Subduction-related volcanism in the Gula Nappe, southeastern Trondheim Nappe Complex, Central Norway

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McClellan, E.A., 1995: Subduction-related volcanism in the Gula Nappe, southeastern Trondheim Nappe Complex, Central Norway. *Nor. geol. unders. Bull. 428,* 1-26.

Field and geochemical evidence from two meta-igneous complexes that occur in the Einunnfjellet-Savalen area, southeastern Trondheim Nappe Complex, indicates that both complexes formed in an arc-related setting. Metabasalts of the Lomsjødalen complex, that have been correlated with the Gula greenstone, are primitive arc tholeiites. Overlying metalliferous sediments suggest a spreading-ridge environment, however, which may signify either an opening marginal basin or the earliest stages of island-arc development. Mafic rocks of the Bangardsvola complex, previously correlated either with the Fundsjø Group or with rocks equivalent to the structurally lower Seve Nappe, have boninitic affinities uniquely characteristic of subduction-related settings. Meta-igneous rocks of the Einunnfjellet-Savalen area are lithologically and geochemically similar to Early Ordovician Norwegian ophiolites that formed in a suprasubduction-zone environment. In this study, the Lomsjødalen and Bangardsvola complexes are interpreted as components of an internally imbricated thrust sheet initially emplaced prior to or during the earliest Ordovician, then further translated and deformed during the Scandian orogeny. The association of primitive IAT, boninite, and Fe- and Mn-rich metalliferous sediments is strongly analogous to the upper parts of the Troodos ophiolite, Cyprus.

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Introduction

Reconstruction of the tectonic history of the Iapetus Ocean basin between Laurentia and Baltica prior to and during its final closure in the Siluro-Devonian Scandian orogeny depends largely upon deciphering the tectonic setting and age relationships of the numerous fragments of oceanic crust, forming parts of the Köli Nappes, that occur in the Upper Allochthon of the Scandinavian Caledonides. In the central-southern Caledonides of Norway, rocks of the Upper Allochthon occur in the Trondheim Nappe Complex, which extends approximately 300 km north to south, and has a maximum width of over 100 km. The central Trondheim Nappe Complex, as shown on the Røros 1:250,000 scale map (Nilsen & Wolff 1989), comprises the dominantly metasedimentary Gula Nappe, that contains subordinate discontinuous mafic/ultramafic horizons informally termed the Gula greenstone (Nilsen & Mukherjee 1972). The Gula Nappe is flanked by metavolcanic sequences, the Støren Group and related complexes in the west and the Fundsjø Group/Hersjø Formation on the east (Fig. 1). Whereas the Lower Ordovician or older metavolcanic rocks in the Støren Group and Fundsjø/Hersjø complexes are distinctly of oceanic origin and represent either major ocean, marginal basin or island arc environments, the tectonic environments of the generally higher-grade rocks of the Gula Nappe remain speculative. Insufficient knowledge of age relationships and tectonic affinities of rocks within the Gula Nappe has long presented a major obstacle to understanding the structure and tectonic history of the Trondheim Nappe Complex.

Mafic and ultramafic rocks are also found in the lower (Seve) nappes of the Upper Allochthon. The rocks are generally at a higher metamorphic grade than those of the Köli Nappes, however, and the tectonic affinities are even less well-defined. Based on geochemistry and associated sedimentary rocks, some of the mafic horizons appear to be correlative with Late Proterozoic dolerite dikes in the Särv Nappe, Middle Allochthon, that are interpreted to mark rifting of the Baltic margin during the opening of Iapetus

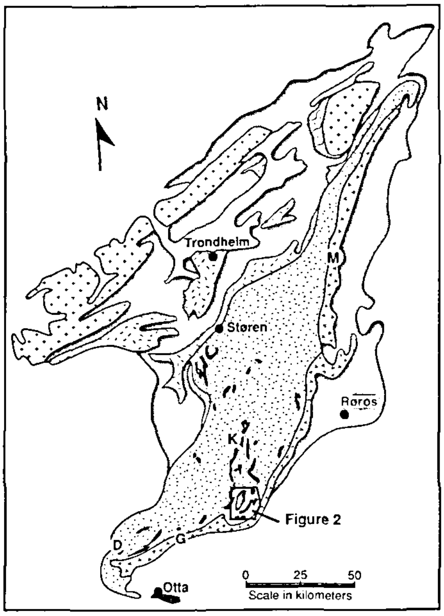

Fig. 1. Simplified tectonic map of the Trondheim Nappe Complex, showing locations of major metavolcanic sequences. Cross-hatch pattern-Støren Group and related units (western sequence); 'V' pattern-Fundsjø Group and related units (eastern sequence); Black-mafic horizons in Gula Nappe. D-Dombås; G-Grimsdalen; K-Kvikne; M-Meråker. Polygon-location of Einunnfjellet-Savalen map area (shown in Fig. 2). Modified from Grenne (1988), with data from Nilsen & Wolff (1989).

(Gee 1975, Solyom et al. 1979, Gee et al. 1985). Others, however, may be higher-grade equivalents of the oceanic crustal sequences in the Köli Nappes, indicating that the Seve Nappes contain units representative of the continent-ocean transition. In the western and northern part of the Trondheim region, Seve equivalent rocks, including mafic horizons, occur in the Skjøtingen Nappe (Wolff 1979); and in southwestern areas in the Blåhø Nappe (Krill 1980). Similar rocks were assigned to the Essandsjø Nappe in the eastern part of the region (Nilsen & Wolff 1989), and also surround the Einunnfjellet dome in the present study area.

This study presents field and geochemical investigations of two distinct meta-igneous complexes that occur in the Einunnfjellet-Savalen area, southeastern Trondheim Nappe Complex (Figs. 1 & 2). One, informally referred to here as the Lomsjødalen complex (McClellan 1993, 1994), has been correlated with the Gula greenstone (Rui & Nilsen 1988; Nilsen & Wolff 1989). The other, informally the Bangardsvola complex (McClellan 1993, 1994), was previously shown as two separate units, correlative with the Essandsjø Nappe and Fundsjø Group (Rui & Nilsen 1988, Nilsen & Wolff 1989). The tectonic affinities of the Lomsjødalen and Bangardsvola complexes, their mutual relationships, and associations with surrounding metasedimentary rocks have significant implications for the original tectonic setting of the Gula Nappe, as well as for the relationship between rocks of the Trondheim Nappe Complex and those of the Seve Nappes.

Metavolcanic sequences in the Trondheim region

The Trondheim Nappe Complex contains three major metavolcanic sequences – the Støren and Fundsjø Groups that flank the Gula Nappe on the west and east, respectively, and greenstone within the Gula Nappe itself (Fig. 1). The western Støren Group and possibly related metavolcanic complexes (Løkken, Vassfjell, Grefstadfjell) comprise the Hølonda terrane of Stephens & Gee (1985). The complexes are largely mafic and commonly preserve at least a partial ophiolite stratigraphy (Furnes et al. 1985). Based on biostratigraphic control in the unconformably overlying sediments, the Støren Group is unambiguously mid-Arenig or older. The Laurentian affinity of faunal assemblages in the overlying sedimentary units (Bruton & Bockelie 1980) has led some (Stephens & Gee 1985; Pedersen et al. 1988) to suggest that this oceanic crust formed on the Laurentian side of Iapetus, although the significance of the faunal provinciality has been questioned by others (Roberts & Gale 1978, Roberts et al. 1984, Sturt & Roberts 1991).

Metavolcanic rocks of the eastern Trondheim district occur within the Meråker

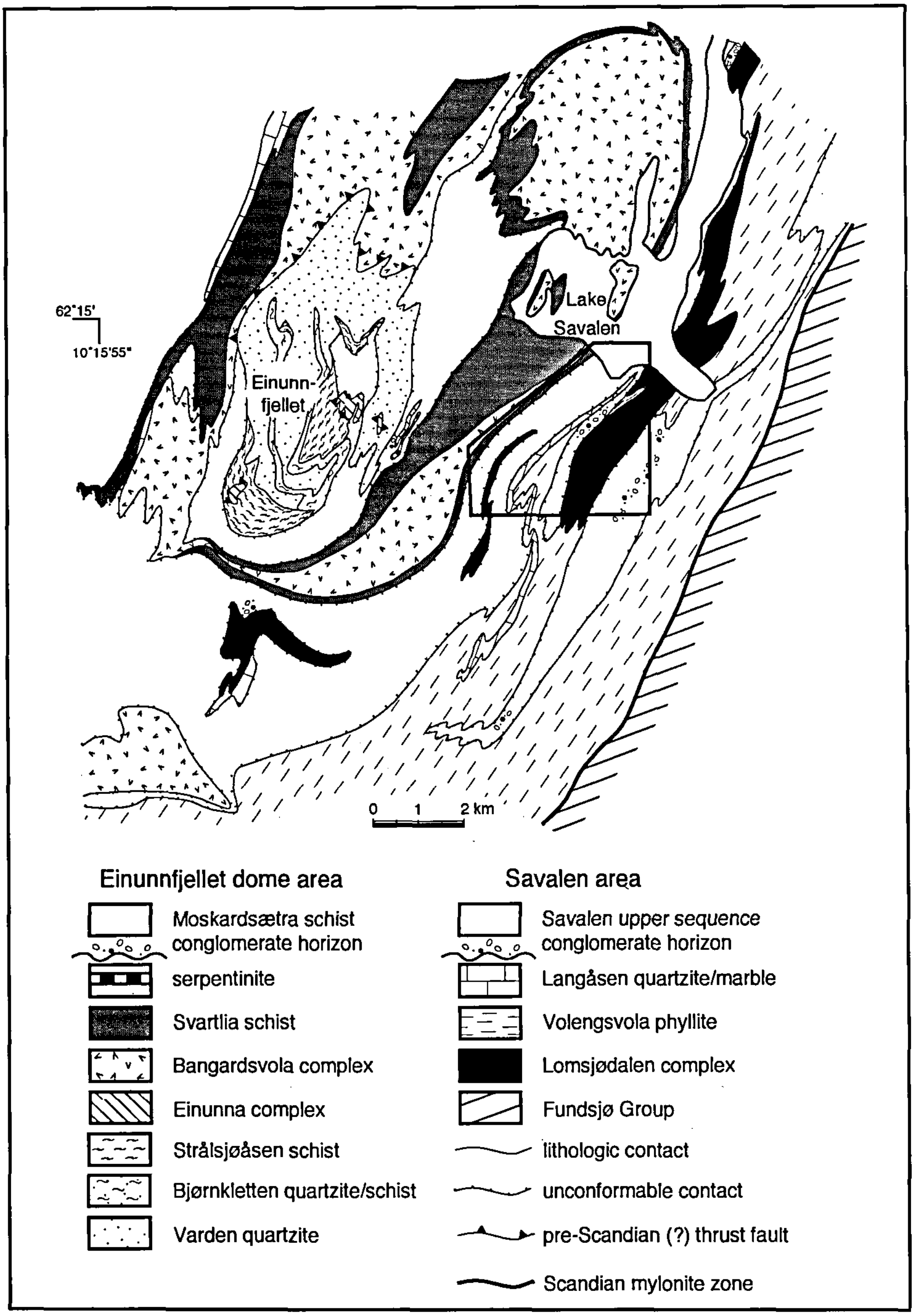

Fig. 2. Geologic map of the Einunnfjellet-Savalen area; location shown in Fig. 1. With the exception of the Fundsjø Group, all stratigraphic units are informal (see regional correlations in Fig. 3). Lithologic contacts on the two islands in Lake Savalen after Rui & Nilsen (1988) and Quenardel (1970). Polygon–location of Fig. 4.

Nappe, and form an essentially continuous belt that includes the Fundsjø Group (Wolff 1967) in the Meråker area, the Hersjø Formation (Rui 1972) in the Røros-Folldal district, and the Musadal Group (Guezou 1978) near Dombås, at the southern termination of the Trondheim Nappe Complex (Fig. 1). Lithologically more diverse than the metavolcanic rocks of the western district, all the units are characterized by greenstone or amphibolite interlayered with variable amounts of quartz keratophyre and tuffaceous rocks. Mafic rocks in both the Fundsjø Group (Grenne & Lagerblad 1985) and the Hersjø Formation (Grenne 1988) display geochemical heterogeneity as well, and can be divided into island-arc, MORB, and transitional types. Deformation and metamorphism have largely obscured the interrelationships and relative ages of the different types, but the heterogeneities have been explained by models involving either an incipient rifted arc or an arc-related marginal basin setting (Grenne & Lagerblad 1985, Grenne 1988).

Based on overall lithologic similarities and the apparent symmetry across the Trondheim Nappe Complex, metavolcanic sequences of the eastern and western Trondheim districts were traditionally assumed to be correlative (Wolff 1967). However, although the sequences may be temporally equivalent, more recent models propose that they may be parts of different thrust sheets within the nappe complex, and are not directly correlative (Gee & Zachrisson 1974, Gee 1978). This is supported by distinct differences in geochemistry, and the inferred paleotectonic environment (Grenne & Lagerblad 1985) and nature of associated massive sulfide deposits (Grenne 1988).

Mafic metavolcanic rocks in the Gula Nappe

The most enigmatic sequence of mafic metavolcanic rocks in the Trondheim Nappe Complex is the Gula greenstone. A two-fold division of the Gula Group (Törnebohm 1896, Rui 1972) was modified by Nilsen (1978), who divided the unit into three formations. The central Singsås Formation consists mainly of calcareous psammite and mica schist, and is bordered on the west and east by carbonacous phyllite and biotite schist of the Undal and Åsli Formations, respectively. Mafic rocks, termed the Gula greenstone (Nilsen & Mukherjee 1972, Nilsen 1974), occur as discontinuous horizons throughout the Gula Nappe (Fig. 1), but are concentrated particularly at the contact between the Singsås and Åsli Formations. The Gula greenstone consists of amphibolite with subordinate metagabbroic and ultramafic lenses (Nilsen 1974). The amphibolite horizons are commonly associated with black schist and banded quartzite, and contain numerous pyritic sulfide deposits capped by cherty iron formation (Nilsen 1978). On the basis of the apparently exhalative nature of the stratabound sulfide deposits, the mafic rocks are considered to have resulted from submarine volcanic activity (Rui 1973; Nilsen 1974, 1978, 1988), although primary igneous structures have been obscured by polyphase deformation and the typical amphibolite facies metamorphism. Recently, however, pillow lava and volcanic breccia were reported from relatively low-grade greenstone in the area of this study (McClellan 1992, 1994).

Based on the association of mafic volcanites with thick clastic sequences, Nilsen (1978) suggested that the Gula greenstone represented volcanism in an island-arc related environment. This suggestion was supported by mafic rock geochemistry. Rainey (1980) showed that Gula amphibolites from the Kvikne area (Fig. 1) plot consistently as island arc tholeiites on discriminant diagrams utilizing Ti, Zr, Y, and Zr/Y. Nilsen (1974), however, had previously noted a striking resemblance in the AFM diagram between Gula amphibolite and Archaean high-Mg basalts or komatiites. The relatively high concentrations of Cr and Ni are also worthy of note, because these features are uncharacteristic of typical island-arc tholeiites. Rainey's analyses (1980) yield similar results when plotted on the AFM diagram, and average approximately 400 ppm Cr, as compared to an average of 111 ppm in island-arc tholeiites (Pearce 1982). Given the significant geochemical contrasts with typical IAT, the absence of associated intermediate or felsic lithologies, and the nature of the sulfide deposits, it appears that the tectonic setting of the Gula greenstone cannot be adequately explained by a simple island-arc model. On the basis of lithologic similarities and comparable deformational and intrusive phases, Stephens & Gee (1985) suggested that the higher-grade parts of the Gula Nappe are correlative with the Krutfjellet Nappe farther north, which they interpreted as representing a fore-arc basin. In the present study, this and other possible interpretations of the tectonic setting of the Gula Nappe are considered from the standpoint of both field and geochemical characteristics.

Age and contact relationships in the Meråker and Gula Nappes

Metavolcanic rocks in the eastern Trondheim district (Meråker Nappe) are overlain by a thick sequence of clastic rocks, the highest of which contains a graptolite-bearing black phyllite of Llandovery age (Getz 1890). Recently, from the Folldal area, a U-Pb zircon date of 488 ± 2 Ma was obtained from a trondhjemite dike that intrudes metabasalts of the Fundsjø Group, indicating that the basalts are at least slightly older (Bjerkgård & Bjørlykke 1994).

The Gula Nappe is likely a composite tectonic unit and age constraints are few, although Klingspor & Gee (1981) reported an Early Ordovician isotopic age from a syntectonic trondhjemite that intruded mica schist of the Singsås Formation. A potentially very important fossil locality occurs at Nordaunevoll, where Vogt (1941) described the distinctive Tremodocian dendroid graptolite *Dictyonema flabelliforme* from highly organic black shale. Unfortunately, the stratigraphic position of this unit is still controversial, having been variously ascribed to the Gula (Nilsen 1971), the Hersjø (Gee 1981), or a transition zone between the two groups (Rui 1972).

McClellan (1993, 1994) suggested a possible correlation of greenstone in the Gula Nappe with the Vågåmo ophiolite in the Otta Nappe (Sturt et al. 1991), indicating an Early Ordovician or older age for the correlative Gula rocks.

The nature of the contact between metavolcanites of the eastern district and the Gula Nappe is equivocal, interpreted as either stratigraphic (Rui 1972) or tectonic (Gee 1975). Commonly, the contact is marked by a transition zone of quartzite conglomerate, crystalline limestone, metagraywacke, tuffite, and mica schist (± amphibole)–the 'heterogeneous banded rock sequence' of Rui (1972) or the Gudå Formation of Wolff (1973). Lagerblad (1984a, 1984b) concluded that the Gudå-Fundsjø contact in the northern Trondheim Nappe Complex is primary, whereas the Gudå-Gula contact is tectonic. He presented strong evidence for a gradual increase in metamorphic grade from east to west across all three units, and surmised that the tectonic contact is an early structure, entirely overprinted by later deformation and metamorphism.

Einunnfjellet-Savalen area

Two major metavolcanic sequences in the Einunnfjellet-Savalen area (Fig. 2) are the subjects of this study. One has been correlated with the Gula greenstone (Nilsen & Wolff 1989), while the other encompasses rocks that were previously divided into the Essandsjø Nappe and the Fundsjø Group (Mosson et al. 1972; Nilsen & Wolff 1989). Although the previous correlations were based on reasonable stratigraphic divisions for this region, they do not explain several observations and similarities noted below. Therefore, in this study the informal names of Lomsjødalen complex and Bangardsvola complex, as defined by McClellan (1993, 1994), will be used.

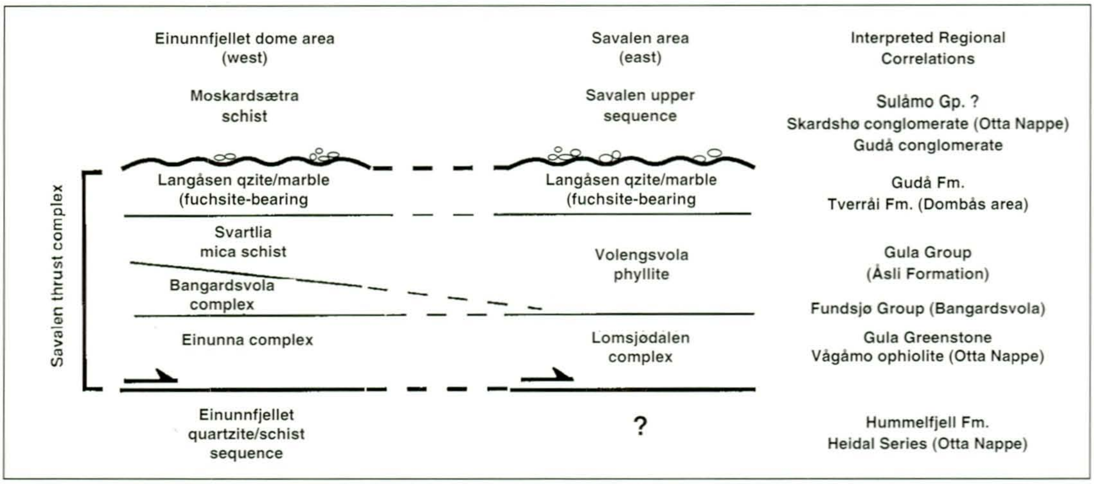

Fig. 3. Interpreted stratigraphic relationships and regional correlations of informal stratigraphic units in the Einunnfjellet-Savalen area (from McClellan 1993).

The stratigraphy and structure of the Einunnfjellet-Savalen map area has been described in detail elsewhere (McClellan 1993, 1994), and the main observations, interpretations, and correlations are summarized in Figure 3. Structurally, the area can be divided into two domains–shallowly to moderately dipping foliation and overturned folds surrounding the Einunnfjellet dome on the west pass into a series of steep, NE-SW-striking folds east of the dome. These folds are commonly doubly plunging, and produce a lenticular outcrop pattern. A strong component of simple shear in the later stages of deformation is evident from the abundance of asymmetric folds and crenulations, and asymmetric, boudinaged veins in some lithologies. Metamorphic grade increases continually from middle greenschist facies in the southeast to lower amphibolite in the northwest of the map area.

The Einunnfjellet dome is cored by a polydeformed quartzite-schist sequence correlated with the Hummellfjell Formation (Rui 1972). These rocks are considered to be higher-grade equivalents of Late Proterozoic sandstone and quartzite of the Särv Nappe, which probably represents a part of the Baltoscandian continental margin. The quartzite-schist sequence was overthrust by an internally deformed thrust sheet, referred to as the Savalen thrust complex (McClellan 1993), that contains the Lomsjødalen and Bangardsvola complexes, along with pelagic, volcaniclastic, and turbiditic sediments and carbonate. An unconformable sequence of polymict conglomerate and finer-grained clastic sediment is interpreted to overstep both the continental margin rocks and the thrust complex. Regional correlations of rocks in the Savalen thrust complex are complicated by varying terminology and interpretations by different workers. In terms of the Gula stratigraphy, this study generally recognizes the nomenclature of Nilsen (1978) and Nilsen & Wolff (1989) (Fig. 3). However, it must be noted that north of the study area, rocks along strike and equivalent to the Åsli Formation (pelites, limestone, and conglomerate) were included in the Gudå Formation (Wolff 1973), which Lagerblad (1984a) extended to include associated greenstone horizons. Lagerblad interpreted the 'Gudå group' to be separated from the main part of the Gula Group (i.e., Singsås Formation) by a fault. The possibility that the Åsli-Singsås contact is either a fault or a primary unconformity was also discussed by Bjerkgård & Bjørlykke (1994). Evidence from this and other studies (e.g.

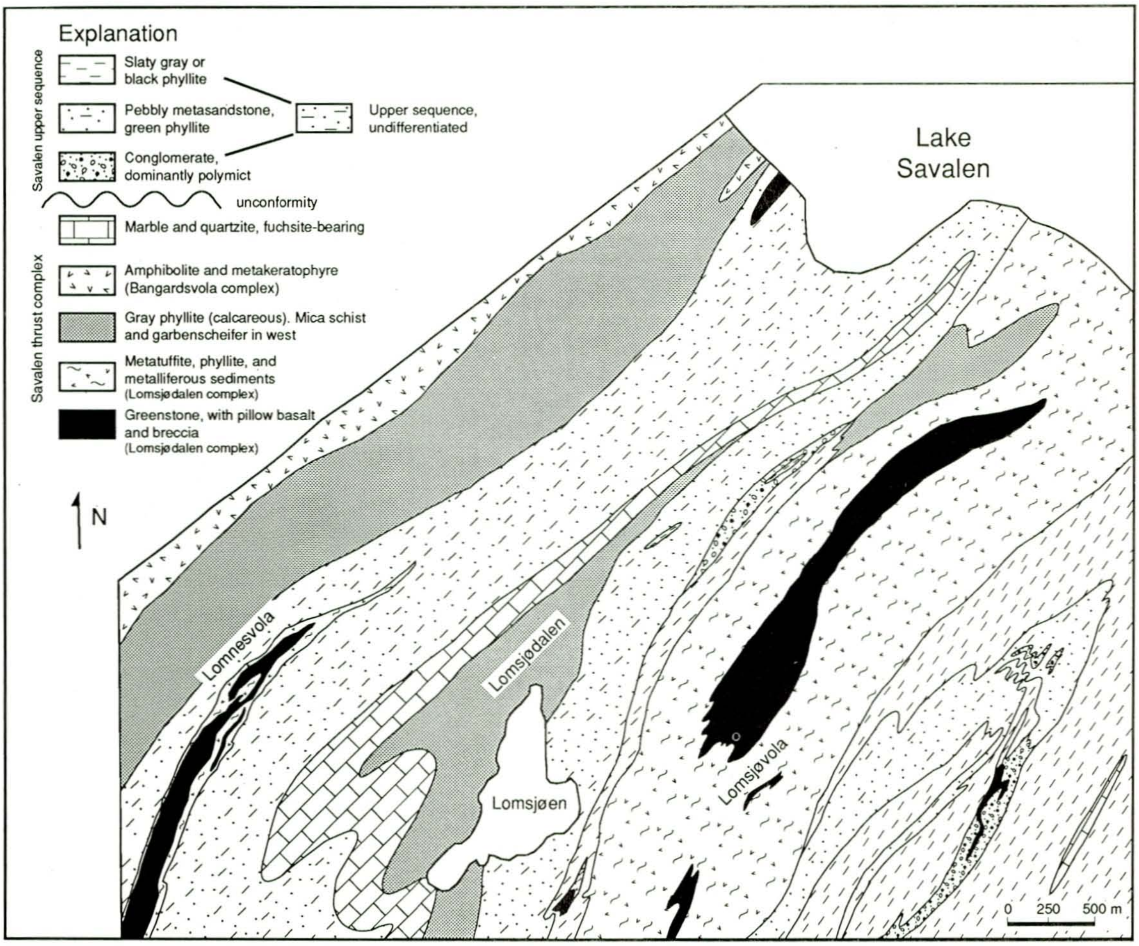

Fig. 4. Geologic map of the Lomsjødalen area; location shown in Fig. 2.

Rui 1972, Lagerblad 1984a) recognize the association of greenstone with Åsli-equivalent lithologies, raising the possibility that a fault separates the Gula greenstone from the Singsås Formation as well. Further studies are needed to determine whether all mafic bodies mapped as Gula greenstone are equivalent.

The Bangardsvola complex encompasses rocks that were previously correlated with both the Essandsjø Nappe and the Fundsjø Group (Mosson et al. 1972, Nilsen & Wolff 1989). Based on similarities in field appearance, lithology and geochemistry, however, the unit was not separated in this study, with the exception of the Einunna complex as discussed below. It should be noted that similar rocks in the Folldal area, just to the west of this study area, were correlated with the Fundsjø Group (Nilsen and Wolff 1989). Comparison with recent work in the Folldal area (Bjerkgård & Bjørlykke 1994) reveals strong lithological and geochemical similarities between rocks of the Fundsjø Group in that area and the Bangardsvola complex, even with rocks previously considered to belong to the Essandsjø Nappe.

Lomsjødalen complex

The Lomsjødalen complex, which has been correlated with the Gula greenstone (Nilsen & Wolff 1989), consists of greenstone or amphibolite and overlying volcaniclastic and sedimentary rocks. Detailed mapping at the scale of 1:5,000 in the Lomsjødalen area south of lake Savalen (Fig. 4) shows that the complex occurs in several lenticular exposures as a result of intense folding. The most extensive exposure in the area is located on Lomsjøvola, where fine-grained greenstone is generally massive to schistose, but commonly contains calcite- and epidote-rich segregations giving the impression of pillow shapes. Indisputable pillow lavas (Fig. 5) occur in a few outcrops, and are associated with volcanic breccia apparently derived from the pillow material. In thin-section, the greenstones consist of fine-grained felted masses of amphibole and feldspar interspersed with epidote and chlorite, with accessory sphene and rutile.

Fig. 5. Pillow structures in Lomsjødalen complex greenstone (Locality: UTM 762 996).

Greenstone is overlain by fine-grained, dark gray-green laminated tuffite that contains abundant millimeter to centimeter-scale interlayers of fine-grained pink coticule, consisting of quartz and masses of tiny (0.01 to 0.20 mm), zoned, spessartine-rich garnets. Higher in the overlying sequence, tuffite grades into coarser-grained, laminated and quartz-veined phyllite rich in chlorite and epidote, and containing some coticule intercalations. Sulfidic black phyllite is locally associated with the greenstone and the overlying rocks. Small pods (2-3 m^2) of ore mineralization within the sedimentary/volcaniclastic rocks near the greenstone contact consist of siliceous 'iron formation', as described in detail by Nilsen (1978, pp. 47-51).

On Lomnesvola (Fig. 4), the Lomsjødalen complex is more intensely deformed and tectonically thinned. Sheared amphibolite and metagabbro are surrounded by a heterogeneous cover of dark chert, coticule, fine-grained metalliferous sedimentary rocks, and tuffite, again with pods of iron formation. Texturally, all rocks are coarser-grained and more schistose than those on Lomsjøvola, and consequently appear to represent a higher metamorphic grade. An increase from greenschist to amphibolite facies between the Lomsjøvola and Lomnesvola exposures is confirmed by mineral chemistry in both mafic and pelitic rocks (McClellan 1993).

Of the meta-igneous and related rocks surrounding the Einunnfjellet dome (included in the Essandsjø Nappe by Nilsen & Wolff 1989), the structurally lowest rocks comprise a sheared and fragmented body of metagabbro, amphibolite, chlorite-biotite schist, and amphibole schist locally containing thin, boudinaged layers of coticule. This unit, referred to informally as the Einunna mafic complex (Figs. 2 & 3), was suggested to be correlative with the Lomsjødalen complex on the basis of lithologic similarity and the presence of the distinctive coticule interlayers (McClellan 1993, 1994). In addition, conglomerate with mafic and carbonate clasts locally overlies the Einunna complex, a situation that is very similar to that on Lomsjøvola (Fig. 4).

Bangardsvola complex

A bimodal igneous suite, informally called the Bangardsvola complex, encircles the core of the Einunnfjellet dome (Fig. 2). The dominant lithology of the Bangardsvola complex is dark green to black schistose amphibolite, typically pervasively banded with thin felsic laminae. The medium- to coarse-grained amphibolite consists of hornblende, epidote, feldspar, and quartz, with accessory rutile and minor secondary chlorite (Fig. 6a). Metagabbroic rocks form a subordinate component of the Bangardsvola complex; the fine-grained, banded amphibolite, however, is typically basaltic in composition (see following section), and is interpreted to have formed from an extrusive volcanic protolith.

Layers of quartz keratophyre up to several meters thick occur within the amphibolite. In thin-section, the keratophyre consists of a fine-grained groundmass of interlocking quartz and feldspar surrounding larger plagioclase porphyroclasts (Fig. 6b). Variable amounts of hornblende and chlorite are present, and the subparallel alignment of these minerals defines the foliation. Based on its appearance on both the outcrop scale and thin-section scale, the fine-grained layered keratophyre probably represents tuffaceous material. Slightly coarser-grained varieties that in places show intrusive relationships with amphibolite or metagabbro may represent hypabyssal feeder dikes to the finer-grained rocks. The ratio of keratophyre to amphibolite increases just northwest of Lake Savalen, where it becomes the dominant rock type in some areas.

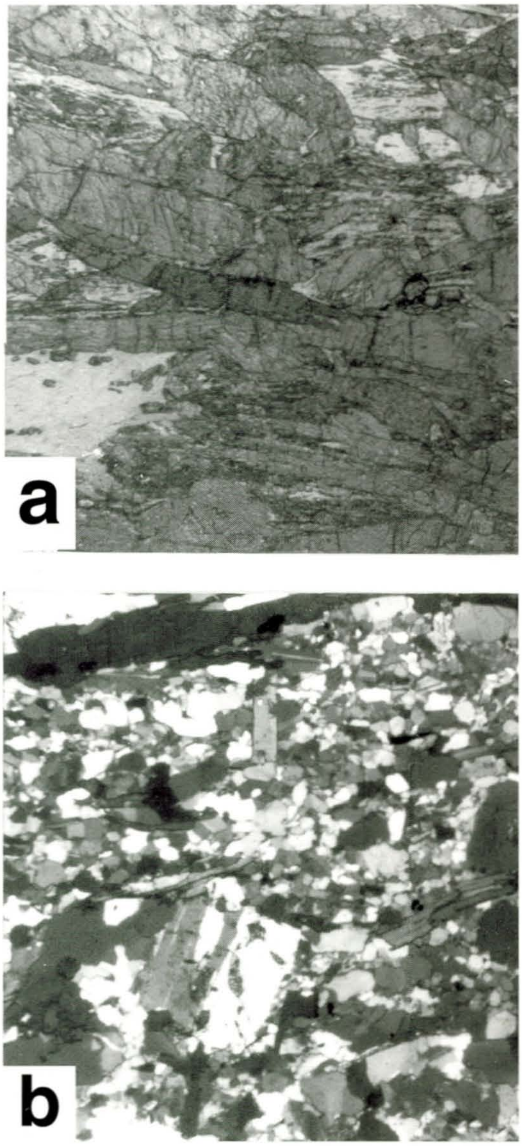

Fig. 6. Photomicrographs of lithologies in the Bangardsvola complex. a) Amphibolite. Long dimension of photograph 4.5 mm. b) Quartz keratophyre. Long dimension of photograph 4.5 mm.

The Bangardsvola igneous complex is in contact, and locally intricately folded, with mica-quartz schist, metasandstone, and garbenschiefer. The contact between the two units is continuously exposed in some areas (e.g., UTM 732 995 to 745 008), and appears to be a primary contact. In a few locations near the contact, mafic layers are present in the metasedimentary rocks and possibly represent dikes. These mafic layers, which range from a few centimeters up to three meters thick, are geochemically distinct from the Bangardsvola layered metavolcanic rocks (see below).

Relationships within the Savalen Thrust Complex

The Lomsjødalen and Bangardsvola complexes are interpreted to have been transported together with sedimentary and volcaniclastic rocks in the Savalen thrust complex. The interpreted stratigraphic order within the thrust complex is shown in Fig. 3. Contact relationships are uncertain, however, due to internal deformation and lack of consistent facing criteria. McClellan (1993) interpreted the Bangardsvola complex to overlie equivalents of the Lomsjødalen complex, and both metavolcanic complexes to be overlain by mica schist and garbenschiefer, or calcareous phyllite at lower metamorphic grade (Fig. 3).

The schist and phyllite are both interpreted to represent the Åsli Formation of the Gula Nappe, the difference in appearance due to increasing metamorphic grade across the study area (McClellan 1993). A distinctive horizon of fuchsite-bearing marble and quartzite, or conglomerate containing marble and quartzite clasts, occurs within both the schist and the phyllite, or is locally in contact with the igneous complexes (Fig. 2). Similar lenses of conglomerate and marble (some fuchsite-bearing) associated with the Åsli Formation throughout the eastern Trondheim Nappe Complex were correlated by Nilsen (1978) with the Gudå conglomerate of Wolff (1967), as discussed previously. Some phyllites occurring in the northeastern part of the present study area were previously assigned to the Singsås Formation (Nilsen & Wolff 1989). However, the similarity of many of these rocks to phyllites elsewhere in the study area, and the presence of coticule intercalations and ore horizons in some, leads me to suggest that these rocks should be considered either as part of the Åsli Formation, or as sedimentary rocks associated with the Lomsjødalen complex. This, in turn, leads to the possibility that true Singsås Formation rocks are absent in the study area.

The Bangardsvola complex pinches out toward the east; whether this signifies internal faulting or original volcanic stratigraphy is uncertain. In the study area, the eastern contact between the Savalen thrust complex and metavolcanic rocks of the Fundsjø Group is characterized by a prograde ductile shear zone that can be traced for at least 15 km along strike (McClellan 1993, 1995). Bjerkgård and Bjørlykke (1994), however, interpreted the Åsli-Fundsjø contact in the Folldal area as a stratigraphic transition, similar to the Åsli-Bangardsvola contact in the study area.

Geochemistry

A total of 25 samples were analyzed by XRF for this study. XRF analyses were performed by Bjørn Nilsen and the technical staff at the Analytical Chemistry Section, Norges geologiske undersøkelse, Trondheim, using a Philips PW 1480 WD-spectrometer with Sc/W dual anode side-window X-ray tube, and equipped with LIF 220, LIF 200, GE, PE, PX-1, PX-2 crystals. Major elements were analyzed on fused disks melted with lithium tetraborate in the proportions 1:7, and trace elements were determined on pressed pellets. Calibrations for major and trace elements are based on international standards. FeO was determined by titration, H_2O by the Courville-Penfield method, and CO_2 by the rate of change of gas pressure liberated by adding sulfuric acid to the sample in a closed vacumn system.

Major and trace element data are given in Table 1. Note that trace elements consistently at or near the detection limit of the XRF (e.g. Nb, Yb, Ce) are not used in the following arguments. Of the samples analyzed, ten metabasalts are from the Bangardsvola complex, nine metabasalts are from the Lomsjødalen complex (including pillow lavas), and two samples represent the dike-like layers from within the overlying metasedimentary rocks. Four

Table 1. Major and trace element concentrations of metavolcanic rocks in the Einunnfjellet-Savalen area.

	Bangardsvola Group I						Bangardsvola Group II			*BAS	Dikes(?)	
Sample	**Fiskt-2**	**Slia-2**	**Slia-3**	**A114**	**A1145**	**Gruv**	**Slia-1**	**Slia-7**	**K283**	**K2201**	**K47**	**A112A**
SiO_2	49.60	48.20	54.67	47.35	51.54	57.28	48.84	51.18	46.58	50.90	46.65	45.64
Al_2O_3	9.79	11.58	13.76	10.27	12.60	15.47	16.40	15.64	17.67	15.14	14.87	14.88
Fe_2O_3	0.82	0.65	1.49	1.17	2.99	1.43	1.58	1.76	1.57	3.05	0.69	1.14
FeO	7.00	7.27	6.45	6.98	6.14	5.34	8.56	7.46	8.2	10.07	9.36	9.41
TiO_2	0.08	0.10	0.15	0.13	0.16	0.21	0.57	0.52	0.51	1.55	1.04	1.01
MgO	10.47	9.69	9.22	11.45	8.38	6.35	7.08	8.56	9.46	5.10	8.92	7.22
CaO	11.28	12.40	8.28	11.98	10.84	7.49	9.80	6.07	8.63	7.58	10.86	10.40
Na_2O	1.56	2.15	3.34	1.01	2.68	3.70	3.55	4.63	3.20	3.69	2.30	2.87
K_2O	0.48	0.21	0.24	1.40	0.21	0.37	0.27	0.19	0.31	0.33	0.28	0.62
MnO	0.13	0.16	0.15	0.17	0.14	0.09	0.13	0.17	0.10	0.20	0.24	0.18
P_2O_5	0.07	0.07	0.05	0.05	0.05	0.04	0.10	0.07	0.07	0.19	0.12	0.11
H_2O+	2.58	2.98	1.56	2.07	1.51	0.96	3.02	2.97	2.56	1.78	1.50	1.16
H_2O-	0.05	0.11	0.26	0.02	0.05	0.10	0.10	0.09	0.03	0.03	0.04	0.05
CO_2	7.87	5.77	0.11	6.09	1.67	0.10	1.56	0.74	0.31	0.28	2.03	4.36
Total	101.78	101.34	99.73	100.14	98.96	98.96	101.56	100.05	99.20	99.89	98.90	99.05
Mg#	0.73	0.70	0.72	0.75	0.71	0.68	0.60	0.67	0.67	0.47	0.63	0.58
Nb	<5	6	<5	11	11	11	<5	7	7	6	12	12
Zr	10	11	16	9	10	29	20	21	18	72	57	61
Y	<5	<5	<5	9	6	8	17	2	14	27	25	23
Sr	139	167	150	76	146	210	226	110	149	127	221	90
Rb	11	8	5	5	5	10	8	7	5	8	5	19
Cr	1384	1639	503	1530	1525	378	177	315	216	18	393	422
Ni	304	354	121	336	339	82	69	97	72	9	170	123
V	200	217	155	174	196	165	297	260	271	429	216	276
Sc	33	28	34	32	31	35	37	39	45	42	35	38
Ba	35	33	29	28	14	41	27	<10	13	55	49	57
Zn	60	59	64	37	61	54	85	75	84	117	99	114
Cu	9	25	<5	5	62	207	13	9	5	13	<5	5
Yb	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Co	47	42	38	45	45	27	38	35	40	35	43	46
Ce	<10	<10	13	<1	<10	<10	22	13	<10	24	<10	<10

	Lomsjødalen Complex									Fundsjø Group			
Sample	**Lomsjø-1**	**Lomsjø-2**	**Lomsjø-3**	**Lomsjø-4**	**Lomsjø-6**	**Lomsjø-6**	**A1457**	**A1463**	**A1698**	**Sivil-2**	**Sivil-4**	**Sivil-5**	**Sivil-6**
SiO_2	50.06	50.61	49.41	49.27	48.31	48.10	52.00	49.31	47.74	50.99	57.97	48.93	55.56
Al_2O_3	13.47	13.94	13.85	14.42	14.08	13.99	15.72	13.11	15.59	13.81	14.55	14.37	14.06
Fe_2O_3	1.77	1.68	1.36	2.08	1.33	2.53	0.59	1.17	2.96	3.21	1.74	3.37	2.23
FeO	8.10	7.90	6.82	6.06	7.88	7.71	6.32	7.57	7.86	7.46	6.91	8.45	7.19
TiO_2	0.87	0.84	0.76	0.73	1.07	1.00	0.70	1.03	1.19	1.23	1.40	1.56	1.46
MgO	9.67	9.51	11.55	9.02	9.47	11.31	9.37	10.04	8.10	5.97	4.22	5.08	4.36
CaO	9.02	8.90	9.59	10.92	9.64	10.02	6.21	11.80	9.83	4.65	2.27	6.10	3.70
Na_2O	3.45	3.62	2.64	3.11	3.31	2.51	4.79	2.35	3.19	3.98	5.54	5.05	5.02
K_2O	0.18	0.18	0.12	0.15	0.14	0.12	0.07	0.14	0.43	0.05	0.04	0.08	0.32
MnO	0.14	0.13	0.12	0.10	0.15	0.15	0.09	0.14	0.20	0.23	0.22	0.26	0.13
P_2O_5	0.07	0.07	0.07	0.09	0.14	0.14	0.06	0.11	0.12	0.16	0.16	0.17	0.30
H_2O+	2.29	2.24	3.33	2.64	2.94	3.27	2.82	1.65	1.39	4.70	3.48	3.73	3.38
H_2O-	0.06	0.05	0.04	0.06	0.12	0.06	0.04	0.00	0.40	0.06	0.02	0.10	0.03
CO_2	0.11	0.66	0.06	0.90	0.73	0.07	0.10	0.10	0.10	3.59	1.75	1.63	2.79
Total	99.26	100.33	99.72	99.55	99.30	100.98	98.88	98.52	99.10	100.09	100.27	98.88	100.53
Mg#	0.68	0.68	0.75	0.73	0.68	0.62	0.73	0.70	0.65	0.59	0.52	0.52	0.52
Nb	5	<5	<5	6	12	9	9	15	12	<5	8	5	6
Zr	33	33	27	28	58	56	30	58	62	87	106	102	109
Y	18	17	18	17	21	21	16	19	26	27	34	32	33
Sr	107	124	128	170	89	139	88	146	97	69	46	67	99
Rb	5	6	8	7	7	8	5	5	7	<5	7	<5	9
Cr	882	869	1039	812	1443	690	681	683	413	52	5	21	<5
Ni	379	363	432	347	299	228	262	217	130	12	<5	9	<5
V	175	166	192	177	235	227	176	225	273	273	219	349	205
Sc	31	29	27	28	34	34	35	29	46	35	21	42	18
Ba	12	14	27	31	31	33	14	19	50	21	<10	14	69
Zn	82	80	58	63	87	72	58	68	94	145	430	84	101
Cu	<5	<5	95	65	41	6	5	19	5	21	45	53	<5
Yb	13	13	10	12	<10	<10	<10	<10	<10	<10	<10	<10	
Co	57	52	47	45	51	42	40	38	47	19	18	30	19
Ce	13	15	11	12	22	17	<10	<10	<10	17	20	23	28

*NOTES: Major elements given in wt.(, trace elements in ppm. Fe_2O_3 calculated as stoichiometric difference between FeO and total Fe as Fe_2O_3. Mg# calculated as Mg/(Mg + Fe^{2+}. *BAS–Bangardsvola 'anomalous' sample (see text).*

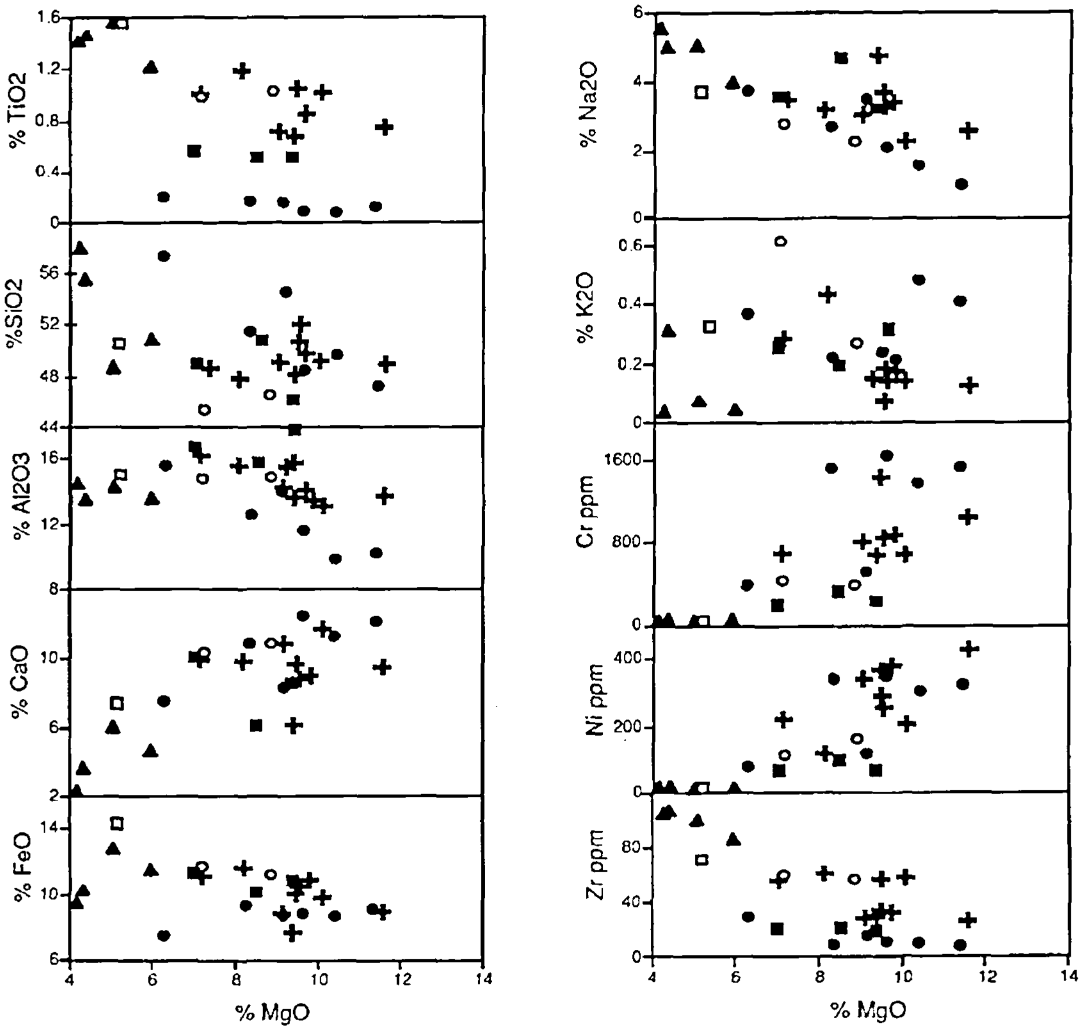

Fig. 7. Variation diagrams of major and trace elements versus %MgO. Filled circles–Bangardsvola Group I; filled boxes–Bangardsvola Group II; open box–'anomalous' Bangardsvola sample; crosses–Lomsjødalen complex; open circles–dike (?) samples; triangles–Fundsjø Group.

Fundsjø Group samples from just east of the shear zone contact are included for comparison.

Major and trace elements

Because the samples were all metamorphosed to greenschist or lower amphibolite facies, it can be expected that some elements, such as K, Ca, Na, and Si, may have been selectively mobilized (e.g. Geary & Kay 1983). Therefore, variation diagrams were constructed in order to assess the intensity of the alteration. When plotted against MgO as a differentiation index (Fig. 7), good igneous trends are present for most elements; for instance, CaO, Cr, and Ni tend to increase with increasing MgO, while Al_2O_3, FeO (total), Zr, and Na_2O decrease. Na_2O is particularly surprising in its consistent covariation with MgO, because it is considered mobile during both ocean floor alteration and greenschist facies metamorphism (Pearce 1975), although K_2O values are somewhat scattered, probably reflecting element mobility. The rock units of this study can be distinguished on the basis of their TiO_2 and Zr trends. With respect to TiO_2, the Bangardsvola samples can be divided into two distinct geochemical groups (Fig. 7). Group I is strongly depleted in TiO_2, and shows only a slight decrease with increasing MgO, while Group II is less depleted than Group I, but more so than samples from the Lomsjødalen complex or Fundsjø Group. The distinction between Groups I and II is less obvious with respect to Zr, although both are highly depleted in this element relative to the other units. The two groups can also be distinguished with respect to Cr and Ni, as most of the Group I samples are highly enriched in both elements in comparison with Group II. It should be noted that the two groups do not represent separate outcrop belts; in fact, some Group I and Group II samples were collected from the same outcrops. In such outcrops, they appear to be interlayered; however, this is at least in part due to transposition and development of metamorphic foliation, and it cannot be ruled out that one type originated as dikes cross-cutting the other.

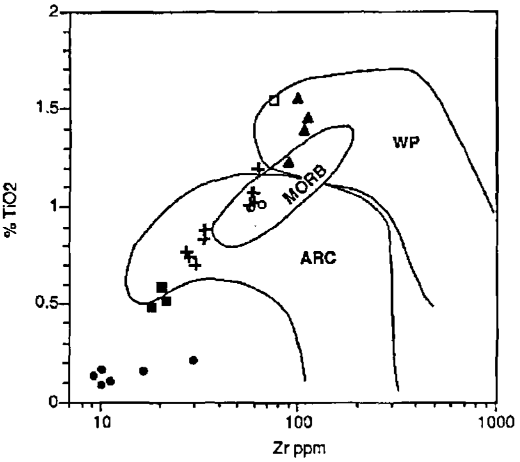

Fig. 8. TiO_2 vs. Zr plot (Pearce & Cann 1973). Symbols same as in Fig. 7.

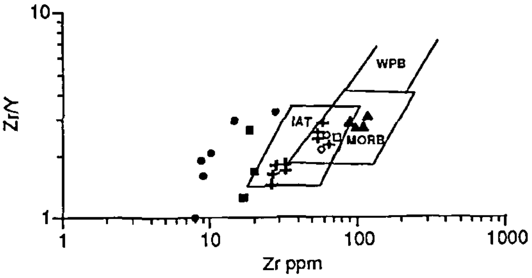

Fig. 9. Zr/Y vs. Zr plot (Pearce & Norry 1979). Symbols same as in Fig. 7.

Samples from the Lomsjødalen complex show consistent trends of decreasing TiO_2 and increasing Cr and Ni with increasing MgO, and the absolute abundances of Cr and Ni are relatively high. When Zr is plotted against MgO, the trend is flat and the samples appear to fall into two groups, although the less Mg-rich samples have the highest Zr values. The dike samples show trends similar to the Lomsjødalen metabasalts, and tend to plot with the most evolved of that group, suggesting a possible comagmatic relationship. The Fundsjø Group samples are all characterized by high TiO_2 and Zr, and extremely low Cr and Ni. Interestingly, one Bangardsvola sample (K2201) is quite anomalous, and generally plots with the Fundsjø analyses.

Tectonic discrimination diagrams

The elements Ti, Zr, Y, V, and Cr are considered to be relatively immobile during weathering and greenschist facies metamorphism (e.g. Cann 1970, Pearce & Cann 1971, Humphris & Thompson 1978, Shervais 1982), and several variation diagrams involving these elements have been shown to be useful in discriminating the tectonic setting of altered basic volcanic rocks (Pearce & Cann 1971, 1973; Pearce & Norry 1979, Pearce 1980, Shervais 1982). Pearce & Cann (1973) restricted the use of

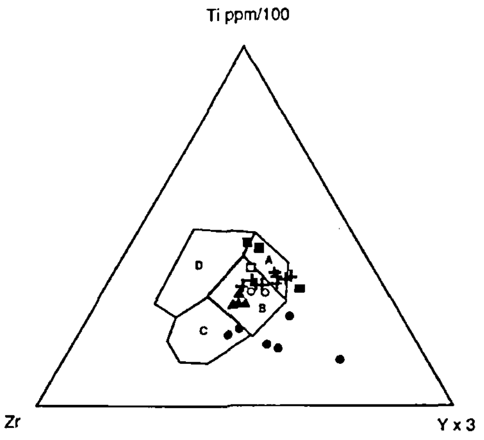

Fig. 10. Ti-Zr-Y plot (Pearce & Cann 1973). Fields are: A & B–island arc tholeiite; B–ocean floor basalts; C–calc-alkaline basalts; D–'within-plate' basalts. Symbols same as in Fig. 7.

the Ti-Zr-Y diagram to basaltic rocks in which CaO + MgO falls between 12 and 20%. In addition, the Ti-Zr (Pearce & Cann 1973) and Zr/Y-Zr (Pearce & Norry 1979) diagrams should not be used for lavas containing cumulate crystals, although the Ti-Zr-Y diagram can be applicable because it considers the relative proportions of these elements (Pearce & Cann 1973). Because the samples of this study are, in general, totally recrystallized, it is impossible to determine petrographically whether cumulate crystals were originally present. Geochemically, however, the Bangardsvola Group I samples tend to follow accumulation trends on the Al_2O_3/TiO_2 vs. Ti and Cr/Ti vs. Ti diagrams (not shown), similar to the Troodos upper pillow lavas (Pearce & Flower 1977), and the absolute abundances of Ti, Zr, Mgo, Cr, and Ni suggest that cumulate olivine may have been present in the original rock (Pearce & Cann 1973). Nevertheless, Bangardsvola samples are shown on the following diagrams in order to highlight their distinctive character relative to the more 'ordinary' behavior of the other units.

On the TiO_2 vs. Zr, Zr/Y vs. Zr, and Ti-Zr-Y diagrams (Figs. 8, 9, & 10), Lomsjødalen metabasalts plot almost exclusively in the island-arc tholeiite field. A few samples with relatively high absolute values of TiO_2 and Zr fall within the overlapping IAT-MORB fields, but lie along a trend suggesting they are comagmatic with the others. Again, the dike(?) rocks plot consistently with the Lomsjødalen samples in the overlapping field. In contrast, Fundsjø Group samples (and the anomalous Bangardsvola sample) show no indication of island-arc affinity, but appear to most closely resemble MORB, although their relatively high TiO_2 values place them in the 'within-plate' field on the TiO2 vs. Zr diagram (Fig. 8).

As discussed previously, Bangardsvola metabasalts are characterized by extreme depletion in Ti and Zr. Consequently, the typical discrimination diagrams are not very useful for these rocks, particularly for Group I samples. Group II rocks, however, do lie in or peripheral to the IAT field in each case. A more useful discriminator, perhaps, is the Ti-V diagram of Shervais (1982) (Fig. 11). Due to the varying valence states of V as a function of oxygen fugacity during partial melting and fractional crystallization, the

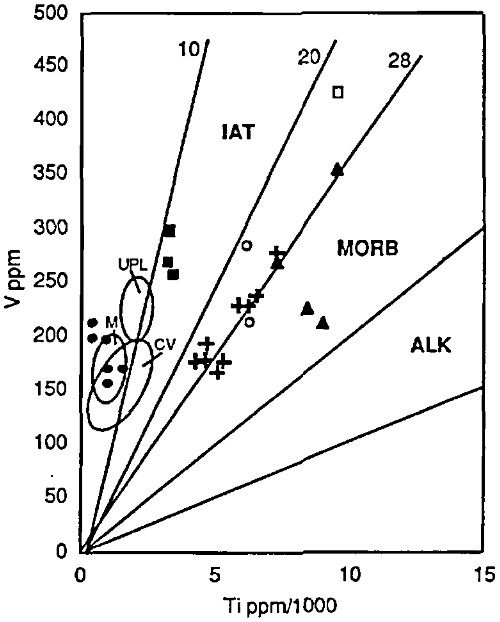

Fig. 11. Ti-V plot (Shervais 1982). Fields are: UPL–Troodos upper pillow lavas; M–Mariana forearc boninites; CV-Cape Vogel high-Mg andesites. Symbols same as in Fig. 7.

Table 2. Comparison of element concentrations and ratios between siliceous high-magnesian basalts (SHMB), komatiitic basalts, boninites, Bangardsvola Group I, and Lomsjødalen metavolcanic rocks.

	SHMB[a]	Komatiitic basalts[b] (average of 4 analyses)	Bonin Island boninites[c]	Troodos high-Ca boninites[d]	Northern Appalachian boninites[e]	Bangardsvola Group I matavolcanics[f]	Lomsjødalen metavolcanics[f]
% SiO_2	51-55	48.3	57-60	50-55	43-60	47.57	48-52
% MgO	6-16	14.7	5.7-12.3	11.1-16.3	6.5-15.6	6.4-11.5	7-11.5
% TiO_2	0.39-1.0	0.6	0.1-0.3	0.22-0.36	0.11-0.27	0.08-0.21	0.7-1.19
%FeO*	9.6-12.8	13.3	8.3-8.8	7.6-9.7	5.6-11.4	7.4-9.9	7.7-11.8
Al_2O_3/TiO_2	20-27	19	50-134	27-56	57-103	74-122	13-29
CaO/TiO_2	≈18	16	30-81	24-47	33-83	36-144	8-17
Sc/Y	2-3	-	4.5-22.5	4.4-5.8	3.3-34	3.5-13.6	1.5-2.1
Ti/Zr	50-75	128	16-48	56-239	29-102	43-96	106-169
Ti/Sc	≈74	-	3.5-5.5	32-49	14-45	14-36	120-213
Ti/V	≈15.5	16		6.0-9.5	-	2.7-7.6	24-30

Data sources: [a]Sun et al. 1989 (Archaean–W. Australia and early Proterozoic–Antarctica); [b]Arnt & Nesbitt 1982 (*in Schaefer & Morton 1991*) (Munro Township, Ontario); [c]Hickey & Frey (in Wilson 1989); [d]Cameron 1985 (in Crawford et al. 1989); [e]Coish 1989 (Ordovician–Betts Cove); [f]Present investigations.

covariation of these two relatively immobile elements can be a useful indicator of tectonic setting of various volcanic rock associations. MORB basalts have Ti/V ratios of 20-50 (Fig. 11), whereas the ratios for alkaline rocks are generally greater than 50. With the exception of calc-alkaline basalts, most modern island-arc related volcanic basalts have Ti/V less than 20. The ratios for calc-alkaline basalts are more variable due to the effects of magnetite fractionation (Shervais 1982); this should not be a problem for the present study, however, because there are no field, petrologic, or geochemical indications that any true calc-alkaline rocks are present among the units sampled.

Despite the consistent IAT affinity of Lomsjødalen rocks in the previous diagrams, all of the samples plot in the MORB field on the Ti/V diagram. The fact that some overlap occurs between IAT and MORB ratios (between 20 and 27) at V<350 ppm (Shervais 1982) may provide an explanation for this phenomenon, since the range of V in the Lomsjødalen samples is 166-273 ppm (Table 1). It must be noted, also, that ratios from back-arc basin basalts overlap both IAT and MORB fields, and these rocks tend to be less highly enriched in both Ti and V than typical island arc or MORB basalts.

Shown in Fig. 11 are fields for several volcanic suites considered to comprise lavas of the 'boninite series' (Meijer 1980, Crawford et al. 1989). Ti/V ratios of these suites are generally <10, implying a subduction-related setting, either within an island arc or a small marginal basin (Shervais 1982). Bangardsvola Group I samples all have Ti/V

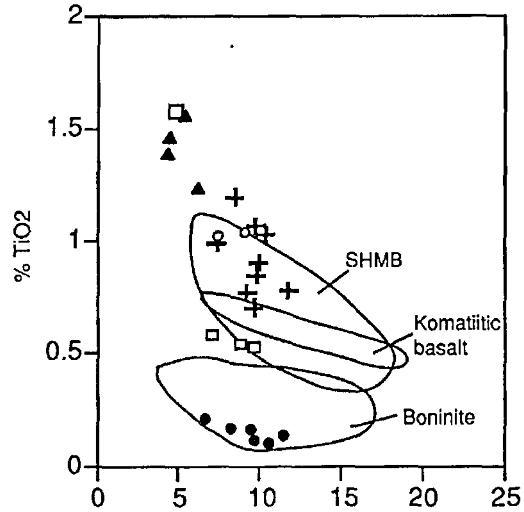

Fig. 12. TiO_2 vs MgO plot. SHMB–siliceous high-Mg basalt. Fields for boninite and komatiitic basalt from Coish (1989); field for SHMB from data in Sun et al. (1989). Symbols same as in Fig. 7.

less than 10, and fall in or peripheral to these fields, suggesting a similar tectonic setting. The Bangardsvola Group II ratios fall between 10 and 15, compatible with the resemblance to IAT in the previous diagrams.

Boninite vs. komatiitic basalt

Boninite (Cameron et al. 1979) is an unusual and relatively rare rock type identified from Mesozoic and Tertiary forearc and/or backarc settings, and from some older ophiolites. Meijer (1980) defined magmas of the 'boninite series' as characterized by silica saturation, enrichment in Mg, Cr, and Ni, and depletion in the high field strength elements (Ti, Zr, and Y) and rare earth elements relative to the tholeiitic series. Crawford et al. (1989) divided boninitic magmas into high-Ca and low-Ca suites, based on major element compositions. Both suites are characterized by magnesium numbers (Mg/Mg + Fe^{2+}) generally >0.6, but low-Ca boninites have SiO_2>55% and CaO/Al_2O_3<0.75, whereas high-Ca boninites have SiO_2<56% and $CaO/Al_2O_3 \leq 0.75$. In some areas, a transition between low-Ca and high-Ca types, and between high-Ca boninites and low-Ti arc lavas has been identified (Crawford et al. 1989). If the Bangardsvola Group I samples are indeed 'boninitic', as suggested by the Ti-V diagram (Fig. 11), they most closely resemble the high-Ca suite, similar to the Troodos upper pillow lavas.

Komatiitic basalts (SiO_2<50%) and siliceous high-Mg basalts (SiO_2=51-55%) are geochemically and petrographically similar to boninites (Cameron et al. 1979, Sun et al. 1989). Given the similarities, the possible 'boninitic' affinity of the Bangardsvola metabasalts, and 'komatiitic' affinity of the Gula greenstone (Nilsen 1974), it is important to ask how these rock types can be distinguished from one another, and how the Bangardsvola and Lomsjødalen samples compare with either boninites or komatiitic basalts. Some key element concentrations and ratios are given in Table 2. Whereas there is a wide overlap in most of the major element concentrations, the variations in the high field strength elements (Ti, Zr, Y) are noticeably different between komatiitic basalt or SHMB and boninite (Coish 1989). Boninites are characterized by TiO_2 contents generally less than 0.3%, regardless of SiO_2 or MgO content (Fig. 12), and the various ratios involving Ti consequently reflect its extreme depletion. Likewise, the Sc/Y ratio is higher for boninites than for komatiitic basalts or SHMB, due to depletion of Y in boninitic rocks. The Bangardsvola Group I samples compare well with boninites in the very low TiO_2 content (0.08-0.21%), and also in the comparable Sc/Y ratios. Bangardsvola Group II samples (not shown in Table 2) are more similar to SHMB because of their higher TiO_2 content, and appear to be geochemically transitional between these rocks and boninites (Fig. 12).

Lomsjødalen metabasalts do not show boninitic affinities, and are more similar, although not identical to komatiitic basalt or SHMB (Table 2). Most of the samples fall within the SHMB field on the TiO_2 vs. MgO diagram (Fig. 12). These samples compare favorably with other Gula greenstone samples of similar SiO_2 content (Nilsen 1974).

Trace element patterns

Trace element characteristics of basalts from different tectonic settings are commonly compared by use of the MORB-normalized spider diagram (Pearce 1982). Average compositions of different types of basaltic lavas show various patterns of enrichment or depletion relative to MORB (Fig. 13a). In particular, the broad concave-upward, U-shaped pattern of Tertiary boninites reflects the extreme depletion in the incompatible elements of high ionic potential, and enrichment in Cr (and to a lesser extent, Ni) relative to MORB. This pattern appears to be unique among basaltic lavas – although komatiitic basalt has a similarly shaped pattern (Coish 1989), the extent of depletion in the incompatible elements is not nearly so great.

Shown in Fig. 13b is the average compositi-

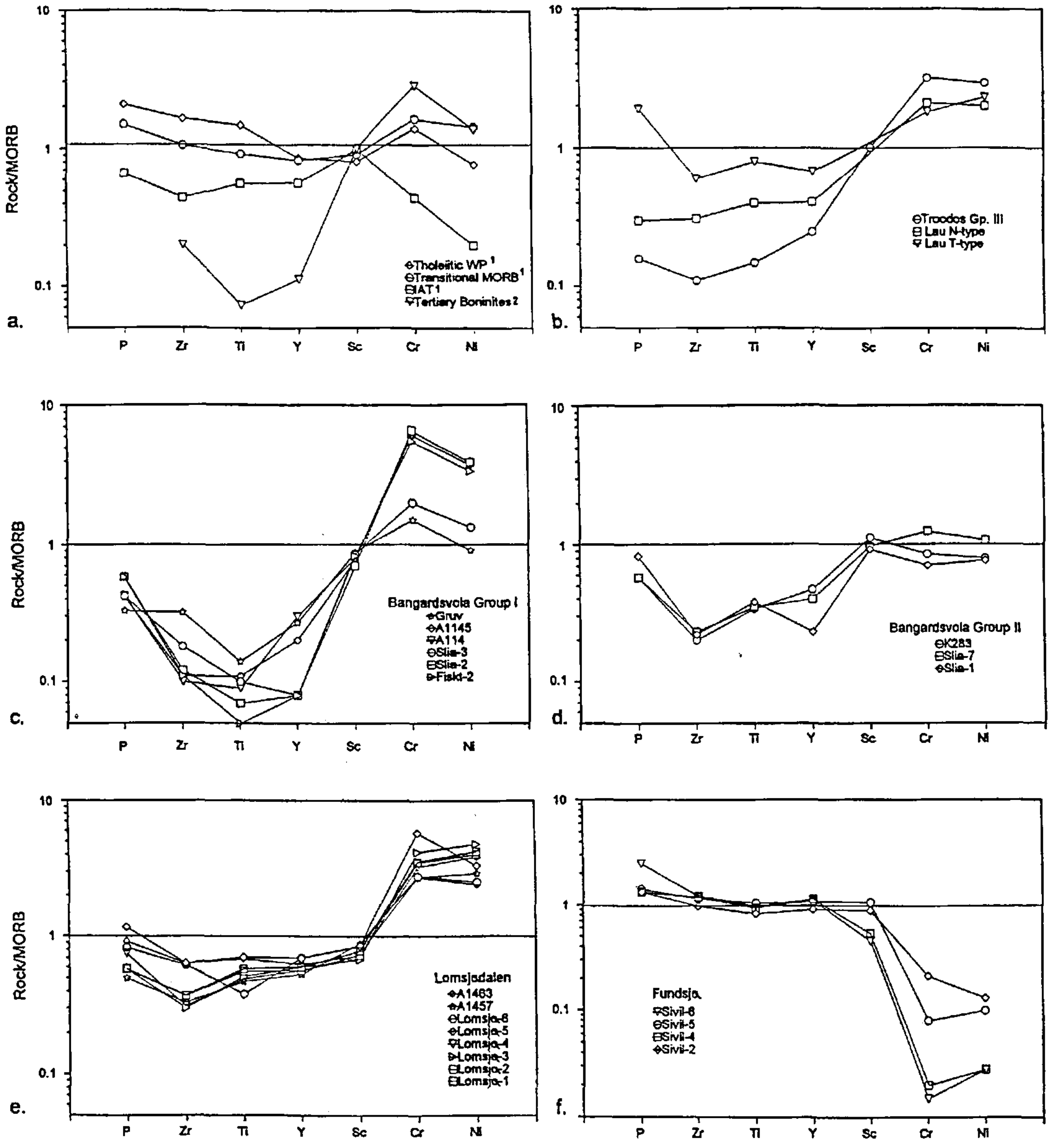

Fig. 13. MORB-normalized trace element diagrams: a) Trace element patterns for typical volcanic rock types. Sources: [1]Pearce (1982); [2]Hickey & Frey (1982). b) Average values for Troodos upper pillow lavas (Group III) (Cameron 1985), and Lau basin basalts (Hawkins & Melchior 1985). c) Bangardsvola Group I, this study. d) Bangardsvola Group II, this study. e) Lomsjødalen complex, this study. f) Fundsjø Group, this study. Normalizing values from Pearce (1982).

on of the 'Group III' upper pillow lavas of the Troodos ophiolite (Cameron 1985), which comprise the reference suite for the high-Ca boninites of Crawford et al. (1989). The Bangardsvola Group I samples (Fig. 13c) exhibit patterns that are nearly identical to that of the boninites (Figs. 13a & b). The Bangardsvola Group II samples differ in the less extreme depletion in Ti and Y, and in lower Cr and Ni values (Fig. 13d), resulting in patterns that are more similar to average IAT.

The trace-element patterns of the Lomsjødalen complex (Fig. 13e) resemble that of IAT with respect to the incompatible elements, but the high concentrations of Cr and Ni are uncharacteristic of typical IAT. This enrichment in the compatible elements, along with the rather high magnesium numbers (Table 1), indicates the primitive nature of the Lomsjødalen metabasalts. A comparison of the Lomsjødalen samples with basalts from the Lau basin, a backarc basin developed behind the Tonga-Kermadec ridge (Gill 1976, Hawkins 1976, Hawkins & Melchior 1985), shows similarities particularly in TiO_2, MgO (and Mg#), Cr, and Ni abundances. Lau basin basalts (LBB) are divided into two main geochemical groups (Hawkins & Melchior 1985). N-type LBB, suggested to be akin to N-MORB, occurs in the central part of the basin, while T-type LBB is found on the margins of the basin. For LBB having comparable magnesium numbers to Lomsjødalen metabasalts, the MORB-normalized trace element patterns for average abundances (Fig. 13b), particularly of the N-type, show a strong resemblance to those of the Lomsjødalen samples.

The four Fundsjø Group samples are characterized by somewhat transitional compositions (Fig. 13f) – whereas the incompatible elements show a flat pattern, near unity relative to MORB, the rocks are extremely depleted in Cr and Ni, similar to island-arc tholeiite. Although this study admittedly contains a limited representation of the Fundsjø rocks, the geochemical signature of these samples contrasts highly with that of the Bangardsvola complex, which was previously correlated with the Fundsjø Group (Mosson et al. 1972, Nilsen & Wolff 1989).

Discussion

Paleotectonic setting

Metabasalts of the Bangardsvola complex comprise a combination of primitive island-arc tholeiites and basalts having boninitic affinities. Although the latter are generally lower in SiO_2 than most Tertiary boninites, they are essentially identical to the 'high-Ca' boninite suite of Crawford et al. (1989). Various models have been proposed for the generation of boninitic lavas (Cameron et al. 1979, Meijer 1980, Crawford et al. 1981, Hickey & Frey 1982, Crawford et al. 1989), but there is a general consensus that they form by partial melting of a depleted mantle source in a subduction-zone setting. Boninites are generally associated with tholeiitic basalts of island-arc, or less commonly, MORB to BABB affinity, and the spatial and temporal relationships are important to the petrogenetic models. In the western Pacific Mariana-Bonin arc systems, boninites occur in the forearc regions and have been interpreted to represent the earliest stages of island arc volcanism (Hickey & Frey 1982, Hawkins et al. 1984, Bloomer & Hawkins 1987). The characteristics of the earliest stages of arc volcanism are still relatively unknown, because the roots of most modern-day arcs are covered by subsequent volcanic material and sediment. Stern and Bloomer (1992) based a model for the early evolutionary stages of subduction-zone development on observations from the Izu-Bonin-Mariana arc system, the characteristics of which include formation of tholeiitic and boninitic magmas in an extensional environment prior to stabilization of the volcanic-arc axis. Boninitic lavas also occur overlying arc tholeiites, for instance, in DSDP Hole 458 in the Mariana forearc (Meijer 1980), the Thetford Mines ophiolite, Quebec (Coish 1989), and the Troodos ophiolite (Cameron 1985), or interlayered with arc tholeiites on Guam (Reagan & Meijer 1984), and in the Betts Cove ophiolite, Newfoundland (Coish et al. 1982, Coish 1989). In addition, at Betts Cove, the boninites are overlain by lavas similar to MORB or BAB basalts. These observations suggest that boninites may also be generated during arc rifting and initiation of backarc spreading (Crawford et al. 1981). Based on its boninitic geochemical signature, the Bangardsvola complex most likely formed in a supra-subduction zone setting as defined by Pearce et al. (1984), either in the initial stages of arc formation or during subsequent backarc development. The absence of a major overlying arc sequence could argue for the former interpretation.

Based on geochemistry alone, the Lomsjødalen complex appears to be arc-related (e.g. Figs. 8-10); however, the paleotectonic setting is more equivocal, particularly since mid-ocean ridge lavas showing depletion of incompatible elements relative to normal MORB have been identified (Marsh et al. 1983). Field relationships, however, may provide some insight into its derivation. The association of thick sequences of quartzose and calcareous metasedimentary rocks and volcaniclastics (Volengsvola/Svartlia units) with the Lomsjødalen complex suggests proximity of either an island or a continental margin (Nilsen 1978). In contrast, the thinly layered metachert, coticule, sulfidic black phyllite, and metalliferous sedimentary rocks that directly overlie the pillow lavas appear to be analogous to pelagic muds and hydrothermal deposits that blanket oceanic crust at modern-day spreading ridges. Indeed, the pods of iron formation and sulfide mineralization may represent 'fossil' black smokers, loci of hydrothermal vents where circulating metalliferous brines are exhaled(McClellan 1992, 1993). The abundance of high-Mn coticule horizons is greatest in rocks surrounding the mineralized zones, and decreases gradually away from the zones. This pattern is predictable from modern-day hydrothermal vents, where the readily oxidized Fe-rich phases are precipitated at the vent, while the Mn-rich phases (less easily oxidized) are carried farther from the exhalation site (Bonatti 1975, Jenkyns 1986). In a comparison of sedimentation in marginal basins vs. volcanic arcs, Carey & Sigurdsson (1984) noted that Fe- and Mn-rich hydrothermal deposits have been documented at backarc spreading centers (for instance, Bonatti et al. 1979; Cronan et al. 1984). In fact, the discovery of high Fe and Mn concentrations in sediment from the Lau basin led Cronan et al. (1984) to suggest the presence of hydrothermal vents in the vicinity of the axial rift of the basin.

The combined sedimentological and geochemical evidence from the Lomsjødalen complex in this study and from the correlative Gula greenstone in previous works (Nilsen 1974, 1978; Rainey 1980) suggests derivation of the volcanic complex in a subduction-related setting, but one that was characterized at least locally by an extensional regime. A back-arc spreading center such as the Lau basin example discussed previously may provide the most likely analogy. However, the extensional environment would also be compatible with the initial stages of subduction, as in the model by Stern & Bloomer (1992) discussed above.

The Lomsjødalen and Bangardsvola complexes are interpreted to have been emplaced onto the continental margin as a composite thrust nappe (McClellan 1993, 1994). Geochemically, both complexes could be considered as part of the common boninite/tholeiite association. Stratigraphic relationships between the complexes remain unresolved, however, because of internal deformation within the thrust sheet and lack of age constraints. Although the uncertainties preclude a comprehensive model that ties together the formation of both complexes, several observations suggest that the mafic complexes may have been associated both spatially and temporally. In the study area, the Lomsjødalen and Bangardsvola complexes are in contact with quartzose or calcareous schist that locally contains dike-like mafic layers bearing similar geochemical signatures to that of the Lomsjødalen basalts, and may be slightly more evolved products of the same magmatic event. Fuchsite-bearing marble and quartzite and associated conglomerates that comprise the highest unit in the Savalen thrust sheet are locally in contact with both mafic complexes; the nature of the contact suggests either an early fault or an unconformity that developed prior to emplacement of the Savalen thrust sheet. The presence of fuchsite indicates the proximity of a high-Cr source, possibly derived from erosion of the boninitic rocks or Lomsjødalen basalts.

A possible analogy for the Bangardsvola and Lomsjødalen complexes is the upper part of the Late Cretaceous Troodos ophiolite, Cyprus, in which a sequence of higher-Ti 'lower pillow lavas' is overlain by low-Ti 'upper pillow lavas.' The upper pillow lavas include not only the type high-Ca boninites of Crawford et al. (1989), but also less depleted lavas similar to komatiitic basalts (Cameron, 1985). Massive sulfide deposits are intercalated with, or overlie the lower pillow lavas, and are in turn overlain by Fe-rich metalliferous sediments (ochres) (Constantinou 1980, Hamelin et al. 1988), while sediments rich in both Fe and Mn (umbers) overlie the upper pillow lavas (Robertson & Hudson 1974). Fragments of hydrothermal vents, or black smokers, have also been identified from massive sulfide deposits intercalated between the lower and upper pillow lavas (Oudin & Constantinou 1984). Although Troodos is one of the most well-studied ophiolites in the world, its tectonic setting is still highly debated. Early workers recognized the complex as a section of oceanic crust (Gass 1968, Moores & Vine 1971, Gass & Smewing 1973), and the presence of an extensive sequence of sheeted dikes is indicative of formation in a spreading environment. Early geochemical studies, however, showed island-arc affinities for the complex (Miyashiro 1973, Pearce 1975). The necessity of reconciling the spreading center field characteristics with the arc geochemistry has led to numerous hypotheses concerning the tectonic setting, including formation in an interarc basin (Pearce 1975; Gass 1980), in a supra-subduction zone environment with no arc development (Pearce et al. 1984), or as the earliest stages of an island arc (Rautenschlein et al. 1985). Moores et al. (1984) suggested that an actualistic model for the Troodos and related Mideast ophiolites may be the Andaman Sea region of the Indian Ocean, where short spreading segments formed above an oblique subduction zone, and are separated by transform faults. The region is characterized by an active ridge-transform system rather than development of a continuous, mature arc. This model was later modified to include the possibility of splitting of an immature, submarine arc prior to back-arc spreading (Flower & Levine 1987, Thy & Moores 1988).

Comparisons with Norwegian ophiolite sequences

Although a complete ophiolite stratigraphy has not been recognized in the Einunnfjellet-Savalen area, the complexes can be compared with the higher volcanic/sedimentary parts of more complete ophiolite sequences. Norwegian ophiolites can be divided into two main groups (Pedersen et al. 1988, Sturt & Roberts 1991): Early Ordovician complexes that developed mainly in a suprasubduction-zone setting; and Late Ordovician to Early Silurian complexes that probably represent small, spreading-related marginal basins. Isotopic dating is not yet available for meta-igneous rocks in the Einunnfjellet-Savalen area, but they are lithologically and geochemically most similar to the former group of Early Ordovician ophiolites. For example, they compare well with those in southwestern Norway, including the extensively studied Karmøy ophiolite (Sturt & Thon 1978b, Sturt et al. 1979). The Karmøy igneous complex, which formed between 493 and 470 Ma (Dunning & Pedersen 1988), consists of an axis sequence of gabbro and sheeted dikes formed from IAT and MORB-like magmas, that was subsequently intruded by magmas with boninitic affinities (Pedersen & Hertogen 1990). Later intrusions graded from boninitic back into IAT- and MORB-like compositions, whereas the youngest intrusions and extrusions were calc-alkaline to alkalic. Pillow lavas in the Karmøy ophiolite are capped by a well-developed pelagic sequence, the Torvastad Group (Sturt et al. 1979, Solli 1981), that contains Mn-rich chert and various metalliferous sediments similar to those associated with the Lomsjødalen complex. Comparable Mn-rich metasedimentary rocks and metachert are also associated with mafic rocks in the Samnanger Complex, Major Bergen Arc (Thon 1985) and in the correlative but more strongly deformed Nordåsvatn Complex, Minor Bergen Arc (Fossen 1989).

Regional tectonic relationships

Previous studies of the Fundsjø and correlative (?) Hersjø rocks in the eastern Trondheim Nappe district (Grenne & Lagerblad 1985, Grenne 1988, Skyseth & Reitan 1992) have shown both along-strike and across-strike geochemical variations that range from IAT (Skyseth & Reitan 1992, Grimsdalen area), to MORB and transitional types, including HFSE-depleted types (Grenne & Lagerblad 1985, Meråker area; and Grenne 1988, Røros area). The latter type from the Røros area resembles the Bangardsvola Group II rocks, and in some respects the least Mg-rich samples from the Lomsjødalen complex, although it does not show the extreme depletion characteristic of the boninitic Bangardsvola Group I metabasalts. More recently, boninitic rocks have been identified within the Fundsjø sequence in the Folldal area, immediately west of the present study area (Bjerkgård & Bjørlykke 1994). Based on lithologic, stratigraphic, and geochemical similarities, as well as proximity, these rocks are almost certainly correlative with the Bangardsvola complex. As discussed previously, Bjerkgård and Bjørlykke (1994) described the contact between the Fundsjø Group and the Åsli Formation of the Gula Nappe as primary in the Folldal area. In that area, they recognized only one thin horizon of Gula greenstone separating the Åsli from the Singsås Formation. Evidence from this study has shown no evidence of a fault contact between the Åsli pelites and rocks equivalent to the Gula greenstone. To the east of the Einunnfjellet-Savalen area, a fault contact does exist with metavolcanic rocks of the Fundsjø Group (Fig. 2), although the amount of displacement on the fault is unknown (McClellan 1993, 1995). The limited data presented here for Fundsjø basalts from east of this contact, however, show that they exhibit markedly different geochemical characteristics than Fundsjø rocks of the Folldal area, or the Bangardsvola complex. These observations stress the need for continued field, geochemical, and isotopic age studies in order to resolve the relationships between the rocks of the eastern Trondheim district and the Gula Nappe, as well as some units that have been assigned to the Seve Nappes (i.e., parts of the Bangardsvola complex of this study).

Based on the geochemical complexity of the Fundsjø/Hersjø sequence, the eastern Trondheim district metavolcanites were interpreted to have formed in either an immature ensimatic arc (Grenne & Lagerblad 1985), or a marginal basin above a subduction zone (Grenne 1988). Stephens & Gee (1985) also proposed a rifted-arc model for possible Fundsjø correlative rocks in the Gjersvik Nappe. In this model, the Gula Nappe was interpreted as a fore-arc basin developed in front of an arc in the Gjersvik terrane, which formed near the Laurentian margin. The features of the Einunnfjellet-Savalen area, however, show greater resemblance to their Virisen terrane, formed near the Baltoscandian margin; characteristics of this terrane include lack of a significant tectonic break between the Köli and Seve Nappes, presence of solitary ultramafic bodies or detrital serpentinites, and the presence of an overlying sequence of clastic rocks that were apparently derived from an eastern platformal or cratonic source. In addition, the Einunnfjellet-Savalen area is tentatively correlated (McClellan 1993, 1994) with the Otta Nappe, including the Early Ordovician or older Vågåmo ophiolite (Sturt et al. 1991), which Stephens and Gee (1985, 1989) considered to be part of the Virisen terrane. Therefore, the possibility exists that parts of the Virisen and Gjersvik terranes are correlative, and therefore could not have been entirely separated by a segment of the Iapetus Ocean, as in their model. Perhaps these and other Scandinavian ophiolitic sequences are best explained in the context of a complex, rapidly evolving subduction-zone environment such as the modern-day examples of arc systems described by Hamilton (1988), or as segments of oceanic crust separated by a system of transform faults above a subduction zone (Sturt & Roberts 1991), similar to the Andaman Sea example discussed previously. Recently, Bergman (1993) suggested that the Andaman Sea region may serve as an analogy for the Virisen terrane, and for possibly correlative Köli rocks of uncertain age in the Handöl area, central Swedish Caledonides.

Conclusions

The paleotectonic setting of the Gula Nappe is a critical element in attempts to model the development of the Trondheim Nappe Complex. Studies of mafic metavolcanic rocks that occur throughout the Gula Nappe may hold the most promise for determining the environment of formation, and relationship of the Gula rocks to other tectonic units within the Trondheim Nappe Complex. Gula greenstone-equivalent metabasalts in the Einunnfjellet-Savalen area, informally referred to as the Lomsjødalen complex, appear to be primitive arc tholeiites, resembling typical IAT in terms of incompatible elements but enriched in Cr and Ni, and having rather high magnesium numbers. Overlying metalliferous sediments and possible remnants of black smokers, however, suggest formation of the complex in some type of extensional environment. The Lomsjødalen complex is interpreted to have been emplaced prior to or during the earliest Ordovician as part of the Savalen thrust complex. Also in the thrust complex is a bimodal metavolcanic sequence, termed the Bangardsvola complex, that contains mafic rocks with boninitic affinities uniquely characteristic of subduction-related settings.

Geochemically, the complexes could be considered as part of the common boninite/tholeiite association, and the characteristics of both complexes are compatible with formation either during the initial stages of arc development, or rifting of an arc and initiation of backarc spreading. The association of primitive arc tholeiites, boninites, and Fe- and Mn-rich metalliferous sediments is strongly analogous to the upper parts of the Troodos ophiolite, Cyprus.

The Bangardsvola complex was previously correlated in part with the Fundsjø Group (Köli Nappes) and in part with the Essandsjø Nappe (Seve Nappes) (Nilsen & Wolff 1989). Results of this study show that Bangardsvola rocks of boninitic affinity are geochemically and lithologically identical to metabasalts of the Fundsjø Group in the Folldal area, but have distinctly different geochemistry compared to Fundsjø metabasalts in the eastern part of the study area. Correlation with rocks equivalent to the Seve Nappes, if correct, would suggest that the Seve is a composite unit, consisting not only of Baltoscandian miogeoclinal rocks (Stephens & Gee 1985), but also containing higher-grade equivalents of the Köli oceanic terranes.

Acknowledgements

Field work for this project was supported by Norges geologiske undersøkelse (NGU), the University of Tennessee Science Alliance Center of Excellence Distinguished Scientist stipend for Prof. Robert D. Hatcher, Jr., the Geological Society of America, Sigma Xi, and the Discretionary Fund of the Department of Geological Sciences, University of Tennessee. A nine-month research term at NGU was made possible through an American-Scandinavian Foundation Research Fellowship. I am extremely grateful to Brian A. Sturt, Fredrik Chr. Wolff, and the staff of the Analytical Chemistry Section at NGU for their help and support during this period. During my stay in Norway, stimulating field excursions and/or geologic discussions with David Roberts, Odd Nilsen, David Gee, Allan Krill, and Tor Grenne provided many insights into Caledonian tectonostratigraphy. In particular, I thank Tor Grenne of NGU for first suggesting that some of my mafic samples with 'weird' geochemical signatures might be boninites, and then patiently steering me toward some key references when it was obvious that I had never heard of a such a rock. I would also like to thank Allan Krill and his students from Norges Tekniske

Høgskole for logistical and field assistance, and Ivar Killi and Folldal Kraftwerk for access to shallow cores from the Folldal and Savalen area.

Robert Hatcher, Jr., Hap McSween, Steve Driese, and Carl Remenyik are thanked for reviewing an early version of the manuscript; and also Marvin Bennet, Lauren Browning, and Ralph Harvey for helpful comments. The final version greatly benefitted from reviews by Harald Furnes and Tor Grenne.

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Manuscript received August 1994; revised typescript accepted May 1995