Forbordfjell greenstone formation just 15 km to the southeast of Frosta (Figure 1, inset map), which has been divided into 3 members (Grenne and Roberts 1980). Trace element discrimination diagrams and chrondrite-normalised REE plots show that the middle member consists of LREE-depleted, ocean floor tholeiitic basalts, whereas the upper and lower members show flat to slightly LREE-enriched patterns and are more akin to within-plate basalts. The middle member thus shows similarities in the REE pattern to our Fånes greenstone. The Forbordfjell metabasalts have not yet been dated, but an Early to Mid Ordovician age has been inferred (Roberts 1975).

The Jonsvatn greenstones, southeast of Trondheim (Figure 1, inset), have similar compositions with both LREE-depleted ocean floor and slightly LREE-enriched 'transitional within-plate' greenstone types (Grenne and Roberts 1980). In the Trondheim area, the mafic extrusive component of the Bymarka ophiolite fragment (Slagstad 1998) comprises greenstones with mainly ocean-floor basalt affinities, as do the Løkken and Resfjell ophiolites farther to the southwest (Grenne 1986, 1989, Heim et al. 1987).

The Bymarka ophiolite fragment (Slagstad 1998) contains three distinct types of felsic rocks (Slagstad 2003). Geochemically, the Fånes felsites most resemble the Fagervika trondhjemite, inasmuch as they have similar REE patterns (Figure 8), although the latter are slightly more enriched in the LREEs. The Fagervika trondhjemite forms a large, late, cross-cutting body, interpreted by Slagstad (2003) as having been generated in an island-arc setting on recently formed oceanic crust. It is noteworthy that these rocks, like the Fånes felsites, plot on the boundary between volcanic arc and ocean floor granites on trace-element discrimination diagrams. A metarhyolite from the upper volcanic member of the Løkken ophiolite (Grenne 1989) also has a similar rare earth pattern to the Fånes felsites and is interpreted as having formed in a transitional ocean floor to island-arc environment (Grenne 1989).

The geochronology reported in Gromet and Roberts (2010) has shown that one of the felsite sheets in the Fånes complex

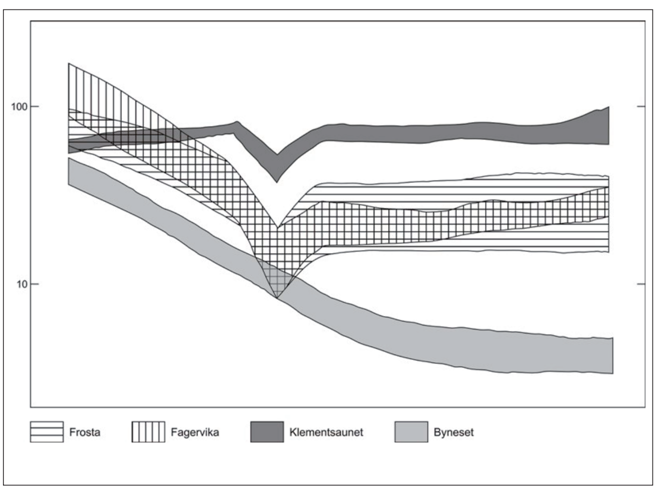

Figure 8. Comparison of the chrondrite-normalised REE patterns of the felsites from Frosta (this paper) with the Fagervika, Klementsaunet and Byneset felsic rock types from Bymarka (Slagstad 2003).

yielded a U–Pb zircon age of 488 ± 5 Ma, interpreted as the age of crystallisation. This age is indistinguishable from an age of 482 ± 5 Ma for a rhyodacite in the Bymarka ophiolite (Roberts et al. 2002). Zircons from the Fagervika trondhjemite yielded a less precise U–Pb age of c. 481 Ma. The bimodal volcanism in the Fånes complex, and at least the dated part of the Bymarka ophiolite, would then be of Tremadocian age. The age of the Granheim greenstone remains unknown. Whilst we can speculate that it may be broadly similar in age to the Fånes complex, it cannot be ruled out that it may be slightly younger, and form part of the Lower Hovin Group, as is the case for the Jonsvatn greenstone formation east of Trondheim (Grenne and Roberts 1980, Solli et al. 2003). The volcano-sedimentary succession of the Lower Hovin Group is generally regarded as having accumulated in a back-arc, marginal basin setting (Bruton and Bockelie 1980, Roberts et al. 1984).

Following the eruption of the Fånes and Granheim volcanic assemblages, a period, or periods, of uplift and erosion led to the deposition of the Helsingplassen and Huva conglomerates. Although the timing and duration of this hiatus is unknown, it is not unreasonable to suggest that, in the case of the Helsingplassen conglomerate at least, it may correspond to the Early Arenig (Floian) *Trondheim event*, during which time several of the fragmented ophiolites and arc rocks in Norway were obducted and variably metamorphosed (Roberts 2003). The pre-depositional foliation recorded in some of the clasts may conceivably relate to this event. In the case of the Huva conglomerate, which lacks a lower age constraint, another possibility for the hiatus is the younger *Ekne disturbance* (Vogt 1936), of Early Caradoc (Sandbian) age. This suggestion may be supported by the fact that the Risset limestone, which appears not far above the Huva conglomerate, is of Late Ordovician, Katian age (Tolmacheva and Roberts 2007). Alternatively, accepting just one tectonothermal and major uplift (Trondheim) event, this may conceivably imply that parts of the Middle Ordovician sedimentary record could be missing in this particular area of the Støren Nappe.

Conclusions

A partial revision of the geology of part of the coastal area of western Frosta peninsula around Småland has demonstrated the presence of two, distinctive, volcanic units, one consisting of a bimodal assemblage of greenstones and felsites (the Fånes complex) and another comprising just greenstones (the Granheim greenstone), both of which are overlain by conglomerates – the Helsingplassen and Huva conglomerates, respectively – consisting largely of clasts derived from the underlying volcanic units.
The volcanite assemblages and their sedimentary cover successions, both to the north and to the south of Småland, dip to the north, but are shown to be inverted based on the compositional and geochemical similarity between the volcanites and the clasts in the conglomerates, and also from the way-up of pillow structures in the Granheim greenstone. Greenstone clasts in the Huva conglomerate closely resemble the Granheim greenstones in their overall geochemical signature.

The Fånes and Granheim greenstones are geochemically distinct, although they plot in broadly the same fields in the Ti–Zr–Y and Th–Hf–Ta discrimination diagrams, which show features intermediate between ocean-floor and primitive island-arc basalts. The Fånes greenstones are LREE depleted, whereas the Granheim greenstones have comparatively flat, chondrite-normalised REE patterns. Both greenstones show large, negative Ta anomalies, indicative of arc involvement during their generation, but their MORB-normalised Ta/La ratios are sufficiently different to confirm their gross geochemical dissimilarities. Overall, the geochemistry of these tholeiitic metabasalts is thus suggestive of extrusion in a supra-subduction zone, arc setting.
The felsites in the Fånes complex and the felsite clasts in the Helsingplassen conglomerate are petrographically and geochemically indistinguishable. They have highly evolved rhyolitic compositions and geochemically they are most closely related to oceanic granites with arc-type geochemical signatures. In terms of extrusive setting, this would be more or less identical to that envisaged for the Fånes greenstones. Interestingly, the felsites have similar, chondrite-normalised, REE patterns (LREE enrichments and marked negative Eu anomalies) to that of the Fagervika trondhjemite from the Bymarka ophiolite – a trondhjemite which has been interpreted as having intruded in a primitive island-arc setting on recently formed oceanic crust.
In a companion paper, zircons from a felsite sheet in the Fånes complex have been U–Pb-dated at 488 ± 5 Ma, interpreted as the age of crystallisation. This Late Furongian to Tremadocian age is similar to U–Pb ages reported from felsic rocks in the Bymarka and related, fragmented ophiolites in the Støren Nappe in the vicinity of Trondheim.

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