Caledonian terrane analysis in Troms–Torneträsk, northern Scandinavia, utilizing the geochemistry of high-level metabasites

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In the Caledonides of the Torneträsk-Troms region, northern Scandinavia several thrust sheets occur above structural units representing the shortened, outermost preserved portions of the Late Precambrian–lower Palaeozoic Baltoscandian continental margin (Seve Nappes). Most are pelitic in character, with sequences of marble and amphibolite occurring at certain levels. On the basis of their position within the regional tectonostratigraphy, they are thought to represent a series of terranes that are suspect and possibly exotic with respect to Baltoscandia. Major- and trace-element characteristics of amphibolite sheets and lenses from most units above the Seve Nappes display remarkably consistent geochemical signatures. These show clear affinities with modern-day basalts from plate-margin settings, notably ocean floor basalts from a back-arc setting. Similarities in lithostratigraphy, tectonometamorphic evolution and metabasite geochemistry suggest that they represent an amalgam of exotic oceanic terranes. These were probably derived from the lower Palaeozoic Iapetus oceanic tract, outboard of their present position along the Baltoscandian continental margin. The Småtinden nappe is quite different, containing mafic dykes (now amphibolite) with a pronounced within-plate basalt geochemistry. This reinforces previously noted differences in lithostratigraphy and tectonothermal evolution, and, on this combined evidence, this unit is defined as part of a separate, interleaved, suspect terrane.

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Introduction

The Caledonides of northern Scandinavia (Fig. 1) are characterized by a series of nappes of contrasting metamorphic grade (Fig. 2) emplaced south-eastward over the Precambrian Baltic Shield and autochthonous cover sequences during the Scandian (440–370 Ma) phase of the Caledonian Orogeny (Gustavson 1966; Stephens et al. 1985; Anderson et al. 1992). The succession of nappes have been classified by Stephens & Gee (1989) as: (i) those representing the tectonically shortened margin of Baltica; (ii) suspect terranes with uncertain palinspastic affinities; and (iii) exotic terranes derived from outboard of Baltica.

Units with Baltoscandian passive margin affinities are represented by the 'Lower' and 'Middle Allochthons' according to the regional classification of Kulling (1972), Gee & Zachrisson (1979) and Roberts & Gee (1985). In central Scandinavia, these units are overlain by thrust sheets of the Seve Nappe Complex (SNC), which represent suspect terranes probably derived from the outermost portions of the Late Precambrian–lower Palaeozoic Baltoscandian continental margin (Stephens & Gee 1989). Their continuity into the Torneträsk–east Troms region is somewhat uncertain, but discontinuous units equated with the SNC have been identified (Stølen 1994a, b; Kathol 1989). As discussed by Andréasson (1994), the debate regarding whether the SNC (and equivalents) should be placed within the Middle or Upper Allochthon is ongoing and unresolved. In order to accommodate these opposing views we prefer to differentiate the SNC as a separate unit on our maps, rather than assigning it to any particular 'Allochthon'. The highest levels of the regional tectonostratigraphy, the 'Upper' and 'Uppermost' Allochthons, comprise nappes classified as suspect terranes with probable oceanic or transitional oceanic–continental affinities (Stephens & Gee 1989). Some terranes are demonstrably exotic, yielding mixed faunas unrelated to Baltica (Bruton & Bockelie 1980). Anderson et al. (1992) provide a summary of the tectonostratigraphic framework and correlations adopted for the Torneträsk–Troms region in this study (Fig. 2).

A severe limitation of terrane analysis in the Troms–Ofoten region is the lack of clear faunal or tectonometamorphic evidence on which to subdivide suspect terranes of the Upper and Uppermost Allochthons. This has led to the suggestion that (with the possible exception of the Tromsø Nappe Complex) the sequences and histories of the various nappes above the level of the Middle Allochthon are broadly related (Stephens & Gee 1989). However, even these tentative conclusions are questionable in the light of evidence for late-stage, out-of-sequence thrusts, such as the Øse thrust, within the regional tectonostratigraphy (Anderson et al. 1992).

Complementing the structural-metamorphic and $^{40}Ar/^{39}Ar$ dating work of Anderson et al. (1992), this study examines the geochemical characteristics of amphi-

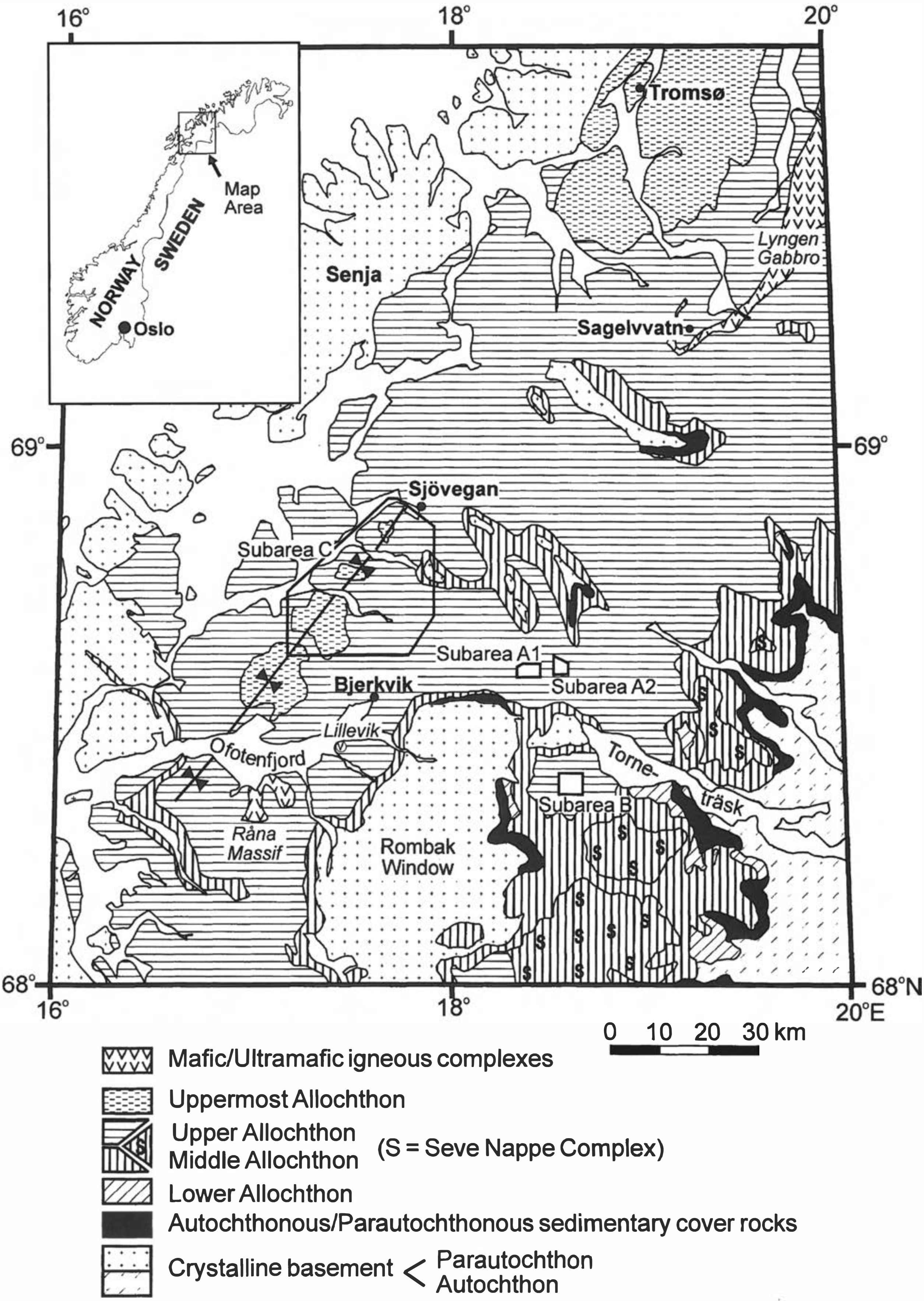

Fig. 1. Regional geological setting of the northern Scandinavian Caledonides, showing geographical location (inset) and main tectonostratigraphic subdivisions (after Roberts et al. 1981). Boxed areas A1 (Päivektjåkka), A2 (Vadvetjåkka), B (Abiskohögfjällen) and C (Gratangen–Salangen) indicate the subareas of this study (Figs. 4, 5, and 6). Major mafic/ultramafic complexes and metabasite localities referred to in text are labelled in italics.

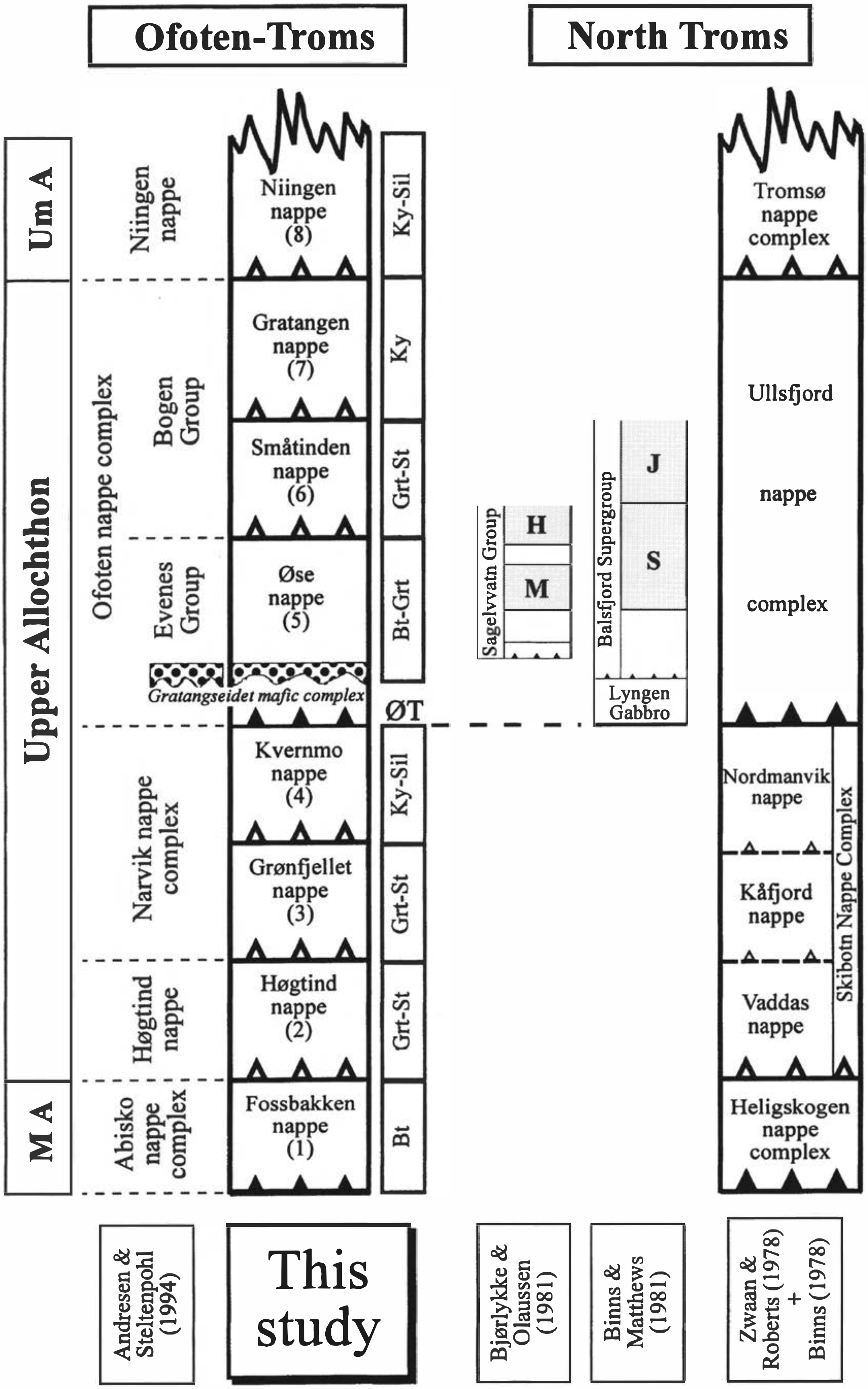

Fig. 2. Tectonostratigraphic nomenclature in the Ofoten–Troms region correlating terminology used in this study with that of previous studies. Metamorphic grade variations based principally on studies in Torneträsk–Troms area (Barker 1989), illustrated by key index minerals in meta-pelites: Bt = Biotite; Grt = Garnet; St = Staurolite; Ky = Kyanite; Sil = Sillimanite. Boundaries with 'teeth' represent thrusts. Filled circles denote unconformity above Gratangseidet mafic complex. Tectonostratigraphic abbreviations: MA = Middle Allochthon; UmA = Uppermost Allochthon; H = Hansvoll Formation; M = Mosberg Formation; J = Jøvik Formation; S = Sandøyra Formation; ØT = Øse Thrust.

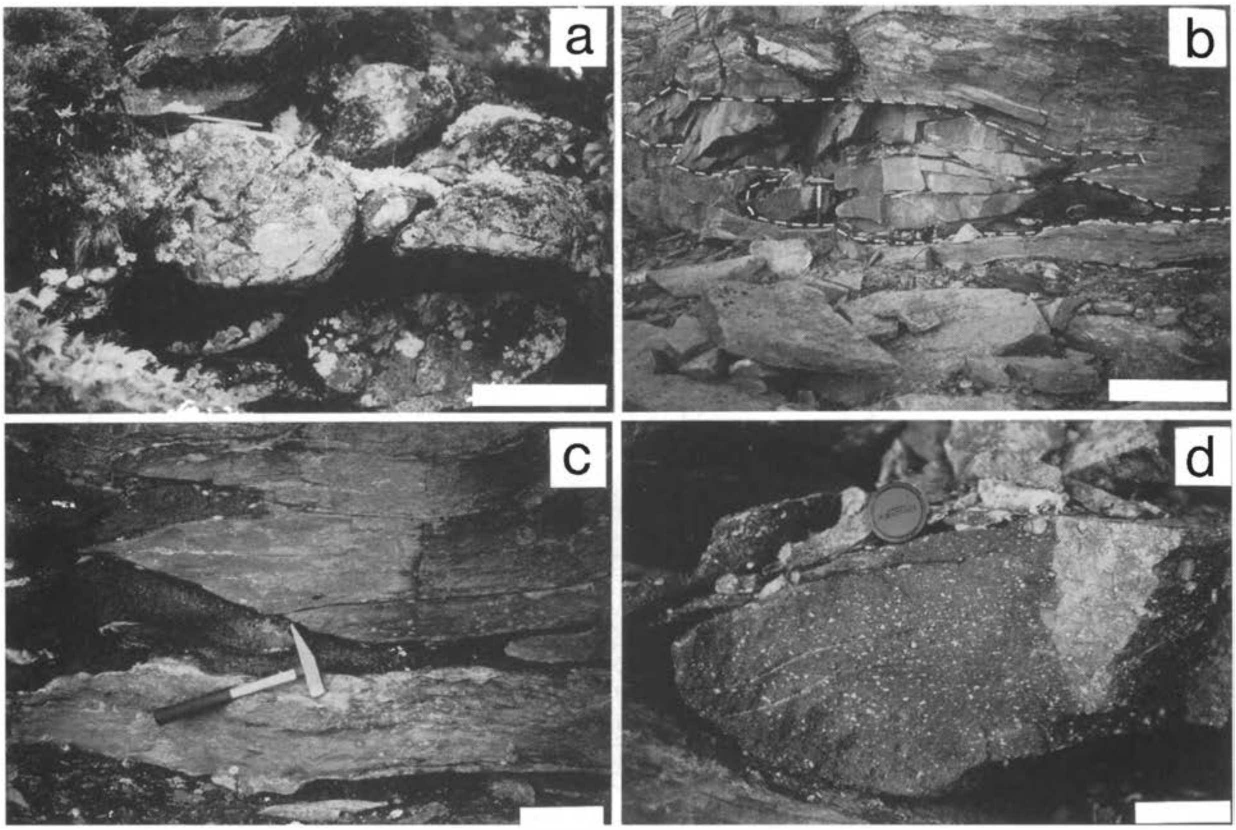

Fig. 3. (a) Pillow lavas (largely undeformed) within the Mosberg Formation of the Sagelvvatn Group, north Troms, Norway. A rare occurrence within the Caledonian nappes of northern Scandinavia. Scale bar = 20 cm. (b) Cross-cutting (deformed) lens of 'porphyritic amphibolite' (outlined by dashed line) within quartz-rich garnet-mica schist, Abiskohögfjällen (Scale bar = 1 m). Sample A9 comes from this lens (Fig. 5). Although modified substantially during Caledonian deformation, cross-cutting relationships are still recognizable with respect to compositional layering of the metasediments. The trace of the subhorizontal regional schistosity is the dominant structural feature observed in this photograph, although compositional layering, which for the most part is schistosity subparallel, can be seen in the upper part of the photograph. (c) Detail of terminations towards the right-hand side (= north) of the amphibolite lens shown in Fig. 3b. Amphibolite (dark) intrudes garnet-mica schist (paler). Scale bar = 20 cm. The subhorizontal fabric observed is the trace of the S_2 regional schistosity. (d) Porphyritic texture of the amphibolite lens shown in Fig. 3b (Scale bar = 10 cm).

bolites from various structural units within the Caledonian Allochthon of the Troms–Torneträsk region (Fig. 1). The aims of the study are to: (i) evaluate the tectonic environment of eruption/intrusion of the metabasites in each nappe; (ii) assess the nature of any variations in metabasite geochemistry between different nappes; and (iii) test whether any units contain metabasites with appreciably different geochemical characteristics that, when coupled with other evidence, give grounds for defining separate terranes.

Previous studies

Broad aspects of the geology of the Torneträsk–Troms region were established by Foslie (1949), Vogt (1950), Kulling (1964) and Gustavson (1966, 1974). More recently, numerous PhD theses have examined specific aspects of the tectonothermal evolution of the region (Bartley 1981; Hodges 1982; Barker 1984; Crowley 1985; Steltenpohl 1985; Tilke 1986; Bax 1988; Bennett 1990; Anderson 1996). Metabasites have been recognized throughout the region at various levels in the nappe pile (Bjørlykke & Olaussen 1981; Boyd 1983; Gayer et al. 1985; Barker 1986a, b; Kathol 1989; Stølen 1994a, b). Published geochemical data relating to these are reviewed below.

North Troms

From the Sagelvvatn area of north Troms (Fig. 1), Bjørlykke & Olaussen (1981) described a 20–40 m thick unit of 'greenstones' from the Mosberg Formation (part of the Sagelvvatn Group). Although locally pillowed (Fig. 3a), metabasites of this unit are mostly massive, and lie within a Llandovery age volcano-sedimentary sequence. They are considered as a lateral equivalent to part of the Øse nappe (Fig. 2). Like metabasites from higher in the Sagelvvatn Group, those of the Mosberg Formation have been shown (Bjørlykke & Olaussen 1981) to have chemical characteristics comparable to modern-day within-plate basalts (WPB).

Gayer et al. (1985) described weakly schistose, concordant metabasite sheets (max. 3 m thick) at several levels

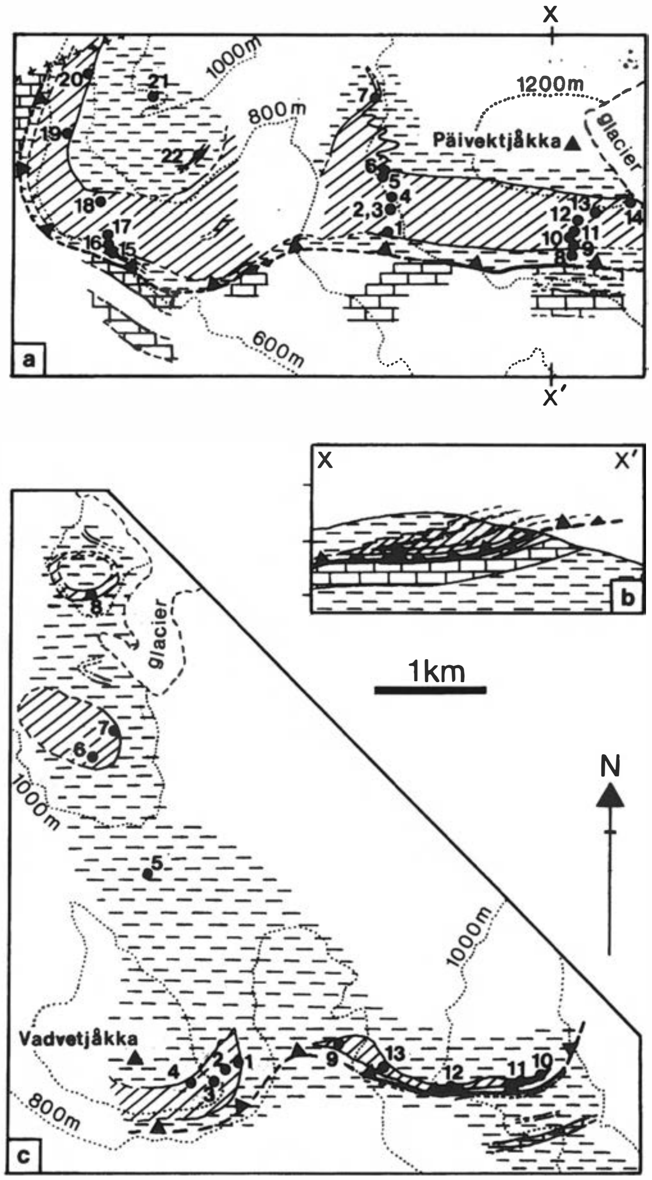

Fig. 4. (a) Geology and sample locations (P1–P22) in subarea A1 (Päivektjåkka). Diagonal striped ornament = amphibolite; brickwork ornament = marble; dashed ornament = schist (various). Saw-tooth boundary is the thrust at the base of the Grønfjellet nappe (nappe 3 in tectonostratigraphy). (b) N–S cross-section X–X' through subarea A1 showing the amphibolite unit of the Grønfjellet nappe occurring in the core of a major north-closing, recumbent, F_2 isocline. (c) Geology and sample locations (V1–V13) in subarea A2 (Vadvetjåkka). Ornamentation the same as in (a).

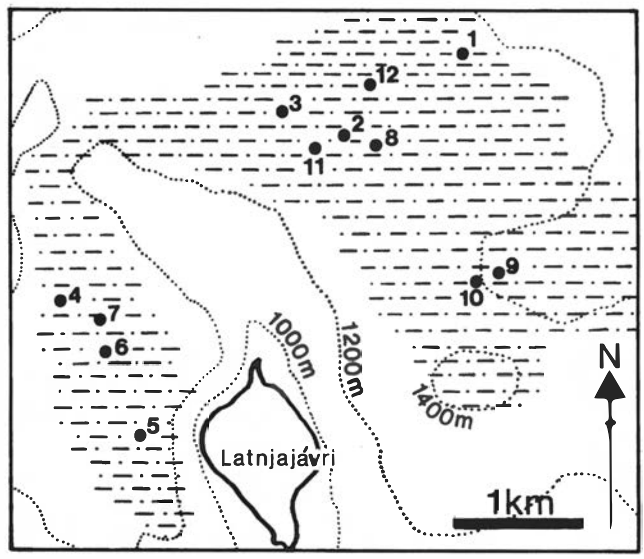

Fig. 5. Geology and sample locations (A1–A12) in subarea B (Abiskohögfjällen) in the vicinity of Latnjajávri (also see Fig. 2). Dash-dot ornament = quartz-rich garnet-mica schist (with localized lenses of amphibolite).

within the Jøvik and Sandøyra Formations of the Ullsfjord nappe complex. They are metamorphosed to greenschist or low amphibolite facies, and locally display pillow structures (Binns & Matthews 1981). Based on major and trace element data for 34 amphibolites, Gayer et al. (1985) suggested that they have transitional alkaline to tholeiitic characteristics. However, on many plots the data show a broad spread rather than a tight cluster. On the Ti/100-Zr-Y*3 plot (Pearce & Cann 1973), half the data fall in the WPB field, whereas the remainder, although probably representing ocean floor basalts or island arc tholeiites, spread from the field of low K tholeiites to calc-alkaline basalts. These amphibolites are interpreted by Gayer et al. (1985) as having weakly tholeiitic chemistry with transitional island arc/within-plate basalt characteristics.

The geochemistry of several groups of metabasites within the Skibotn Nappe Complex has also been described by Gayer et al. (1985). Of these the dominant group is a ca. 300 m thick concordant schistose amphibolite (the 'Green Beds' of Padget 1955), with locally preserved pillow structures and strong mid-ocean ridge basalt (MORB) geochemical characteristics. This group is geochemically distinct from a second group of concordant metabasite bodies within the complex which, although broadly tholeiitic, tends toward WPB on the Ti/100-Zr-Y*3 plot (Gayer et al. 1985). Several late Caledonian gabbros and basic dykes that cross-cut the main D_2 Caledonian structures constitute a third group of metabasites within the Skibotn Nappe Complex.

South Troms–Ofoten

Barker (1986b) studied metabasites from the unfossiliferous, lower amphibolite facies, Grønfjellet nappe (Fig. 2). These stratiform metabasite sheets (usually <2 m thick) form part of a volcano-sedimentary sequence, and generally have a strong schistosity. Less deformed lenses and boudin pods, however, exhibit a relict porphyritic texture. The majority of these metabasites display strong MORB characteristics, although several analyses were more akin to volcanic arc basalts (Barker 1986b).

Boyd (1983) studied the Lillevik Dyke Complex, Narvik (Fig. 1), and found that the majority of mafic dykes had MORB characteristics. He interpreted this unit as an ophiolite fragment and correlated it with the Lyngen Gabbro of north Troms. This is supported by Barker (1986a, b) who recognized a sheared mafic/ultramafic suite

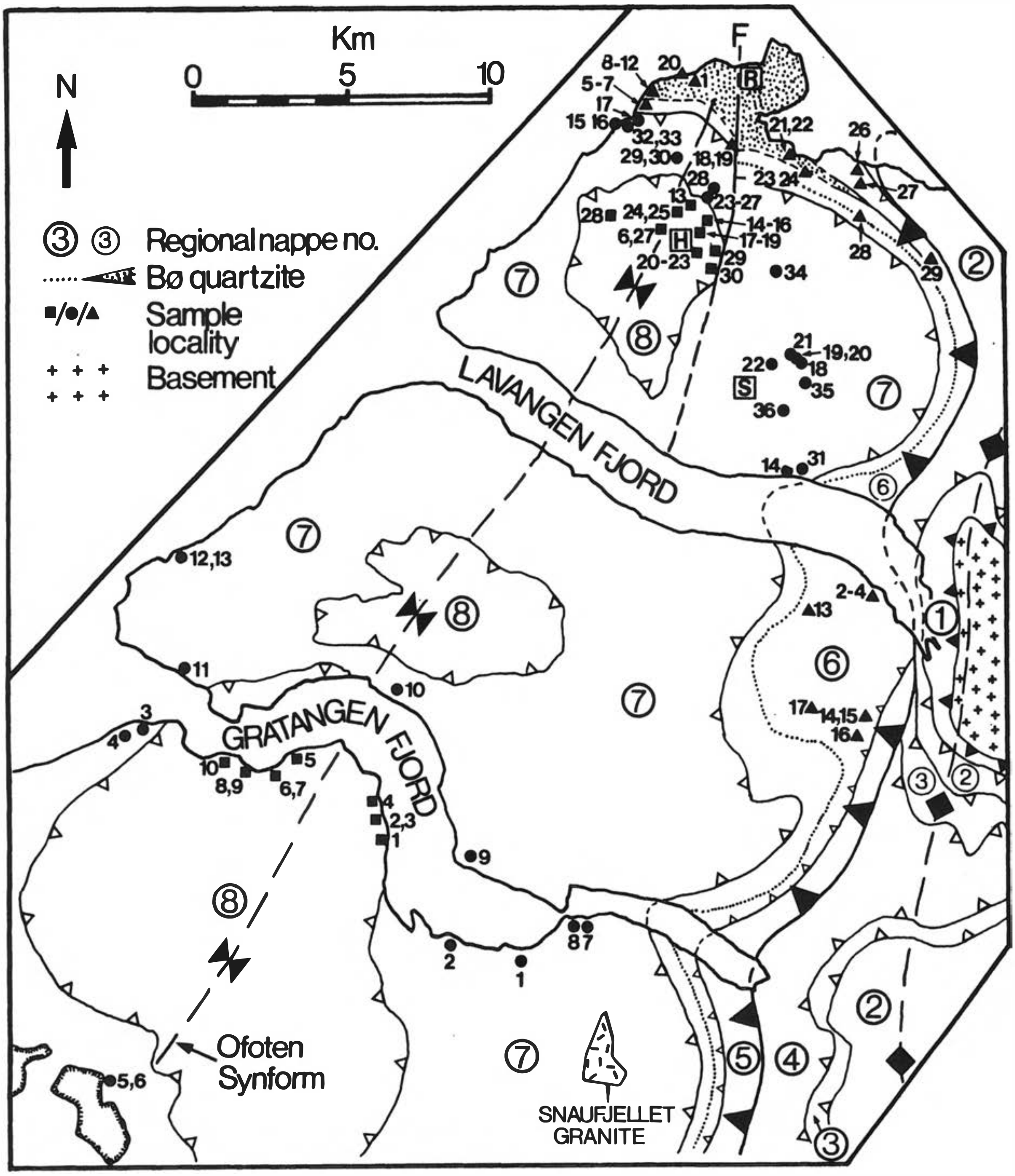

Fig. 6. Geology and sample locations in subarea C (Gratangen–Salangen). Numerical notation for nappes (circled) is same as for Fig. 2. Symbols refer to samples from different nappes: Filled triangles denote samples from the Småtinden nappe; filled circles samples from the Gratangen nappe and filled squares samples from the Niingen nappe. Abbreviations: R = Rotvika; S = Skavneskollen; H = Høgfjellet; F = late fault.

of rocks at a similar level in south Troms. Originally considered by Barker (1986a,b) to represent a discrete nappe (Gratangseidet nappe) this unit has been incorporated at the base of the Øse nappe (Anderson et al. 1992) on the basis of an unconformable relationship with overlying rocks of the Evenes Group (Steltenpohl et al. 1990; Andresen & Steltenpohl 1994). Recent radiometric age determinations (Oliver & Krogh 1995; Northrupp 1997) have shown that both the Lyngen gabbro and a lateral equivalent of the Gratangseidet mafic complex are considerably older than metabasites from the volcano-sedimentary units within nappes of this study.

East Troms–Torneträsk

Kathol (1989) presented a revised tectonostratigraphic framework for the area immediately north of Lake Torneträsk (Fig. 1), including structural levels within the Lower, Middle and Upper Allochthons. He concluded that metabasite dykes, within units correlated with the highest

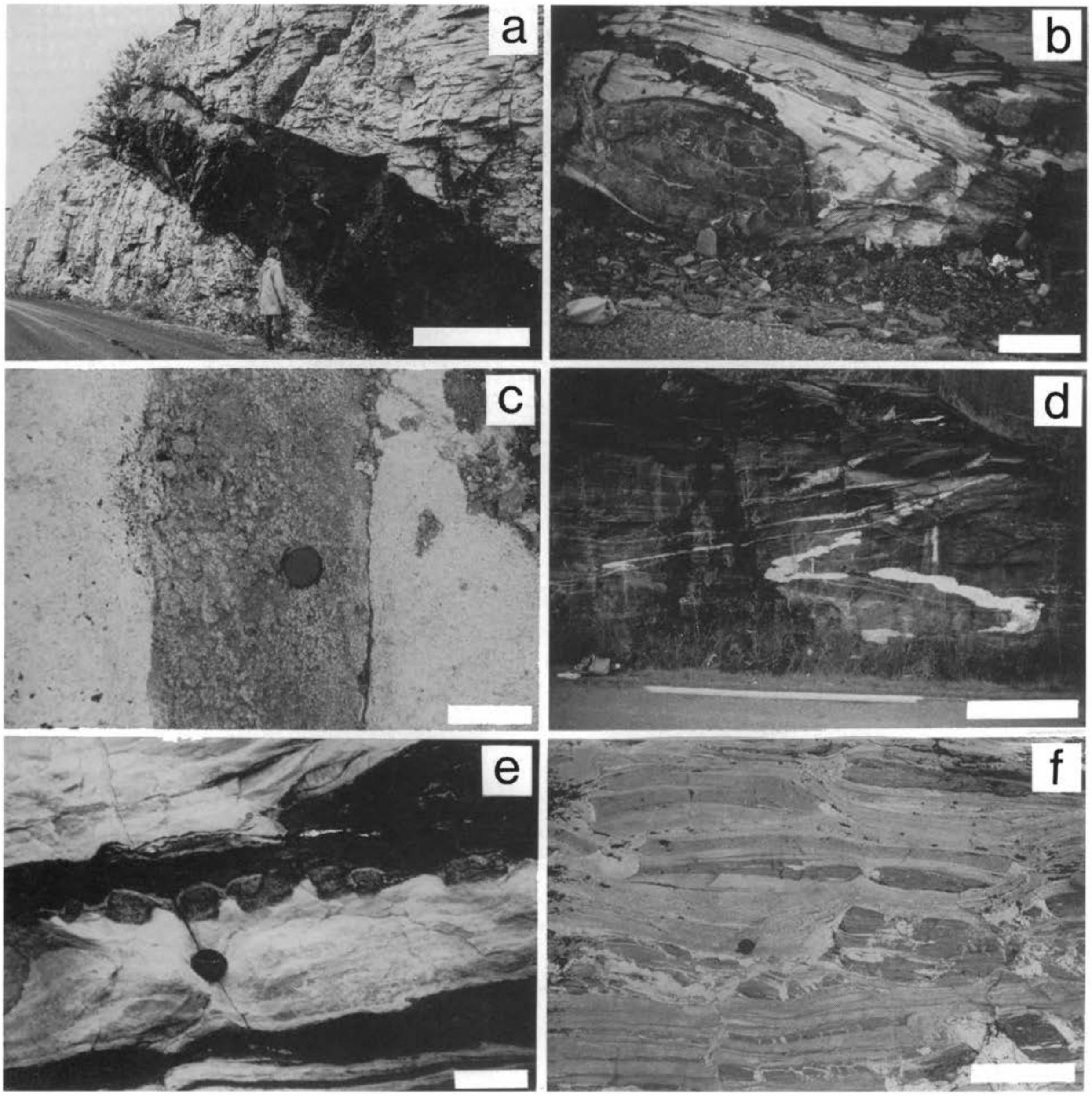

Fig. 7. (a) Cross-cutting amphibolite sheet (dyke) within quartzite of the Småtinden nappe. Scale bar = 2 m. (b) Boudinaged pods of amphibolite within garnet-mica schists of the Gratangen nappe. Scale bar = 1 m. (c) Late (post-S_2) metabasite sheet cutting the Skavneskollen Granite, within the Gratangen nappe. Scale bar = 10 cm. (d) Folded and boudinaged quartzo-feldspathic/trondhjemitic dykes cross-cutting pelitic and semi-pelitic gneisses at the base of the Niingen nappe (south side of Gratangenfjord). Scale bar = 2 m. (e) Rare occurrence of amphibolite sheets (dark) interbanded with marble (white) and diopside-rich calc-silicate layers (boudinaged) within the Niingen nappe (south side of Gratangenfjord). Scale bar = 10 cm. (f) Boudin pods of amphibolite (dark) within gneisses of the Niingen nappe. Scale bar = 30 cm.

structural levels of the Seve Nappe Complex of central Scandinavia, had a tholeiitic MORB geochemical signature and probably represented parts of the Late Proterozoic Baltoscandian passive margin. In east Troms, at an identical structural level, Stølen (1994a, b) describes similar metabasite dykes, reinforcing the interpretation of a rift-related origin with REE data.

Field relationships

In the present study metabasites have been examined from four nappes in three subareas (Fig. 1). The field relationships are described below.

Subarea A – North-west Torneträsk

Mapping has shown that the amphibolites exposed in the Vadvetjåkka and Päivektjåkka areas of Sweden (Fig. 4) are a continuation of the Grønfjellet nappe of Barker (1986a, b). The unit comprises rusty weathering graphitic schists towards the base, succeeded by interbanded 'pin-striped' amphibolites, garbenschiefer and garnet mica schist. A few laterally continuous amphibolite sheets attain thicknesses

Table 1. Summary of whole-rock major and trace element analyses for each subarea and structural unit of the Torneträsk–Troms region. LOI refers to calculated loss of volatiles during ignition. FeO* total iron recalculated from Fe_2O_3. Major and trace element analysis was carried out at the University of Southampton using a Phillips PW1400 XRF spectrometer (< indicates analysis at or below lower limit of detection).

	Subarea A		Subarea B		Subarea C					
	Grønfjellet nappe				Småtinden nappe		Gratangen nappe		Niingen nappe	
	Mean ($n = 35$)	SD	Mean ($n = 12$)	SD	Mean ($n = 29$)	SD	Mean ($n = 36$)	SD	Mean ($n = 30$)	SD
SiO_2	48.46	0.98	49.84	2.55	48.75	1.24	49.04	1.82	49.67	1.64
TiO_2	1.57	0.25	2.28	0.76	2.96	0.71	1.40	0.52	1.22	0.44
Al_2O_3	15.33	0.77	14.92	1.62	13.78	0.99	14.76	1.98	15.94	0.95
Fe_2O_3	12.38	1.15	13.36	1.92	15.19	1.67	12.19	2.49	11.06	1.04
MnO	0.18	0.02	0.22	0.03	0.22	0.03	0.21	0.06	0.19	0.02
MgO	7.39	0.95	6.32	1.26	5.83	0.90	7.97	2.41	8.26	0.99
CaO	11.61	1.54	10.18	1.64	9.43	1.07	10.88	1.80	10.91	1.10
Na_2O	2.78	0.83	2.20	0.43	2.63	0.66	2.44	1.05	2.26	0.77
K_2O	0.26	0.13	0.41	0.15	0.60	0.27	0.62	0.59	0.52	0.23
P_2O_5	0.13	0.03	0.22	0.11	0.45	0.30	0.20	0.18	0.11	0.08
Cr	229	63	154	82	178	104	312	231	364	118
V	312	45	373	52	339	57	278	96	252	69
Ba	83	102	58	19	131	140	148	404	57	36
La	6	3	7	5	22	16	9	8	8	11
Ce	<		<		33	15	18	20	<	
Pb	4	7	15	5	12	5	11	15	6	3
Th	<		<		<		<		<	
Rb	<		6	6	18	19	12	24	6	7
U	<		<		<		<		<	
Sr	195	47	197	158	335	127	251	158	178	84
Y	32	6	59	23	44	19	34	11	30	5
Zr	97	18	191	91	192	53	108	48	89	31
Nb	6	2	6	2	20	8	7	5	5	4
Ga	21	1	24	3	27	3	20	4	19	3
Zn	95	9	126	27	148	34	156	339	85	14
Ni	92	32	58	20	64	26	100	55	104	28
LOI	N/A	N/A	N/A	N/A	1.52	1.28	0.59	0.72	0.26	0.24
FeO*	11.14	1.04	12.02	1.73	13.67	1.50	10.97	2.24	9.95	0.93

of up to 10–15 m, whereas thinner bodies (<1 m thick) typically occur as isolated boudins. In the Ståktjekvare-Paivektjåkka area the main amphibolite unit attains a thickness of 150 m, where it forms the core of a major F_2 recumbent synform (Fig. 4b).

Subarea B – South-west Torneträsk

In the Abiskohögfjällen region (Fig. 1), isolated lenses of amphibolite occur around Latnjajávri within a monotonous unit of quartz-rich garnet mica schist (Fig. 5). These amphibolites are situated at a comparable structural level to similar rocks from the Grønfjellet and Vadvetjåkka areas. They overlie thick bands of 'flat-lying' marble and garnet-mica schist exposed on the slopes of Njulla (5 km to the east), directly correlated with the Høgtind nappe of south Troms. However, the thick amphibolites characteristic of the Grønfjellet nappe in the type area and adjacent regions are absent from Abiskohøgfjällen, and indeed no thrust equivalent to the Grønfjellet thrust (Barker 1986a) has been recognized. The amphibolite of Abiskohøgfjällen occurs as isolated pods or discontinuous lenses, derived from boudinaged sheets. Typical dimensions in outcrop are 1 m × 3 m, the largest being about 2 m × 5 m (Fig. 3b). Cross-cutting relationships in this area (Fig. 3c) indicate that the dismembered sheets originated as dykes. In outcrop, the amphibolites of this region comprise both the 'pin-striped' and 'porphyritic' types (Fig. 3d) described by Barker (1986b) from a similar tectonostratigraphic level in nearby Norway.

Subarea C – Gratangen–Salangen

Småtinden nappe. – The Småtinden nappe has been mapped between Bjerkvik and Sjøvegan (Fig. 1), and is particularly well exposed in the north of subarea C around Rotvika (Fig. 6). Amphibolites are locally present throughout the unit, the majority occurring as strongly schistose lenses and thin sheets (max. 3 m thickness) that appear concordant with the regional S_2 schistosity.

Clearly discordant dykes account for 8 of the 29 samples from the Småtinden nappe (Fig. 7a). Angular discordance of up to 25° is preserved between dyke margins and compositional layering in the country rock. Such discordant metabasites are only observed within the Bø Quartzite where it is greatly thickened around Rotvika. Most metabasites within the Småtinden nappe are probably intrusive, but the intensity of shear within less competent, pelitic lithologies has obliterated original relationships.

Table 2. Correlation coefficients (r) from linear regression analyses of major and trace element concentrations against Zr for nappes within each subarea. Also shown are the critical values of 'r' for each data set when tested at 1and 5% significance levels. Figures in bold are those that exceed critical values at 1% level of significance. Elements in bold are those considered to be immobile for the purposes of this study (see text for explanation).

	Grønfjellet nappe ($n = 47$)	Småtinden nappe ($n = 29$)	Gratangen nappe ($n = 36$)	Niingen nappe ($n = 30$)
SiO_2	**0.4220**	−0.1878	0.1036	−0.0970
TiO_2	**0.9698**	**0.8142**	**0.7033**	**0.8417**
Al_2O_3	**−0.6306**	**−0.5105**	−0.2229	−0.2313
Fe_2O_3	**0.6782**	**0.8166**	0.3023	**0.6175**
MnO	**0.5751**	**0.5553**	0.0765	0.2086
MgO	**−0.6127**	**−0.7976**	−0.3218	**−0.7104**
CaO	**−0.6010**	−0.4113	−0.2018	−0.4213
Na_2O	−0.2942	−0.4382	−0.1049	**0.6031**
K_2O	0.2322	−0.0307	0.2463	0.1658
P_2O_5	**0.9086**	**0.7504**	**0.6102**	**0.9106**
Cr	**−0.7027**	**−0.4904**	−0.0062	−0.3751
V	**0.6897**	−0.1191	0.1695	−0.0892
Ba	−0.0634	−0.1071	0.2536	**0.4962**
La	**0.4187**	0.4599	**0.4773**	0.3461
Ce	<	<	**0.4990**	<
Pb	0.4178	−0.0886	0.0490	−0.0503
Rb	<	0.1436	0.2626	0.0551
Sr	−0.1858	0.0772	0.2509	**0.5230**
Y	**0.9861**	**0.5225**	**0.5292**	**0.6267**
Nb	**0.4064**	**0.8038**	**0.5849**	**0.8930**
Ga	**0.8252**	**0.7335**	**0.6513**	0.1996
Zn	0.0531	**0.5619**	0.0602	0.4259
Ni	**−0.5978**	**−0.6292**	−0.2975	−0.4395
		Critical 'r' values (5% and 1% significance levels)		
5%	0.2876	0.3673	0.3291	0.3610
1%	0.3721	0.4705	0.4238	0.4629

Gratangen nappe. – The Gratangen nappe outcrops over an extensive area in the coastal region of south Troms and Ofoten (nappe 7 of Fig. 6). Metabasite dykes have been described from an equivalent unit in west Ofoten (Steltenpohl 1985; Steltenpohl et al. 1990) although these are relatively uncommon in the present study area. Concordant sheets and boudin 'trains' (Fig. 7b) are more typical of metabasite bodies in the Gratangen–Salangen area. Some sheets are 8–10 m thick, but more characteristically they are less than 2 m thick. The XZ dimensions of amphibolite pods are typically 1.0×0.15 m to 4.0×1.0 m, although large pods up to 7.0×3.0 m are occasionally encountered. Most amphibolites are of the schistose 'pin-striped' type but several pods show relict 'porphyritic' texture. Although modified during metamorphism, it is clear that the original phenocrysts were of calcic plagioclase and constituted about 5–10% of the rock. Many amphibolites contain significant amounts of biotite, at least partly from alteration of amphibole.

Most metabasites in the Gratangen nappe appear concordant with the compositional layering of interbanded marble and pelitic schist (gneiss). All of the metabasites sampled displayed sharp boundaries with adjacent lithologies and thus represent original lavas, sills or highly sheared dykes.

Others mafic rocks (not sampled) include those which display transitional contacts with interbanded garbenschiefer, pelitic and calcareous lithologies, possibly representing tuffaceous horizons, and an isolated coarse grained 'stock-like' mafic body in the Skavneskollen area (Fig. 6). The latter intrudes a foliated Caledonian granitoid and has amphibolite dyke offshoots (Fig. 7c) cross-cutting S_2 and the contact between granite and schist.

Niingen nappe. – The Niingen nappe of the Gratangen–Salangen area (Fig. 6) is a kyanite-sillimanite grade unit dominated by pelitic and semi-pelitic gneisses. Deformed granitoid sheets and megaboudins are common throughout, and locally migmatite complexes have been recognized (e.g. Høgfjellet area, Anderson 1996). Folded and boudinaged quartzo-feldspathic dykes cross-cut pelitic and semi-pelitic gneisses at many localities (Fig. 7d). Within these gneisses, seemingly concordant, thin (<2 m) schistose amphibolite sheets are locally present. In rare cases, they are interlayered with thin (<1 m) units of white calcite marble and associated diopside-rich calc-silicate rock (Fig. 7e). More commonly, the amphibolites occur as boudin pods (Fig. 7f), comparable in size to those of the Gratangen nappe. Most are strongly schistose although a few retain a relict porphyritic texture (feldspar phyric).

Petrography

Amphibolites from the Grønfjellet nappe have a consistent epidote-amphibolite to low amphibolite-facies assemblage of hbl + pl + qtz + ep + rt/ilm ± bt. Features of retrogression are uncommon although coronas of sphene around

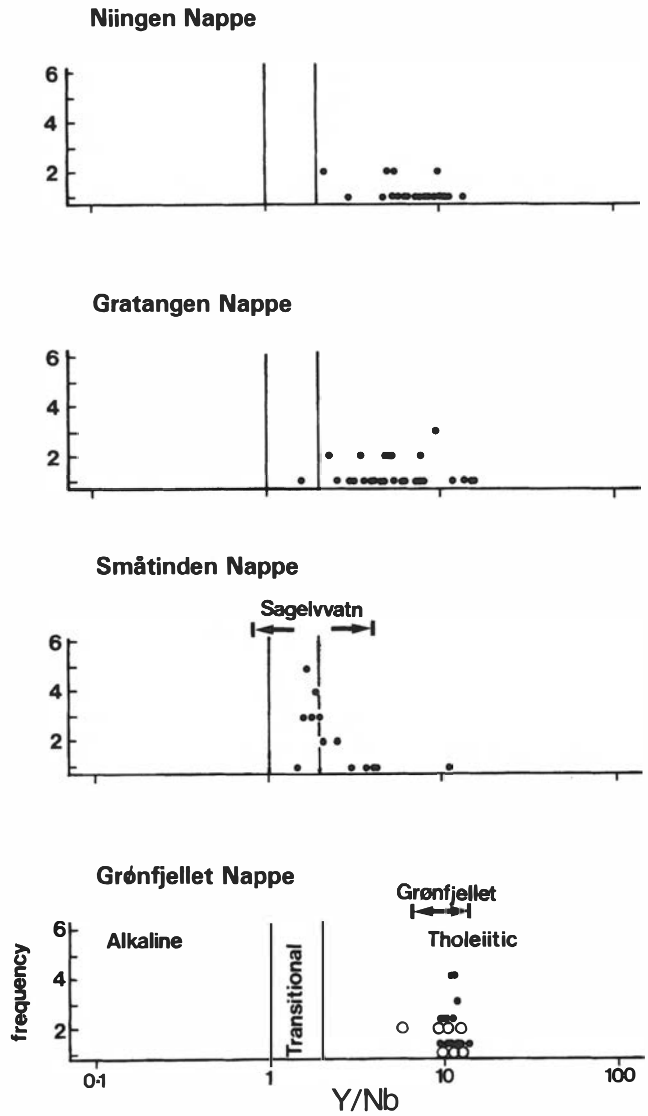

Fig. 8. Plot of Y/Nb (after Pearce & Cann 1973) to distinguish tholeiitic from alkaline basalts. Frequency denotes number of samples falling within any particular Y/Nb class interval (class interval = 0.5). For Grønfjellet nappe: open circles = samples from subarea A; filled circles = samples from subarea B. The range of values obtained from metabasites of the Grønfjellet area (Barker 1986b) and Sagelvvatn area (Bjørlykke & Olaussen 1981) is shown as shaded areas on the plots for the Grønfjellet nappe and Småtinden nappe respectively.

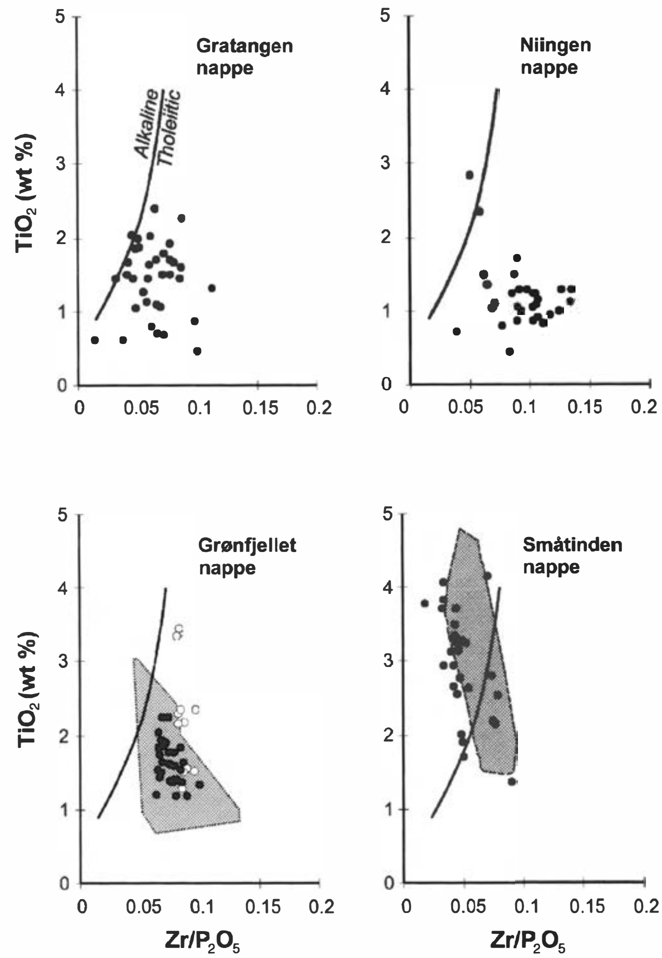

Fig. 9. TiO_2 vs. Zr/P_2O_5 plot of Winchester & Floyd (1976) to further distinguish alkaline from tholeiitic basalts. For Grønfjellet nappe: filled circles represent samples from subarea A; open circles represent samples from subarea B. Shaded areas on the plots for the Grønfjellet nappe and Småtinden nappe show fields of comparative data for metabasites from the Grønfjellet area (Barker 1986b) and the Sagelvvatn area (Bjørlykke & Olaussen 1981) respectively.

amphibolite facies metamorphism and is supported by the presence of kyanite, sillimanite and anatectic melt in associated pelitic lithologies.

rutile and localized chloritization are occasionally noted. For amphibolites from the Småtinden nappe a distinctive feature is the lack of epidote minerals and the ubiquitous presence of calcite and ilmenite, the characteristic assemblage being hbl + pl + qtz + ilm + cal + bt (± grt ± spn). Since associated pelites from both units have ubiquitous garnet with rare occurrences of staurolite, we attribute this mineralogical difference in the metabasites to variations in the bulk rock chemistry or fluid composition.

The most common assemblages in metabasites from the Gratangen and Niingen nappes are hbl + pl + qtz + grt + ilm/spn ± bt (24 out of 67 samples) and hbl + pl + qtz + zo + spn/ilm (17/67 samples). More than half the samples contain no epidote group minerals and a high proportion contain garnet. This is consistent with mid- to upper

Geochemistry

The chemical compositions (Table 1) of all amphibolites studied are broadly basaltic (SiO_2 ranging from 48 to 53 wt.%). Although some retain a relict 'porphyritic' texture, the original igneous mineral assemblages have, however, been entirely transformed during Caledonian epidote-amphibolite to amphibolite facies metamorphism. The possibility of earlier sea-floor weathering and hydrothermal alteration is an additional consideration. In view of this potentially complex history, it is likely that the original major and trace element chemistry of the amphibolites will have been modified to some extent from the original basalts/dolerites. Before proceeding to employ any of the commonly used plots for discriminating the tectonic

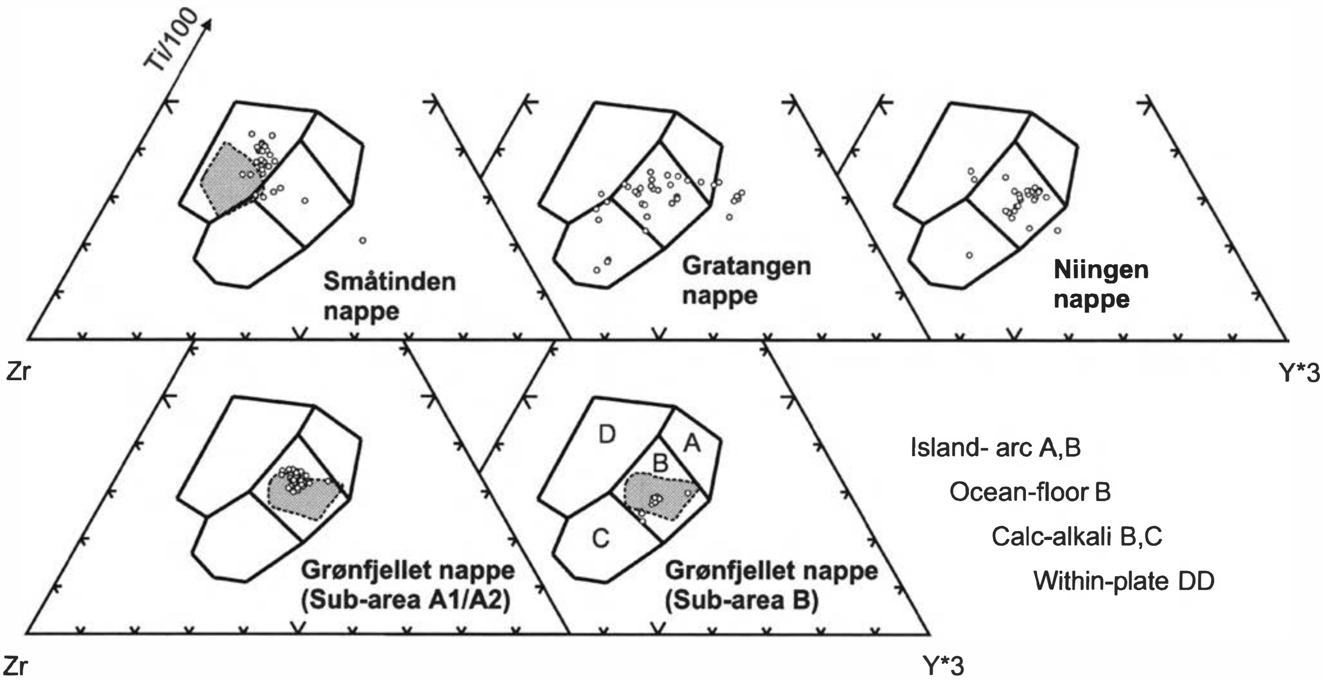

Fig. 10. Tectonic setting of metabasites from Torneträsk–Troms region determined using the ternary Ti/100-Zr-Y*3 variation diagram of Pearce & Cann (1973). Symbols as for Fig. 9

environment of eruption/intrusion, it is important to evaluate element mobility.

Element mobility during metamorphism and secondary alteration was evaluated using Zr-variation diagrams, since Zr is generally recognized as relatively immobile across a wide range of P-T conditions. Systematic variations in element concentrations with Zr content are, therefore, taken to reflect primary igneous processes such as fractional crystallization or partial melting. Conversely, scattered distributions probably reflect either crustal contamination or variable mobility by secondary processes. Elements displaying scatter are therefore considered to be poor indicators of original igneous trends. Linear regressions were performed on all data and correlation coefficients (Table 2) tested against critical values at 5% and 1% significance levels. The elements/oxides displaying linear trends in relation to Zr at the 1% significance level in amphibolites from all nappes were TiO_2, P_2O_5, Y and Nb. All other elements/oxides displayed variable degrees of scatter with respect to Zr, and discriminant plots using these were therefore not employed during subsequent analysis.

Magma type

The Y/Nb plot of Pearce & Cann (1973) and the TiO_2 vs. Zr/P_2O_5 plot of Winchester & Floyd (1976) have been used to establish for each of the amphibolite suites whether the original basaltic magmas had tholeiitic or alkaline chemistries. This distinction can be made since tholeiites have a mantle source that has been progressively depleted in the

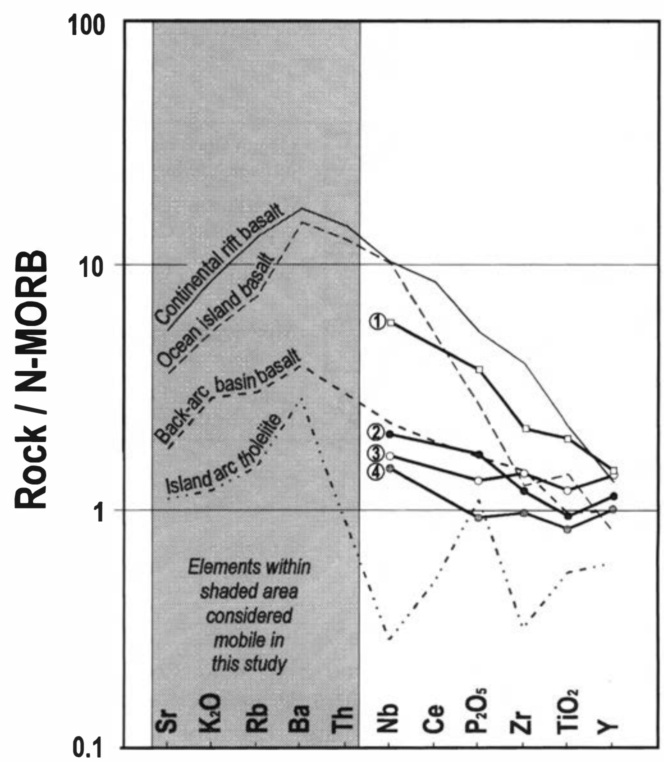

Fig. 11. Partial N-type MORB normalized trace element variation diagram (spidergram) for metabasites of the Torneträsk–Troms. Numbers in circles refer to nappes as follows: ① = Småtinden nappe; ② = Gratangen nappe; ③ = Grønfjellet nappe; and ④ = Niingen nappe. Typical trends for continental alkali rift basalts (Baker et al. 1977), ocean island alkali basalts (Basaltic Volcanism Study Project 1981), back-arc basin basalts (Saunders & Tarney 1979) and Island arc tholeiites (Luff 1982) are shown for comparison. Normalizing values for average N-type MORB are from Pearce (1983). Shaded area denotes elements considered mobile in this study (see text for explanation).

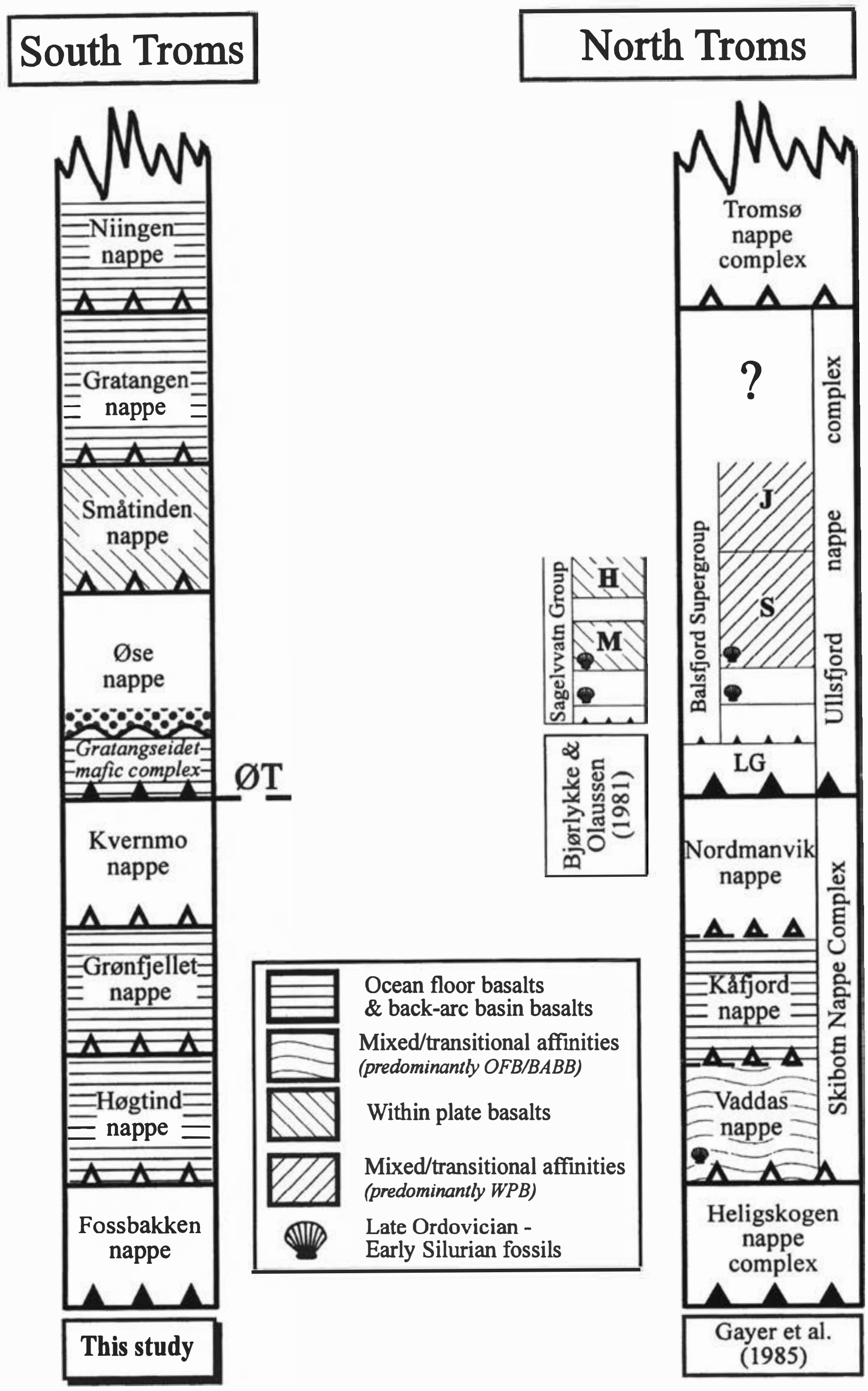

Fig. 12. Summary of results of this study with all published geochemical data for metabasites from the Upper/ Uppermost Allochthon of the Torneträsk–Troms region. Tectonostratigraphic abbreviations as for Fig. 2, with the exception of LG = Lyngen Gabbro. See text for explanation.

light rare earth (LREE) and high field strength (HFS) elements by extraction of previous melt fractions. In contrast, alkaline magmas are generally sourced from relatively undepleted parts of the mantle. O'Nions (1987) considers that these chemically distinct mantle sources are likely to have existed to some degree through much of the Earth's history. This being the case, it is reasonable to assume that Palaeozoic alkaline and tholeiitic basalts would show the same (or similar) REE characteristics compared to modern basalts.

A strong tholeiitic signature is evident for most nappes on both the Y/Nb plot (Fig. 8) and the TiO_2 vs Zr/P_2O_5 plot (Fig. 9). The clear exceptions are metabasites from the Småtinden nappe, which have noticeably lower Y/Nb ratios (Y/Nb = 1–3) and show enrichment in TiO_2 and low Zr/P_2O_5 ratios, suggesting a transitional alkaline to tholeiitic signature.

Tectonic setting

The previous section established that, with the exception of the Småtinden nappe (showing transitional tholeiitic to alkaline features), all amphibolites studied have strongly tholeiitic characteristics. However, since neither tholeiitic nor alkaline rocks are unique to any one tectonic setting, the next step is to consider the precise environment in which each set of metabasites were originally formed. The commonly employed Ti/100-Zr-Y*3 plot (Pearce & Cann 1973) is particularly useful in this study since it utilizes a combination of immobile elements that allow a distinction to be made between within plate, and plate margin basalts (e.g. MORB). Of the amphibolites analysed in this study, those of the Småtinden nappe show a strong WPB affinity (Fig. 10). Amphibolites from other units are consistent with MORB (largely contained within field B), although the Gratangen nappe shows a broader spread of data, which we interpret to reflect primary variations in magma chemistry.

'Pearce-type' spidergrams (Pearce 1983) provide a useful approach to evaluating magma type in terms of tectonic setting. The absence of a full set of REE data and the proven secondary mobility of many of the key LREE means that, in this study, such diagrams have more restricted use. Utilizing demonstrably immobile elements (Nb, P, Zr, Ti, Y), partial spidergrams have been constructed for amphibolites of this study (Fig. 11). This plot depicts the characteristic trends for each of the nappes and allows comparison with average trends for modern-day basalts from a range of settings. The Grønfjellet, Gratangen and Niingen nappes show broadly similar flat profiles with values slightly elevated above those of N-type MORB across the limited range of elements. Slight enrichment in Nb is apparent, possibly indicating a back-arc environment with a degree of crustal contamination or alternatively an enriched (E-type) MORB source. Småtinden nappe metabasites, however, show considerable Nb enrichment and complementary enrichment in other elements producing a trend which is clearly not MORB, but which is more comparable to within plate basalts (i.e. ocean island or continental rift basalts).

Summary of geochemical characteristics of amphibolites from each nappe

Our study reveals some important differences in the geochemical characteristics of amphibolites from the four tectonic units under consideration. Metabasites from the Småtinden nappe have a distinctive signature, quite different from amphibolites in all other nappes. They show transitional tholeiitic to alkaline features and trace and REE abundances indicative of within-plate basalts. All other nappes have a strongly tholeiitic geochemical signature with a close similarity to MORB. The Grønfjellet, Gratangen and Niingen nappe amphibolites have a consistent and strong MORB signature with variable enrichment in Nb indicative of a back-arc environment.

Discussion and conclusions

In the introduction, a brief summary was given of previous work on Caledonian amphibolites in suspect terranes of the Torneträsk–Troms region. Let us re-evaluate the conclusions from these earlier studies in the light of the new data presented, and assess any regionally significant features. Figure 12 summarizes interpretations of the tectonic setting of allochthonous units in the Troms region, based on all published geochemical data at the time of writing. Data from the island of Senja (Bergh & Andresen 1987) are excluded since tectonostratigraphic correlations with mainland units remain unclear (Dallmeyer 1988; Bergh & Andresen 1988). The Høgtind nappe contains relatively few amphibolites, but four unpublished analyses by Barker have indicated MORB affinity comparable with amphibolites in the immediately overlying Grønfjellet nappe.

The principal feature of Fig. 12 is that parts of the Balsfjord Supergroup in north Troms, a lateral equivalent of the Småtinden nappe (and underlying Øse nappe), show the same distinctive WPB transitional tholeiitic to alkaline characteristics. Amphibolites (in part pillowed) from the lower part (= Vaddas Nappe) of the Skibotn Nappe Complex (Gayer et al. 1985) show strong MORB geochemical characteristics and compare well with the data obtained from the Grønfjellet and Høgtind nappes of south Troms. At the time of writing, no published geochemical data exist for amphibolites from units in north Troms equivalent to the Gratangen and Niingen nappes.

It is concluded that although amphibolite geochemistry alone does not define a 'terrane', it may provide important information to corroborate other evidence. This is particularly true in areas with limited stratigraphical or palaeontological control. We have identified the Småtinden nappe as a unit which on the basis of lithostratigraphy and tectonothermal evolution (Anderson et al. 1992), as well as amphibolite geochemistry (this study), is quite distinct from many other units within the Upper and Uppermost Allochthons. These same characteristics can be traced 100 km along strike to equivalent units within the Balsfjord/Skibotn region of north Troms (Fig. 12), suggesting that there are good grounds for considering this unit as part of a separate terrane. Furthermore, on the basis of established correlations (Steltenpohl et al. 1990; Andresen & Steltenpohl 1994) these arguments can probably be extended to include the underlying Øse nappe (Anderson et al. 1992). We tentatively suggest, therefore, that these Late Ordovician–Early Silurian sequences developed together, in an evolving intraplate basin on thinned continental lithosphere at the margin of Baltica.

The presence of thick marble sequences in several units from the Høgtind nappe upwards to the Niingen nappe suggests a shallow marine setting. Associated metabasites, however, display strong MORB geochemical signatures, demonstrating that the environment of formation must lie outboard, and thus exotic to, the Lower Palaeozoic continental margin of Baltica. The present arrangement of nappes has been brought about by Scandian thrusting giving rise to marked metamorphic grade variations (Barker 1989; Barker & Anderson 1989). However, their structural-metamorphic evolution, although diachronous, is considered to be broadly similar (Anderson et al. 1992). Interleaving of the proposed new terrane with the dominantly oceanic exotic terranes of the Upper and perhaps the Uppermost Allochthons resulted from out-of-sequence thrusting within the nappe stack, in the Mid–Late Devonian, and represents one of the latest Caledonian structural events recognized in this region (Anderson et al. 1992).

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