Geology and petrochemistry of the Smøla-Hitra Batholith, Central Norway

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The plutonic rocks which compose the Smøla-Hitra Batholith (SHB) cover an exposed area of c. 1000 km² and intrude folded, Arenig-Llanvirn, low-grade metasedimentary and bimodal metavolcanic rocks and higher-grade, polydeformed gneisses of probable Proterozoic age. The SHB is unconformably overlain by Old Red Sandstone sediments of possible Late Silurian to definite Middle Devonian age. Field relations demonstrate that the oldest rock-types in the batholith comprise gabbro, monzodiorite and hornblende diorite. These are succeeded by tonalite, granodiorite and granite, which occur both as plutons and as abundant dykes and veins. Later members of the SHB include composite dykes, porphyritic microdiorite, appinitic pipe-like bodies, dolerite dykes and, lastly, granophyre dykes. The hypabyssal rocks post-date a phase of weak, heterogeneous deformation manifested locally within the various plutons. Pressure estimates from hornblende compositions indicate a pressure of solidification of 0.26 ± 0.1 GPa, corresponding to a depth of about 9 km. Preliminary isotopic dating has indicated an age range from c. 450 to c. 428 Ma; latest Mid-Ordovician to Early Silurian. The rocks of the SHB show little sign of the Scandian deformation and metamorphism which are so common elsewhere in this part of Norway.

The plutonic and hypabyssal members of the SHB are characterised by fairly high-K calc-alkaline compositions, which suggest emplacement in a mature magmatic arc setting, probably at the terminal stage of a subduction cycle. The observed major and trace element variations and high LREE/HREE ratios are compatible with the evolving magmatic processes in such a tectonic environment. Chemical variations in the diorites and granites can be explained by fractionation of plagioclase, hornblende, pyroxene and K-feldspar. In age and composition the SHB has much in common with other plutonic complexes in southern and central Norway e.g. the Sunnhordland Batholith and the Heilhornet Pluton. This bears witness to an important Ordovician to Early Silurian tectonomagmatic cycle prior to the continent-continent collision which initiated the Scandian orogeny.

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Introduction

The Smøla-Hitra Batholith (SHB) is one of the major plutonic complexes within the Upper Allochthon of the Norwegian Caledonides, occupying an exposed area of approximately 1,000 km² mainly on the islands of Smøla and Hitra, ca. 100 km west of Trondheim (Fig.1). In recent time, geological interest in these islands has focused principally on the palaeontology of limestones on Smøla (Bruton & Bockelie 1979), and the occurrence of Upper Silurian to Lower Devonian Old Red Sandstone deposits on Hitra and small islands just south of Smøla (Peacock 1965, Siedlecka & Siedlecki 1972, Bøe 1986, 1988, 1989, Atakan 1988). The geochemistry of Arenig-Llanvirn volcanic rocks on Smøla has also been investigated (Roberts 1980). By comparison, the plutonic rocks which make up the bulk of these islands (Fig.1) have received scant attention, an exception being that of a description (Fediuk & Siedlecki 1977) which accompanied the 1:50,000 map-sheet Smøla (Fediuk 1975). The objectives of this paper are firstly to provide a description of the plutonic rocks in the order of their sequence of emplacement and relationships with the envelope; and secondly to outline the characteristics of the petrochemistry of the plutonic rocks. In our descriptions of field relationships emphasis will be placed on the non-deformed or weakly-deformed parts of the batholith. We will also consider the more peripheral granitic bodies exposed on Frøya and Ørlandet.

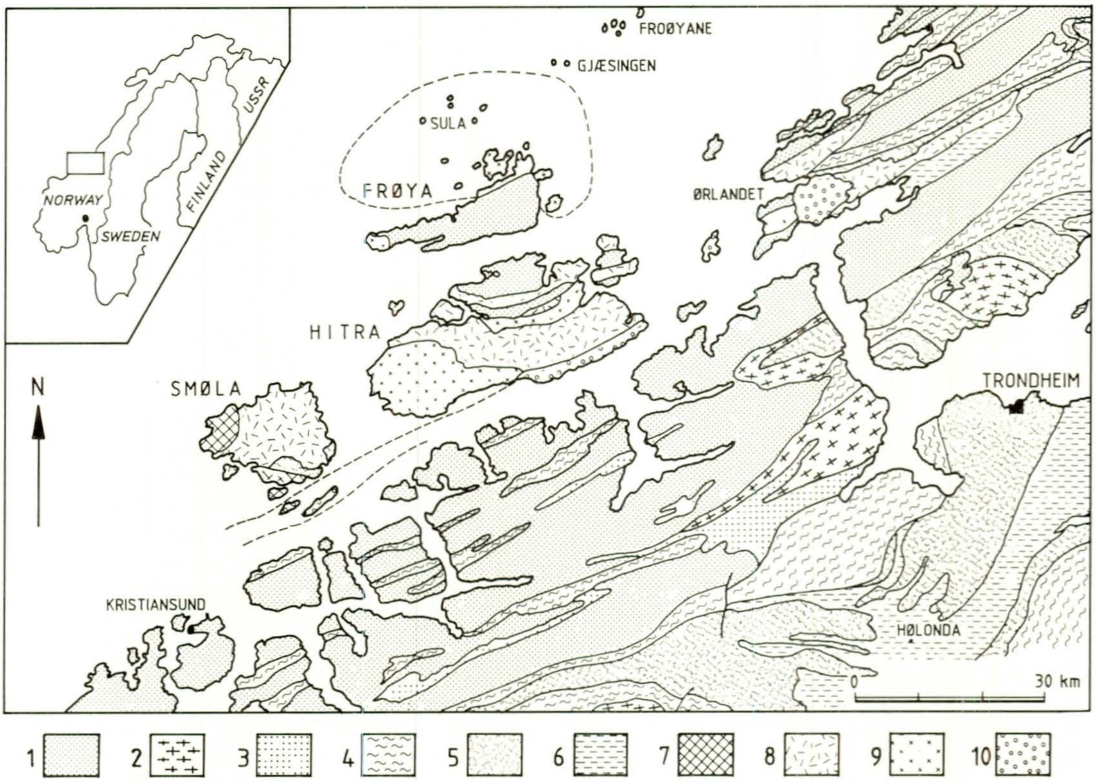

Fig. 1. The regional geological setting of the Smøla-Hitra Batholith. The map is simplified and modified from Sigmond et al. (1984). Units 1-6: allochthonous units in the Caledonides. 1 - Undifferentiated Proterozoic gneisses, Western Gneiss Region/Vestranden. 2 - Granitic gneiss, augen gneiss, Proterozoic age. 3 - Metasandstones, Late Precambrian. 4 - Garnet-mica schist, amphibolite in the Skjøtingen and Blåhø Nappes: phyllite in southeast within the Gula Nappe. 5 - Metabasaltic greenstone, amphibolite, in part ophiolitic; Early Ordovician age. 6 - Low-grade metasediments and volcanites; mostly Ordovician age. Units 7-9: Caledonian intrusive rocks, mainly Ordovician age. 7 - Gabbro. 8 - Hornblende diorite. 9 - Granite, granodiorite, tonalite. 10 - Old Red sandstone sediments, Latest Silurian to Middle Devonian age. The area enclosed by the dashed line in the north (Frøya to Sula) is one exposing granitic rocks on hundreds of islands and skerries.

Geological setting

The first geological investigations in the Smøla-Hitra area were those of Schetelig (1913) and Reusch (1914). They gave an outline of the general geology and described the unconformable contact at the base of the Old Red Sandstone sediments (Fig. 1). Both these authors found an area with Lower Ordovician supracrustal rocks in the southern part of Smøla (Fig. 1), and most of the later investigations have concentrated on these particular rocks (Holtedahl 1914, Carstens 1924, Strand 1930, Bruton & Bockelie 1979, Roberts 1980).

The first comprehensive geological map of part of the batholith was that of Kollung (1964) covering the northern part of Hitra. Fediuk (1975) subsequently mapped the island of Smøla, at the scale of 1:50,000. These maps are the basis for the parts of the batholith which are included on the 1:250,000 mapsheets 'Trondheim' (Wolff 1976) and 'Kristiansund' (Askvik & Rokoengen 1985). In later years, reconnaissance work on parts of the batholith has been reported in Bering et al. (1986) and a more detailed field study of the plutonic rocks on the southern part of Smøla was presented by Gautneb (1987). The structure and modes of emplacement of the dyke phases on Smøla have been described by Gautneb (1988).

During our work within the batholith area we have found that most of the published maps are essentially correct. Few of the earlier authors had, however, any clear understanding of the nature of the contacts between many of the rock units, and the sequence of polyphase intrusion had not been established. Also, no comprehensive geochemical study of the plutonic rocks has been undertaken.

Fediuk (1975) considered the foliated hornblende-biotite gneisses and other gneissic and migmatitic rocks from central and northern Smøla as being of probable Precambrian age, and deformed and metamorphosed in Precambrian time. Both Schetelig (1913) and Carstens (1924) had interpreted these gneissic rocks as sheared diorites, an opinion followed by Råheim (cited in Bruton & Bockelie 1979) and shared by the present authors.

Precambrian basement gneisses, of Proterozoic age, do occur in the vicinity of the SHB, in northern Hitra (Kollung 1964), on Frøya, and on the mainland to the south and east (Råheim 1972, Tucker et al. 1987) (Fig. 1), where they form part of the Western Gneiss Region. Dioritic rocks similar to those on Smøla and Hitra, and locally strongly sheared, occur to the north and east of the ORS outcrop at Ørlandet on the Fosen Peninsula. These are probably of comparable age and origin to those in the SHB.

Similarities in geochemistry and mineralisations have also been noted between the volcanic rocks on Smøla and those from the Snåsa district some 130 km along strike northeast of Ørlandet (Roberts 1982a). These volcanites and the associated dioritic rocks (Fig. 1; see also Sigmond et al. 1984) may thus form part of an elongate geological terrane (Roberts 1988). Support for this notion is also found in the distinctive faunas, of North American affinity, occurring in the limestones on Smøla (Bruton & Bockelie 1979) and in the Snåsa district (Spjeldnæs 1985).

Field descriptions of the batholith and its envelope

The envelope

The plutonic and hypabyssal rocks which compose the SHB were emplaced into or are overlain by the following rock-types (fig. 1):

1. Polyphasally deformed, high-grade ortho- and paragneisses of uncertain, but probable Proterozoic age.
2. Arenig to Llanvirn metasupracrustal rocks, comprising marbles, sandstones and conglomerates, with interbedded felsic to mafic volcanites.
3. Upper Silurian to Middle Devonian Old Red Sandstone sediments. These rocks unconformably overlie most of the major rock types within the batholith, and all rocks presently exposed in the batholith occur as clasts in the ORS sediments.

Gneissic rocks

HITRA

On Hitra, most of the gneissic rocks in this category occur north of Strømfjorden and Fillan (Plate 1). This area was investigated by Kollung (1964) who emphasized the petrographical and lithological variations in the gneisses and associated rocks. Kollung (1964) grouped the gneisses into paragneisses and orthogneisses, and divided the former into heterogeneous mica gneisses, biotite gneisses and marbles, locally with zones of mica schists. The presence of minerals such as sillimanite, almandine and K-feldspar indicates metamorphism in the upper amphibolite facies (Kollung 1964). The orthogneisses can be grouped into hornblende gneisses, augen gneiss and amphibolite with small areas of greenschist. In places the gneisses are migmatitic and leucocratic veins are abundant.

The structural and metamorphic history of the gneisses in northern Hitra is virtually unknown, but the rocks have clearly been affected by complex polyphasal deformation. In the northernmost part of the island the gneisses carry a pervasive E-W foliation which gradually fades away towards the south and disappears in the area south of Strømfjorden.

Because of the intense deformation the protoliths to the gneisses of northern Hitra are not known. However, further south in the area around Strømfjorden one can see that some parts of the gneisses investigated by Kollung (1964) represent strongly deformed varieties of rocks belonging to the SHB. On the other hand, it is probable from the contact relationships that most of the gneisses pre-date the batholith. Lithological character and similarities also suggest that some of the gneisses on Hitra may be of the same type as those found along strike to the northeast on the Fosen Peninsula.

SMØLA

Fediuk's (1975) 1:50,000 bedrock map, as noted earlier, shows large areas of gneisses and migmatities on Smøla as enclaves within the plutonic rocks, an interpretation which is difficult to justify. These hornblendic gneisses are merely deformed varieties of the plutonic rocks, but Gautneb (1987) recognised small rafts of gneisses which had a polyphasal tectonometamorphic history entirely post-dated by rocks belonging to the SHB. These gneisses are found near Straumen in southern Smøla and occur as biotite- and hornblende-bearing enclaves in the batholithic rocks. The origin and age of these particular gneisses are presently unknown. It may be speculated that they could represent a basement to the Lower Ordovician supracrustals, but no similar gneisses of this type have yet been reported from Hitra or the adjacent mainland.

FRØYA AND ØRLANDET

On Frøya (Fig. 1), the gneisses are strongly migmatitic and with high-strain zones where the rock is converted to dark, mica-rich, banded gneisses (Bering et al. 1986). The migmatites, which enclose lenses of amphibolite, marble and mica schist in the foliation, are intruded by abundant veins of granite. This granite is a similar type to the Frøya Granite which crops out extensively in NE Frøya (Torske 1983).

On Ørlandet, a flat area representative of the Tertiary 'strandflat', the contacts to the Lerberen Granite (Plate 1) are nowhere seen. The body is considered to be delimited by steep faults (Siedlecka 1975), with gneiss, amphibolite and marble to the north, meta-arenite and schist to the south, and ORS deposits to the east and west.

Arenig to Llanvirn supracrustal rocks

These metasedimentary and metavolcanic rocks occur as large enclaves in the batholith in the southern parts of Smøla (Plate 1) as well as numerous rafts and xenoliths elsewhere and on the adjacent smaller islands and skerries (Fediuk 1975). As mentioned above, these rocks have been the topic of several earlier investigations within the archipelago, attracted by the occurrence of a well-preserved fossil fauna of Arenig to Llanvirn gastropods, brachiopods and conodonts with a North American affinity (Strand 1930, Bruton & Bockelie 1979, 1980).

Bruton & Bockelie (1979) established a stratigraphy for these rocks and demonstrated that they are disposed in open to tight, partly overturned folds. The lithostratigraphy consists of the possibly pre-Arenig, conglomeratic Leirvik Formation overlain by the Arenig-Llanvirn Skjølberg Formation consisting, by definition, of limestones with some siltstones. Volcanic rocks, ranging from basalts to rhyolites (Roberts 1980), interdigitate with the limestones, and are thus not entirely younger than the Skjølberg Formation as Bruton & Bockelie (1979) had suggested. The sedimentary rocks are intruded by numerous basaltic dykes, which are the hypabyssal equivalents of the volcanic rocks.

The greenschist-facies volcanic rocks occur mainly as massive subaerial lava flows up to 10 m in thickness, and igneous textures are preserved locally. The alternation between single flows is most readily made where the degree of deformation is low and there are compositional variations between rhyodacite and basalt. Tuffs are locally associated with the lava flows. A small area of pillow lava has been found at one locality (Bruton & Bockelie 1979 and own observations). In most places, however, the volcanites are so strongly deformed that they can only be recognised as massive greenstones.

Bruton & Bockelie (1979) interpreted the contacts between the plutonic rocks and the supracrustals as exclusively tectonic, even though both Carstens (1924) and Fediuk (1975) had demonstrated that the volcanosedimentary rocks occur as enclaves within the pluton, and that the contacts are characterised by intense contact-metamorphism and calc-silicate-hornfels and skarn formation.

Gautneb (1987) showed that the contact-metamorphic parageneses are characteristic of the pyroxene-hornfels facies. He also demonstrated, from a detailed study of the contacts between large rafts of metasupracrustal rocks and plutonic rocks of the batholith, that the volcanosedimentary rocks were polyphasally deformed prior to the emplacement of the batholith and that the batholith post-dates all deformation structures seen in these rocks.

Old Red Sandstone deposits

These sediments are exposed along the south-eastern coast of Hitra and on several islands south of Smøla (Plate 1). They also occur on Ørlandet and adjacent islands outside the main area of the SHB (Fig. 1). The ORS deposits unconformably overlie the rocks of the batholith but in some places the unconformity is inverted and bedding dips steeply towards the northwest. The sedimentology and structures of these sediments have been described in several accounts (Reusch 1914, Peacock 1965, Siedlecka & Siedlecki 1972, Siedlecka 1975, Roberts 1981, Steel et al. 1985, Bøe 1986, 1988, Atakan 1988, Bøe et al. 1989 and Torsvik et al. 1989). These authors have shown that the ORS sediments have been involved in polyphase deformation associated with very low- to low-grade metamorphism, probably of Late Devonian age. Based on circumstantial evidence from palaeomagnetic studies, Torsvik et al. (1989) tentatively suggested that the ORS deposits, as well as large parts of the batholith, have been influenced by intense block faulting and large-scale block rotation in Late Devonian time. Since the sedimentological evolution and tectonometamorphic history of the Devonian rocks are post-batholith phenomena, we will not discuss them further here.

The batholith

Although the Smøla-Hitra Batholith embraces the association of Caledonian, mafic to felsic, plutonic rocks occurring specifically on the islands of Smøla and Hitra, we also take into consideration the granitic bodies exposed on Frøya and Ørlandet. Diorites occurring along strike further to the northeast, on Fosen (Fig. 1), are in all probability consanguineous with the SHB. These rocks have not been studied in any detail by us and they will not be discussed in this account.

Dioritic rocks and their igneous enclaves

A group of rocks ranging in composition from gabbro to quartz diorite forms the most extensive plutonic subdivision of the SHB; of these, the diorites and quartz diorites (sensu stricto) are the most abundant. Diorites constitute the major part of the batholith, occurring widely on Hitra and Smøla. On Hitra, the dioritic rocks occur in three main areas, separated by ortho- and paragneisses and by the granite just south of Strømfjorden (Plate 1). In the southern area the diorite is generally little deformed and has a relatively monotonous appearance. However, there is a perceptible westward decrease in the colour index from approximately 50 in the easternmost part of Hitra until the diorite grades into tonalitic and granitic rocks in the western part of the island (see below).

On both sides of Strømfjorden and to the east the diorite is slightly more deformed and has an E-W striking foliation. The diorite shows a transitional contact with the granite to the south, but a sharp tectonic contact with the orthogneisses in the north. Kollung (1964) reported the occurrence of microcline-bearing monzodioritic varieties from this area but the regional distribution of this rock-type is unknown.

In the northernmost area, from Stamnes and across the Ansnes peninsula, the diorite is strongly deformed and resembles an orthogneiss in many places. The deformation, however, is very heterogeneous. Both Schetelig (1913) and Kollung (1964) described gradations from strongly deformed to little deformed diorites in this area. Some of the protoliths to the orthogneisses on Fjellværøy may have been dioritic rocks.

On Smøla, diorites constitute the major rock-type. The best exposures are along the coast within the tidal range and on the numerous small islands and skerries around the southern and eastern parts of the island. The diorite on Smøla is essentially homogeneous, but on account of the common occurrence of later intrusions almost every exposure has a misleadingly heterogeneous appearance. In some localities cm-scale modal layering is common in the diorites with plagioclase and hornblende as the main minerals (Fig. 2). Gautneb (1987) considered many of the occurrences of modal layering, which is restricted to small areas, to be situated in autolithic rafts surrounded by homogeneous diorite.

A characteristic feature of the diorites within the SHB is the occurrence of pegmatitic pockets and veins (Kollung 1964 p. 199, Gautneb 1987) (Fig. 3). Typical for these pegmatites is the presence of prismatic crystals of hornblende up to 10 cm in length. The hornblende is commonly cored by plagioclase and in many cases the crystals define a comb-structure. A spotted structure is commonly developed in the diorite in association with the pegmatitic veins and pockets. This structure is characterised by large (up to 5cm across) poikilitic hornblende crystals enveloping inclusions of plagioclase. Locally, the diorite may also show a peculiar wavy banding with schlieren-like clots rich in poikilitic hornblende (Fig.

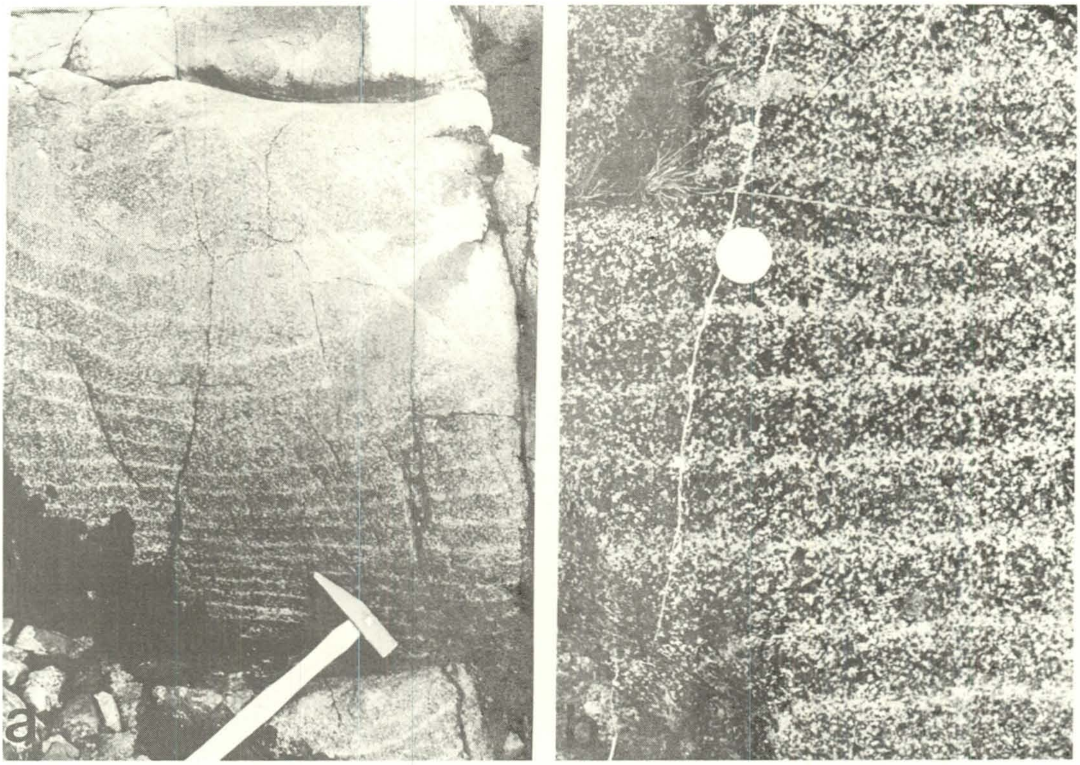

Fig. 2. A) Cm-scale modal layering in diorite. B) Close-up showing the diffuse transition between the modal layers. Straumen, southern Smøla.

4). This structure is remarkably similar to the wavy bands of pyroxene-feldspar rock found in the Tranquil division of the Marginal Series of the Skaergaard Intrusion (Wager & Brown 1968, p. 112) and we believe that some of these structures occur in autoliths, possibly representing parts of an unexposed marginal series.

The pegmatitic and spotted structures in the diorites of the SHB resemble those described from the diorites in the Channel Islands and the name 'appinitic' diorite has been applied to such rocks (Wells & Bishop 1955, Key 1977, 1985, 1987, Brown et al. 1980, Topley et al. 1982, Bishop & Key 1983). Several processes may have led to the development of the appinitic structure in the diorites. Topley et al. (1982) believed that such pegmatitic and spotted structures in diorite were formed by relatively rapid crystallisation from a supercooled volatile-rich melt. On the other hand, Bishop & Key (1983) and Key (1987) suggested that the appinitic structure in the diorites of Jersey was formed by a process involving allochemical recrystallisation of gabbro. Thus, the precise origin of appinitic diorite is not yet known, and more detailed petrological work has to be carried out on these rocks in the SHB in order to obtain a clearer understanding of their mode of formation.

In the southern part of Smøla the diorites grade inwards to a semi-circular area of K-feldspar-bearing monzodioritic rocks. These rocks differ from the surrounding diorites not only in the content of K-feldspar but also in containing slightly more quartz. Moreover, the hornblende-rich pegmatitic pockets and veins are absent.

In western Smøla, part of the batholith occurs as true gabbro which probably represents a separate intrusion. However, contact relationships with the surrounding diorites and granites are obscured by extensive brecciation. The gabbro shows a well defined modal layering which occurs on a much larger scale than is common in the diorites, and can be

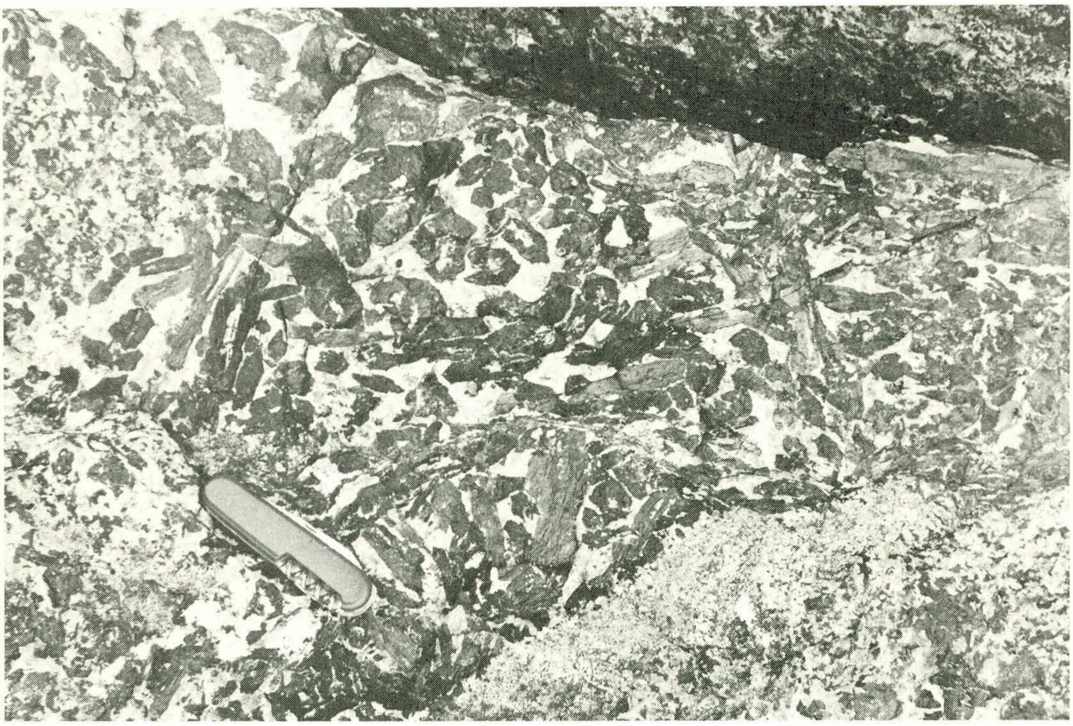

Fig. 3. Pegmatitic segregation in diorite. Note that the amphibole megacrysts have cores of plagioclase. Rosvolløy, Smøla.

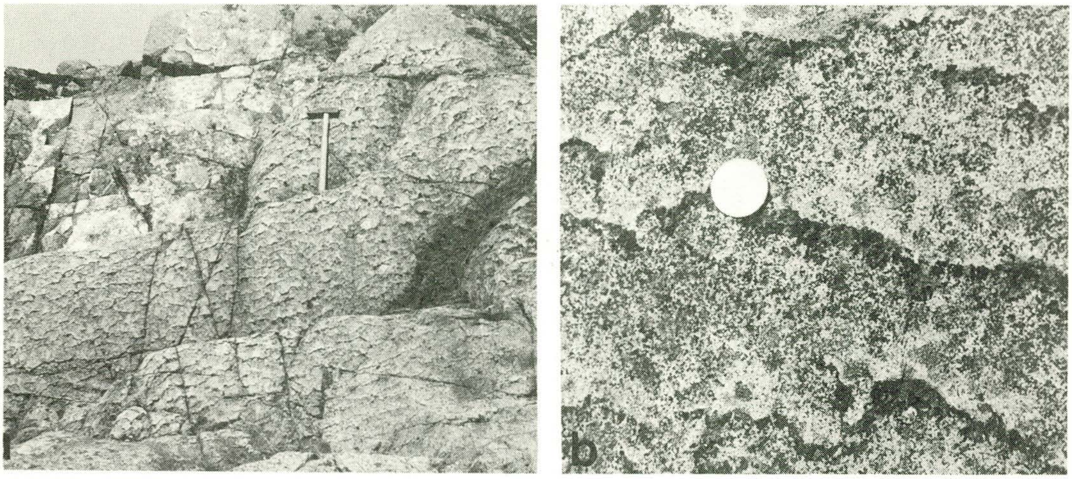

Fig. 4. A) Wavy-banded hornblende-feldspar rock occurring as an enclave in diorite. B) Close-up showing the schlieren-like clots rich in hornblende. Hoøy, Smøla.

followed laterally for tens of metres in many places. The intrusion is also mineralogically zoned, with olivine-bearing rocks exposed on the westernmost small islands, and attains the composition of quartz-gabbro towards the east. This gabbro is associated with a positive gravity anomaly. Gravity modelling indicates that the intrusion is part of a much larger, gabbroic body approximately 30 km long, 12 km wide and 5 km thick, extending offshore to the northwest (Sindre 1977). The diorites and gabbros commonly contain a variety of igneous enclaves which are distinguished from the host rocks by their higher colour index or larger grain size, and may vary in composition from hornblendite to meladiorite. These enclaves, some of which have surface areas of several hundred m^2, are believed to represent fragments of unexposed parts of the batholith.

Tonalite, granodiorite, granite

These rock-types have their greatest areal extent on Hitra. Apart from being the major rock-type in the southwestern part of Hitra, granitic to tonalitic rocks are common as dykes and veins in all other pre-Devonian rock units.

On Dolmøy in northern Hitra, the granodiorite is extremely heterogeneously deformed and contains a large number of inclusions of the surrounding gneissic rocks. The belt of tonalite and granodiorite which extends westwards from Fillan towards Strømfjorden is, in places, virtually non-deformed and contains numerous inclusions of gneisses and dioritic rocks. The contacts with the orthogneisses in the north and the diorite in the south are transitional, in the sense that they are defined by a broad belt of gradually decreasing colour index of the diorite, the disappearance of hornblende-rich pegmatitic pockets and veins, and an increase in the content of quartz and biotite towards the tonalite. Mapping in 1985, reported in Bering et al. (1986), revealed that the tonalite/granodiorite extends further north and west than is shown in the map by Askvik & Rokoengen (1985), and that the contact between diorite and tonalite/granodiorite in some places is characterised by the occurrence of K-feldspar-bearing monzodioritic rocks as, for example, on the smaller islands west of Kvenvær.

Further south there is a general increase in the content of K-feldspar in the granodiorite and the rocks attain a granitic (sensu stricto) composition in the area around Forsnes. On Smøla, granodioritic to granitic rocks are far less abundant than on Hitra. Except for some small occurrences of alkali granite in the southeast and on the smaller islands in the extreme northwest, granite and granodiorite are not found in any larger uniform massif. Granitoids rocks are, however, fairly common and occur both as dykes and as an intense net-veining of the dioritic rocks. Our map and the maps by Fediuk (1975) and Askvik & Rokoengen (1985) give the impression that the diorites are fairly homogeneous rocks, but any one outcrop will show a large number of granitic veins as well as brecciation of the diorite by either granite or granodiorite. This brecciation, described in detail by Gautneb (1988), is considered to have resulted from hydrostatic stresses similar to those required for hydro-fracturing of rocks.

Fig. 5. Granodiorite which has intruded a partly crystallised diorite. Central Smøla.

The emplacement of the granodiorite to granite members of the plutonic complex is believed to have closely followed the intrusion of the diorites and gabbros. Although in most outcrops the granitoids are seen bo brecciate the diorites in a brittle manner, relationships at some localities show that the granitoid magma intruded partly crystallised diorite (Fig. 5). It can also be demonstrated in some places that the diorite appears to have been partly assimilated by the granitoid melts.

Granitic rocks on Frøya, neighbouring small islands and the Sula archipelago are represented principally by the Frøya Granite (Torske 1983) (Fig. 1, Plate 1). This is a comparatively homogeneous, crudely foliated, medium- to coarse-grained, red, biotite granite or granodiorite, in places with megacrysts of microcline several cm in length. Along its exposed southern border the granite is intrusive into migmatitic gneisses. Apophyses, dykes and veins of granite, pegmatite and muscovite-bearing aplite transect the gneisses (Torske 1983). The many occurrences of similar granitoids on Sula and its neighbouring islands and skerries (Fig. 1), together with the Frøya Granite, appear to form part of a major granitoid pluton measuring some 40 x 20 km in areal extent. Recent reconnaissance work, however, has shown that monzodiorite and several types of granite are present in this area. The rocks on northern Frøya are thus more heterogeneous than they appear in Plate 1 (Ø. Nordgulen, written comm. 1989). On Ørlandet, the Lerberen Granite (Plate 1) is interpreted to be fault-bounded (Siedlecka 1975); no contacts with the country rock gneisses have been found. The rock is a massive, medium-grained, white to pink-white granite to granodiorite.

Dyke rocks

Dykes occur in great number and are found transecting almost all rock units in the batholith and its envelope. For clarity, we have omitted all dykes from Plate 1. Gautneb (1988) has presented a comprehensive discussion of the structural and physical aspects of all the hybabyssal rocks from southern Smøla. We will limit our descriptions to the lithological variation of the dyke rocks, to illustrate the complete sequence of intrusive activity within the Smøla-Hitra district.

Dykes intruded during crystallisation of the diorites

Dykes in this category include rocks of tonalitic to granitic composition, composite (felsic/mafic) dykes and some dolerites. Granite to tonalite dykes, as mentioned above, occur most commonly as 'net veins' in the diorite. They also occur as larger, solitary, granitoid dykes up to 3 m in thickness. Dykes of this composition and type have no preferred orientation and this is thought to be a result of random emplacement of net-veins under hydrostatic stress conditions.

The most spectacular dyke rocks in the SHB are the composite felsic-mafic dykes (Fig. 6). These dykes occur widely and particularly good examples are known from the islands and skerries immediately to the south of Smøla and the smaller islands north of Kvenvær on Hitra. The composite dykes have a mean thickness of 1.3 m. The thickness distribution is bimodal with thicknesses of 0.75 and 2 m being the most common (Gautneb 1988). The dykes show two dominant trends, NE-SW and E-W, and are characterised by the mutual occurrence of acidic and basic rocks, the basic variety usually occurring as cauliflower-like pillows in the acidic rock. The pattern of mingling between felsic and mafic rock-types seems to be related to the amount of intruding felsic and mafic magmas, and the width and form of the dyke conduit. It is obvious that there have been large differences in the rheological properties of the acidic and basic magmas.

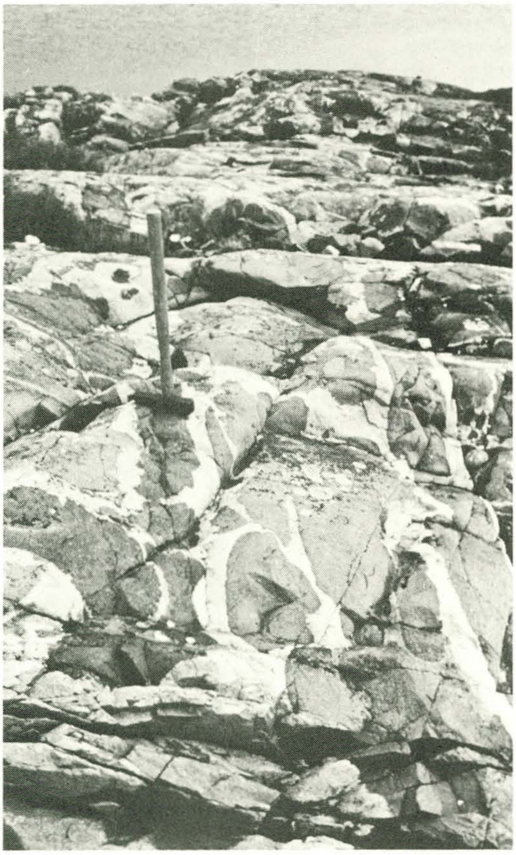

Fig. 6. Composite felsic-mafic dykes with 'pillows' of dolerite in granite; near Jøa on Smøla.

Dykes post-dating the crystallisation of the diorites

The dyke phases described below are distinguished from the above-described dykes on account of their planar and always sharp contacts with the country rocks. The diorite and

Fig. 7. Part of an appinitic intrusion breccia, with xenoliths of the dioritic country rock, in a very heterogeneous mafic to ultramafic appinitic rock; near Jøa, on Smøla.

granitoid plutons clearly behaved in a brittle manner during the emplacement of dykes of this category.

Porphyritic microdiorite

Dykes of porphyritic microdiorite occur as large mappable bodies many tens of metres wide and several kilometres in length. They are recognised by a porphyritic texture with up to 50% by volume of rhombic and lath-shaped plagioclase crystals. Two types can be distinguished petrographically based on the habit of the plagioclase phenocrysts (see below). In outcrop, the microdiorite resembles the Hølonda porphyritic andesites (Chaloupsky 1970) or many of the rhomb-porphyries from the Oslo Rift (Oftedahl 1946). The porphyritic microdiorite dykes constitute an important marker in the tectonic history of the batholith. They occur in large number and they cut the tectonic structures seen in the country rocks. This is clearly demonstrated on Smøla where swarms of porphyritic microdiorite dykes with NE-SW to E-W trends transect the NW-SE-striking foliation in the diorites in the northern and central parts of the island (Fediuk 1975, and own observations). This relationship is also found at several localities on Hitra (Kollung 1964).

These field relationships show that all visible ductile deformation in the batholith, at least on Smøla, occurred prior to the intrusion of the porphyritic microdiorite dykes.

Appinitic plug intrusions

In several places within the batholith we have found plug-shaped ultramafic intrusions. The

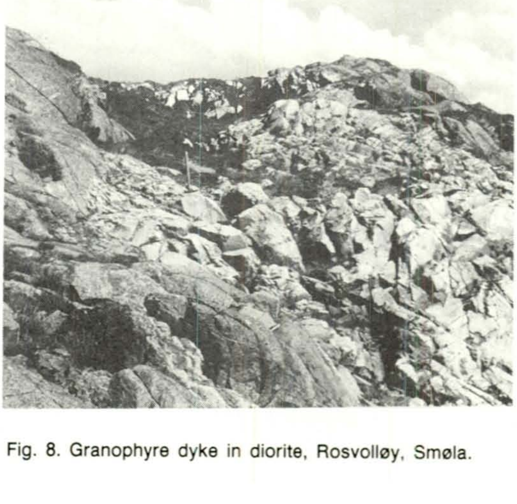

Fig. 8. Granophyre dyke in diorite, Rosvolløy, Smøla.

largest of these occurs on Helgebostadøy on northwestern Hitra and was first described by Kollung (1964). There, the ultramafic rock penetrates deformed diorites in the form of a semicircular plug-like body and covers an exposed area of approximately 0.5 km^2. The rock is a hornblende pyroxenite consisting entirely of primary hornblende and diopside. Several smaller plugs of ultramafic rocks occur in the southern part of Smøla (Plate 1). At all these localities the ultramafic rocks are of very variable composition and contain a large number of xenoliths (Fig. 7). The host rocks immediately adjacent to these intrusions are always strongly brecciated. These particular rocktypes are similar to appinites which have been described from several places in the Scottish and Irish Caledonides. There, the appinites are common as small satellite intrusions, sheets and bosses associated with larger plutons of diorite and granitic composition (Pitcher & Berger 1972 and Pankhurst & Sutherland 1982). The appinites have similarities with mafic diorites but are distinguished from the diorites by the presence of a large amount of prismatic amphibole. Ultramafic variants contain a large modal percentage of primary hornblende.

Dolerites

Dolerite dykes are the most abundant dyke type within the batholith. They occur almost everywhere, but are least common within the granitoid area of SW Hitra. The dolerites are either aphyric or contain phenocrysts of plagioclase and pyroxene. The mean thickness is 0.8 m, but thicknesses up to 30 m have been recorded. Gautneb (1988) has shown that in southern Smøla these dykes have two dominant trends, NE-SW and E-W. The dolerites most commonly occur as solitary dykes, but it is not unusual to find them in clusters or swarms with intervening screens of country rock. In some places there are also multiple dykes, composed of several discrete dolerites emplaced within each other.

Granophyres

The youngest dykes within the SHB are pink to red granophyres (Fig. 8), with an average thickness of 10 m. These dykes are easily recognised in the field and can commonly be followed over several kilometres. In thin-section the rock generally shows a microgranophyric and spherulitic texture with phenocrysts of K-feldspar and quartz. The texture indicates that the rocks initially had a vitrophyric texture and that devitrification resulted in the spherulitic and microgranophyric intergrowth. The granophyre dykes have been dated by the Rb/Sr method and yielded a whole-rock isochron of 428±10 Ma (Gautneb 1988).

Petrography

The diorites are, in general, coarse-grained and have a subhedral-granular to euhedral-granular texture. Some rocks may show a subophitic texture and the modally-layered diorites in most cases have a cumulate texture.

A typidal diorite comprises 30-60% plagioclase, 3-25% of brown amphibole, 1-12% clinopyroxene and less than 1% orthopyroxene (Table 1). Quartz, biotite, apatite, epidote, sphene and opaques are the most important accessory minerals, but rarely constitute more than 10% of the rock. The plagioclase is weakly zoned (An40-20) and is commonly sericitised and cloudy. The amphibole is an important mineral in the diorites and has a composition from magnesio-hornblende to edenitic hornblende, following Leake (1978). The amphibole crystals are commonly zoned and the innermost part is usually brown and shows exsolution opaque lamellae which define a schiller texture. Several generations of colourless amphibole may occur as coronas on the brown amphibole. The pegmatitic pockets show large amphibole crystals with cores of plagioclase, a feature which is very typical for appinitic diorite (Wells & Bishop 1955).

Clinopyroxene has a limited compositional range of Wo_{36-44} En_{37-44} Fs_{13-22}. It is one of the earliest minerals to have formed and occurs as inclusions in plagioclase and amphibole. In the most mafic modal layers, the mafic constituents may make up as much as 60% of the rock.

The gabbro has a medium-grained granular texture and on western Smøla it is relatively fresh. It generally shows a well defined mineral lamination. Plagioclase, clino- and orthopyroxene are the most important minerals. Ortho- and clinopyroxene occur in about equal amounts, but the ratio between femic and mafic minerals is very variable due to the modal layering. Accessory minerals are apatite, biotite, amphibole, quartz or olivine and opaques. The monzodioritic rocks in southern Smøla and northwestern Hitra may contain up to 21% K-feldspar. The amphibole in the monzodiorites generally occurs as overgrowths on pyroxene, and biotite as overgrowths on pyroxene, and biotite as an overgrowth on opaques; this is probably due to crystal growth from the intercumulus melt. Quartz and K-feldspar are always late interstitial minerals. The transition from diorite (sensu stricto) to monzodiorite is marked by the following changes: an increase in the amount of interstitial quartz, K-feldspar, biotite and accessory apatite and zircon; a change in the colour of the amphibole from brown to deep green; and an increase in the amount of amphibole occurring as coronas around pyroxene.

The granites, granodiorites and tonalites generally display an anhedral-granular texture. Modal determinations show that the granitoid rocks contain from 28% to 45% quartz, 20-56% plagioclase (albite-oligioclase) and 8 to 38% K-feldspar (Table 1). Although the plagioclase content is usually at least twice that of K-feldspar, in some rocks these

Table 1. Modal analyses of selected rocks from the Smøla - Hitra batholith. Data mainly from Gautneb (1987). x - present in negligible amounts.

	Diorites and monzodiorites														Porphyritic microdiorite			
Sample no.	317a	354a	317b	277	292	G1	278	Ros3	G4	255	328	G3	R11	218b	310	R8	318a	BV1
Quartz	9.80	8.41	2.87	0.37	3.92	7.19	8.23	13.57	14.13	6.58	16.29	9.44	15.01	18.57	8.29	14.26	9.40	16.23
Plagioclase	63.73	59.75	38.03	31.88	48.22	50.24	46.44	48.11	55.77	50.84	54.73	54.72	45.84	56.63	70.67	67.50	67.50	71.23
K-feldspar	3.68	3.95	1.50	1.12	0.59	8.51	7.37	14.55	7.43	5.38	10.57	15.07	6.68	1.47	0.62	1.74	2.62	1.75
Biotite	1.23	.89	x	1.99	x	1.32	12.08	4.28	1.24	.60	2.99	2.65	8.22	6.39	1.24	2.24	3.24	0.22
Sphene	x	x	x	.12	x	.24	.77	x	0.12	x	x	x	1.03	-	-	-	-	-
Amphibole	6.13	13.50	40.96	25.59	41.92	21.70	9.34	10.64	19.33	21.89	12.06	14.15	13.05	9.08	12.12	11.31	8.79	6.44
Opaques	5.02	1.27	4.99	10.06	2.14	3.84	5.48	1.96	1.61	5.74	0.62	1.73	1.64	3.93	1.86	0.62	1.49	0.45
Clinopyroxene	5.51	9.55	6.23	25.01	1.43	2.88	8.23	5.26	0.37	1.72	0.87	1.61	7.30	2.09	3.71	1.58	4.86	3.62
Orthopyroxene	x	x	0.80	0.50	x	x	x	0.90	x	x	x	0.40	x	-	-	-	-	-
Epidote	0.49	0.64	-	x	x	x	0.34	0.24	x	1.56	0.62	x	0.92	x	0.74	x	x	x
Apatite	4.41	2.04	1.00	1.99	x	0.96	1.71	0.49	x	0.20	0.62	0.23	1.23	0.61	0.25	x	0.23	0.06
Chlorite	-	-	3.62	1.37	1.78	3.12	x	-	x	5.50	0.63	x	-	1.23	0.50	0.75	1.87	x

Granite and granodiorite

Sample no.	25a	Ros13	R6	318b	304
Quartz	28.86	30.32	33.55	38.13	49.77
Plagioclase	56.42	47.91	46.26	22.44	21.18
K-feldspar	8.24	14.13	13.09	37.88	28.57
Biotite	2.94	3.19	5.61	1.38	0.38
White mica	0.59	0.25	x	0.17	0.05
Amphibole	2.12	0.98	0.87	x	0.05
Clinopyroxene	0.47	2.36	x	x	x
Opaques	0.24	0.86	0.62	x	x
Apatite	0.12	x	x	x	x
Zircon	x	x	x	x	x

Appinites and enclaves

Sample no.	UM2(a)	209a(a)	J3(a)	S5(e)	326a(e)	369(e)	Ros2(e)
Olivine	27.16	-	44.84	-	-	-	23.74
Amphibole	46.29	72.60	26.25	69.58	86.07	42.54	35.99
Clinopyroxene	1.98	13.36	3.65	3.37	7.75	20.13	2.26
Orthopyroxene	11.36	8.87	9.60	8.98	2.65	1.52	-
Opaques	0.99	x	0.49	0.37	0.66	2.27	2.02
Talc	6.17	1.23	3.40	2.00	-	-	-
Apatite	-	x	x	x	0.66	x	x
Serpentine	6.05	3.69	5.71	1.33	1.45	x	x
Plagioclase	-	0.25	6.06	14.37	0.76	33.54	35.99

Dolerite dykes

Sample no.	F180b	322a	260b	196	181a
Quartz	10.90	6.93	5.10	6.20	2.15
Plagioclase	64.61	62.69	61.18	62.60	40.39
K-feldspar	1.61	2.82	1.20	3.40	0.72
Biotite	2.60	0.64	1.60	0.54	0.45
Amphibole	12.39	11.55	12.90	14.26	33.12
Clinopyroxene	0.99	9.30	13.20	6.80	9.87
Orthopyroxene	2.68	x	0.92	-	2.69
Chlorite	1.86	1.20	.90	3.10	4.49
Epidote	-	1.28	2.10	-	0.73
Opaques	1.36	3.59	0.90	2.79	5.39
Sphene	-	-	-	0.34	-

Granophyre dykes

Sample no.	179b	312a	F188a	F180a	188a
Quartz	27.39	27.94	29.22	37.35	33.37
Plagioclase	41.30	28.74	30.47	29.94	31.09
K-feldspar	26.74	31.58	29.64	31.17	33.15
Biotite	2.39	2.83	7.15	1.54	1.09
White mica	0.26	1.21	0.31	-	-
Amphibole	x	1.22	0.31	-	-
Clinopyroxene	-	1.21	0.41	x	-
Opaques	1.09	3.64	2.07	x	0.54
Sphene	0.4	1.22	0.21	x	0.22
Apatite	0.40	0.40	0.21	x	0.43
Zircon	x	x	x	x	0.11

minerals occur in equal amounts. Biotite, muscovite, hornblende, pyroxene, apatite, zircon, allanite and clinopyroxene are accessory minerals , and usually constitute less than 10% of the total rock.

In places, granites are semi-porphyritic and textures hypautomorphic-granular, as on Frøya. There, microcline occurs as long megacrysts (Torske 1983) and sphene is the dominant accessory mineral. Chloritisation of biotites is observed in the Frøya and Lerberen Granites.

The porphyritic microdiorite contains up to 3.5 cm-long phenocrysts of plagioclase, which in some dykes are arranged in a trachytoid manner. Gautneb (1987) distinguished between two different types of dykes based on the habit of the plagioclase crystals:

Type 1 has plagioclase phenocrysts of a distinctive rhombic or rectangular shape up to 3.5 cm in size. Type 2 carries plagioclase phenocrysts of square or rectangular shapes, with the size rarely exceeding 0.7 cm. The groundmass in the microdiorite consists of anhedral plagioclase and quartz, and in some fresh rocks prismatic clinopyroxene is common.

The appinitic rocks are petrographically diverse. All appinites contain large, brown to colourless amphibole with a composition ranging from pargasite and edenite to magnesio-hastingsite according to the classification of Leake (1978). Orthopyroxene is common as inclusions in the amphibole and has the composition of bronzite ($Wo_{0.57-1.51}$ En_{79-81} Fs_{18-19}). Olivine (Fo70)is also found as inclusions in the amphibole. Some of the appinites can contain substantial amounts of lath-shaped plagioclase and otherwise have textures and mineralogy similar to those of the diorites.

The dolerites have an intergranular texture dominated by plagioclase and primary amphibole. The groundmass consists of acicular plagioclase and amphibole with accessory amounts of epidote, opaques and in some dykes also quartz.

The granophyres contain euhedral phenocrysts of K-feldspar, quartz and plagioclase in a very fine-grained groundmass of the same minerals. The groundmass commonly has a micro-granophyric and spherulitic texture, indicative of devitrified glass. The modal compositions of the various rocks are shown in Fig.9 and Table 1.

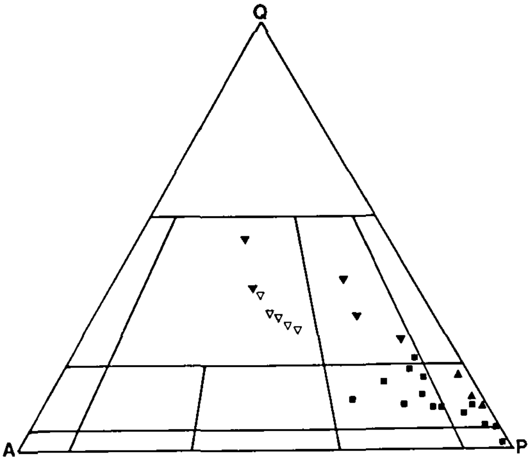

Fig. 9. Modal composition of the major rock types in the SHB. Squares - diorites and monzodiorites; filled triangles - porphyritic microdiorite; filled inverted triangles - granites and granodiorites; open inverted triangles - granophyre dykes.

Table 2. Composition of selected hornblendes (grain margins) in the SHB. Structural formulae calculated with 23 O according to Leake (1978).

Sample no.	Hb1	Hb2	Hb3	Hb4
Na_2O	1.884	1.952	1.358	1.516
MgO	11.186	10.836	10.723	11.316
Al_2O_3	7.744	7.673	7.466	7.601
SiO_2	44.562	44.424	44.498	44.061
K_2O	1.169	1.171	1.018	1.117
CaO	10.580	10.580	10.020	10.267
TiO_2	2.141	2.141	1.982	2.116
MnO	0.262	0.262	0.281	0.284
FeO	17.830	17.830	18.562	17.851
Sum	97.784	96.868	95.907	96.131
Si4+	6.648	6.687	6.685	6.610
Al3+ (IV)	1.351	1.312	1.311	1.344
Al4+ (VI)	0.009	0.048	0.007	0.000
Ti4+	0.222	0.242	0.224	0.238
Fe3+	0.618	0.572	1.044	0.956
Mg2+	2.487	2.431	2.401	2.531
Fe2+	1.631	1.672	1.284	1.238
Mn2+	0.306	0.033	0.035	0.036
Ca2+	1.756	1.706	1.612	1.650
Na+	*0.544*	*0.569*	*0.395*	*0.441*
K+	0.222	0.224	0.195	0.214
Alt	1.362	1.361	1.322	1.344

Depth of emplacement and solidification

The contact-metamorphic mineral assemblages in the Lower Ordovician supracrustals indicate a relatively low pressure of metamorphism. In the calc-silicate rafts, for instance, typical metamorphic minerals are diopside, grossular and wollastonite. Thus, this skarn mineralisation points to a relatively low pressure/shallow depth of emplacement (Greenwood 1967). Recently, Hammarstrom & Zen (1986) and Hollister et al. (1987) have shown that the Al content of hornblende in calc-alkaline plutonic rocks can be used as an empirical geobarometer. The content of Al in hornblende was shown to be dependent mainly on pressure and to be less affected by temperature and oxygen fugacity during crystallisation. The compositions of some selected hornblendes from the SHB are given in Table 2. Following Hollister et al. (1987) an average Alt of 1.35 (Table 2) corresponds to a pressure of solidification of 0.26 ± 0.1 GPa. With an average density of 2900 kg/m^3 for the batholith rocks (Sindre 1977) this pressure is equivalent to a depth of solidification in the range 9 ± 3.5 km. An emplacement pressure of about 0.26 GPa (2.6 kb) agrees well with that expected from the minerals in the contact-metamorphic aureole.

Table 3. Selected major (wt%) and trace element (ppm) analyses of rocks from the Smøla-Hitra Batholith. A list of the complete analytical data is available from the first author upon request. n.a.= not available, b.d.= below detection limit. LOI = Loss-on-ignition FeOt = Total Fe as FeO

	Appinites			Enclaves		Dolerite dykes						Monzodiorite					
Sample no.	209A	209B	UM2	S5	128A	130A	130B	B167	164	256B	B173A	2982	353B	231	365	358	328B
SiO_2	47.48	47.63	42.43	45.27	47.26	51.65	49.84	58.20	57.97	52.74	50.42	53.43	55.89	57.26	58.73	52.44	51.64
TiO_2	.63	.34	.34	.75	.46	1.11	1.17	.94	.93	.88	.91	1.79	1.04	.94	1.17	1.94	2.57
Al_2O_3	8.06	7.59	6.93	11.12	9.29	16.81	16.73	15.93	15.34	14.88	15.82	14.76	17.14	16.72	15.91	16.23	12.02
FeOt	9.90	11.81	11.98	8.65	7.94	7.42	7.21	5.89	7.40	7.70	7.98	10.80	7.50	6.89	7.02	10.47	12.43
MnO	.32	.34	.29	.33	.31	.30	.30	.30	.10	.30	.33	.16	.11	.11	.12	.16	.20
MgO	17.03	15.52	25.06	15.75	18.34	6.65	6.09	2.75	2.52	8.84	8.69	4.79	3.55	2.90	2.71	4.05	6.57
CaO	10.71	13.29	3.51	8.79	7.06	9.45	8.86	5.14	5.08	7.41	8.79	6.84	6.82	5.94	5.03	7.62	6.82
Na_2O	.96	1.58	2.03	6.57	2.41	2.96	3.21	3.71	5.09	2.99	3.38	3.95	3.68	3.83	3.79	3.89	2.55
K_2O	.32	.29	.70	.89	.74	.91	.98	2.12	2.30	1.62	1.24	2.10	2.03	2.84	2.79	1.56	2.15
P_2O_5	.27	.22	.14	.40	.30	.33	.32	.33	.29	.30	.26	.67	.31	.26	.34	.77	.78
LOI	2.61	2.38	5.55	3.01	4.33	1.63	4.43	3.62	3.37	1.45	1.77	.54	.57	.63	.66	.21	.72
Total	98.29	100.99	99.86	101.53	98.44	99.22	99.14	98.93	100.41	99.40	99.59	99.33	98.78	98.40	98.35	99.36	98.59
V	149	156	70	152	107	199	151	147	168	191	214	224	161	118	91	242	319
Cr	872	1068	933	944	1190	75	117	42	720	377	412	52	26	23	21	18	67
Ni	219	127	493	392	569	24	32	18	578	231	122	29	20	17	20	14	53
Zn	89	85	87	81	71	62	87	65	94	77	75	88	58	50	61	72	89
Rb	13	8	40	17	17	31	37	62	15	49	31	57	62	106	95	41	66
Sr	122	216	196	593	220	710	679	567	273	640	675	615	763	605	485	723	413
Y	19	15	10	16	16	19	23	31	11	15	22	44	25	32	32	37	37
Zr	83	53	46	107	94	84	87	220	74	130	96	218	196	336	351	79	246
Nb	3	2	1	6	3	6	4	12	1	11	6	19	8	19	25	22	28
Ba	n.a.	n.a.	n.a.	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	612	513	579	474	474	539
La	7	4	6	27	12	17	20	31	10	28	19	64	37	62	49	43	75
Ce	17	14	19	55	30	29	37	60	20	66	34	104	93	98	141	113	91
Nd	33	51	b.d	33	28	39	43	48	19	47	43	57	35	46	66	55	60

	Microdiorite		Diorite			Granite				Granophyre dykes				Gabbro			
Sample no.	R8	R4	DIO100	DIO102	DIO107	GR13	GR35	GR134	GR135	173C	188B	179A	121	GB5	GB25	GB54	GB18
SiO_2	58.89	56.10	58.50	57.27	57.20	74.11	75.12	77.55	74.31	76.42	73.81	74.71	75.90	52.43	43.96	54.22	40.32
TiO_2	.93	.42	.94	1.02	1.25	.11	.03	.05	.12	.16	.07	.20	.14	.31	2.02	.85	.30
Al_2O_3	16.17	17.40	15.90	16.05	16.28	14.64	14.19	14.55	13.11	12.71	13.41	12.50	12.37	26.49	18.65	18.08	18.32
FeOt	6.23	6.74	8.71	9.34	9.27	1.25	.19	.62	1.34	.96	2.07	1.26	.84	3.02	18.36	7.94	11.66
MnO	.30	.27	.15	.17	.15	.07	.15	.10	.07	.02	1.35	.03	.01	.05	.15	.13	.16
MgO	3.22	3.40	2.94	3.34	3.37	.33	.34	.24	.44	.04	.00	.43	.06	2.30	6.10	4.31	16.46
CaO	5.29	5.84	6.45	6.86	6.71	2.14	.71	1.44	2.45	.97	4.01	.97	.96	13.46	7.96	7.94	10.95
Na_2O	5.02	4.03	3.94	3.19	4.09	4.41	4.75	4.10	4.76	4.07	3.95	3.02	3.62	2.75	2.76	3.19	.82
K_2O	2.01	2.74	1.54	1.60	1.58	2.15	3.40	2.65	1.76	4.03	.25	4.13	4.09	.14	.05	.90	.00
P_2O_5	.35	.41	.31	.32	.32	.04	.04	.04	.04	.02	.03	.04	.03	.06	.01	.20	.10
LOI	2.36	1.87	.30	.10	1.00	.05	.84	.50	.52	.03	.29	.24	.25	.56	.45	2.30	1.46
Total	100.77	99.22	99.68	99.06	101.22	99.30	99.76	100.40	98.40	99.47	99.24	97.57	98.27	101.57	100.47	100.06	100.57
V	153	208	173	196	194	5	26	4	19	7	29	26	8	51	895	222	277
Cr	35	80	24	26	21	9	7	2	5	2	5	7	7	42	75	36	72
Ni	17	44	22	19	16	16	22	17	18	0	3	b.d.	2	19	21	18	39
Zn	74	80	84	86	85	60	12	31	51	53	77	7	2	19	80	59	48
Rb	55	44	34	37	37	38	7	47	32	129	127	141	120	2	1	22	1
Sr	588	804	626	598	555	594	102	396	692	32	280	204	187	1036	704	828	494
Y	29	25	n.a	n.a	n.a	n.a	n.a	n.a	n.a	30	19	4	21	n.a	n.a	n.a	n.a
Zr	194	145	119	126	355	101	39	85	122	117	168	137	95	76	32	109	27
Nb	12	10	n.a	n.a	n.a	n.a	n.a	n.a	n.a	1	1	6	3	n.a	n.a	n.a	n.a
Ba	n.a	n.a	455	441	382	684	180	763	794	865	969	959	869	151	32	248	16
La	17	48	42	22	18	25	0	17	9	54	47	38	44	b.d	b.d	32	b.d
Ce	44	104	54	67	63	44	31	42	52	83	106	72	64	33	6	33	10
Nd	55	68	30	37	45	12	15	12	20	22	26	15	26	13	12	23	2

Time of emplacement

Biostratigraphic constraints on the time of emplacement of the SHB are extremely wide. The plutons transect and envelop rafts of Arenig-Llanvirn supracrustals, and pre-date the deposition of the basal ORS breccias. On Hitra, arthropod fragments, eurypterids and phyllocarids in ORS mudstones (Reusch 1914) have generally been accorded a Ludlow-Pridoli age (Størmer 1935), although Bassett (1985) has argued that a Wenlock or even latest Llandovery age cannot be excluded for the earliest, ORS molasse sediments. In recent years, isotopic dating methods have been applied to the SHB rocks by several workers, and all have yielded compatible results. Sundvoll & Roberts (1977) reported a Rb/Sr whole-rock isochron of 436±7 Ma (recalculated with ^{87}Rb = $1.42 \text{x} 10^{-11} a^{-1}$) with an initial Sr ratio of 0.70499 ± 0.00006. This isochron is based on 9 samples (mostly diorite, but also tonalite, granite and two dolerites) and includes two samples from Hitra. Gautneb (1988) attempted to place a minimum age on the intrusive activity by dating the youngest granophyre dykes on Smøla. The granophyres yielded an 9-point Rb/Sr isochron of 428±10 Ma with an initial Sr ratio of 0.70480±0.0003 and MSWD of 2.0. Recently, Tucker (1988) has reported several zircon and sphene U/Pb ages from this region. The oldest age is 450 +4/-3 Ma on sphene from a microgranite dyke intruding metasedimentary rocks on the coast of southern Hitra. Bøe (1986) considered these sediments to be part of the ORS succession and that the microgranite dyke was of Devonian or post-Devonian age. The age of the microdiorite confirms the assumption of Siedlecka & Siedlecki (1972) of a pre-Devonian age for these metasediments. The main diorite on Hitra yielded a concordant sphene age of 442 ± 3 Ma (Tucker 1988 and written communication). The two sphene dates mentioned above are high-precision U/Pb ages and show convincingly that the plutonic rocks on Smøla and Hitra are of the same general age; namely, that the SHB is mainly of Mid to Late Ordovician (late Llandeilo to Ashgill, McKerrow et al. 1985) age. The latest phase of magmatic activity represented by the granophyre dykes extended into the Early Silurian.

Petrochemistry

Analytical methods

We have compiled the available analytical data primarily from Gautneb (1987) and from our own unpublished data from Hitra, Smøla and Ørlandet. For comparison we have also included some of the analyses reported by Fediuk & Siedlecki (1977). The analyses have been carried out in several laboratories and this is the reason why there is a different number of trace elements analysed in some of the samples. The major elements were analysed by XRF on fused pellets, and the trace elements on powder pellets. Loss-on-ignition (LOI) was analysed gravimetrically after heating the rock to 1000° C and correction for the oxidation of FeO. The mineral analyses were carried out using the ARL-SEMQ microprobe at the University of Bergen. In some plots we have reduced the number of samples for the purpose of clarity. Since this is the first discussion of the geochemistry of the plutonic rocks within the SHB we will firstly give a general overview of the chemical variation and, secondly, classify the rocks by standard methods. We then discuss briefly some of the petrogenetic processes which may have operated.

Selected representative analyses are given in Table 3. Complete analytical data from the plutonic and hypabyssal rocks of the SHB may be obtained from the first author upon request.

General chemical classification

The SiO_2 content ranges from about 40% for some of the most mafic gabbros from western Smøla to about 77% for the granites, but there is a compositional gap between 60 and 68% SiO_2 separating the gabbros and diorites from the granites and granophyre dykes. This gap is a characteristic feature of the SHB, at least in our data-base which comprises 240 whole-rock analyses. Figs. 10 and 11 show the major elements and the most important trace elements plotted against SiO_2. The rocks show fairly regular but dispersed trends which, except for K_2O and Na_2O, become smoother with increasing SiO_2. With increasing SiO_2 there is an increase in the contents of K_2O, Na_2O and Rb. Zirconium shows an increase up to about 60% SiO_2, and then a decrease. Similarly, there are decreases in CaO, MgO, TiO_2, FeOt, Ni and Cr contents with SiO_2. Al_2O_3 shows little variation and the Sr content is fairly constant until it drops at about 75% SiO_2. The dioritic and monzodioritic rocks have SiO_2 contents ranging from about 50% up to almost 60%. The diorites, and in particular the monzodiorites, show elevated levels of K_2O, TiO_2, P_2O_5, Zr, Rb and Ba compared with the gabbros, a feature which is in accordance with

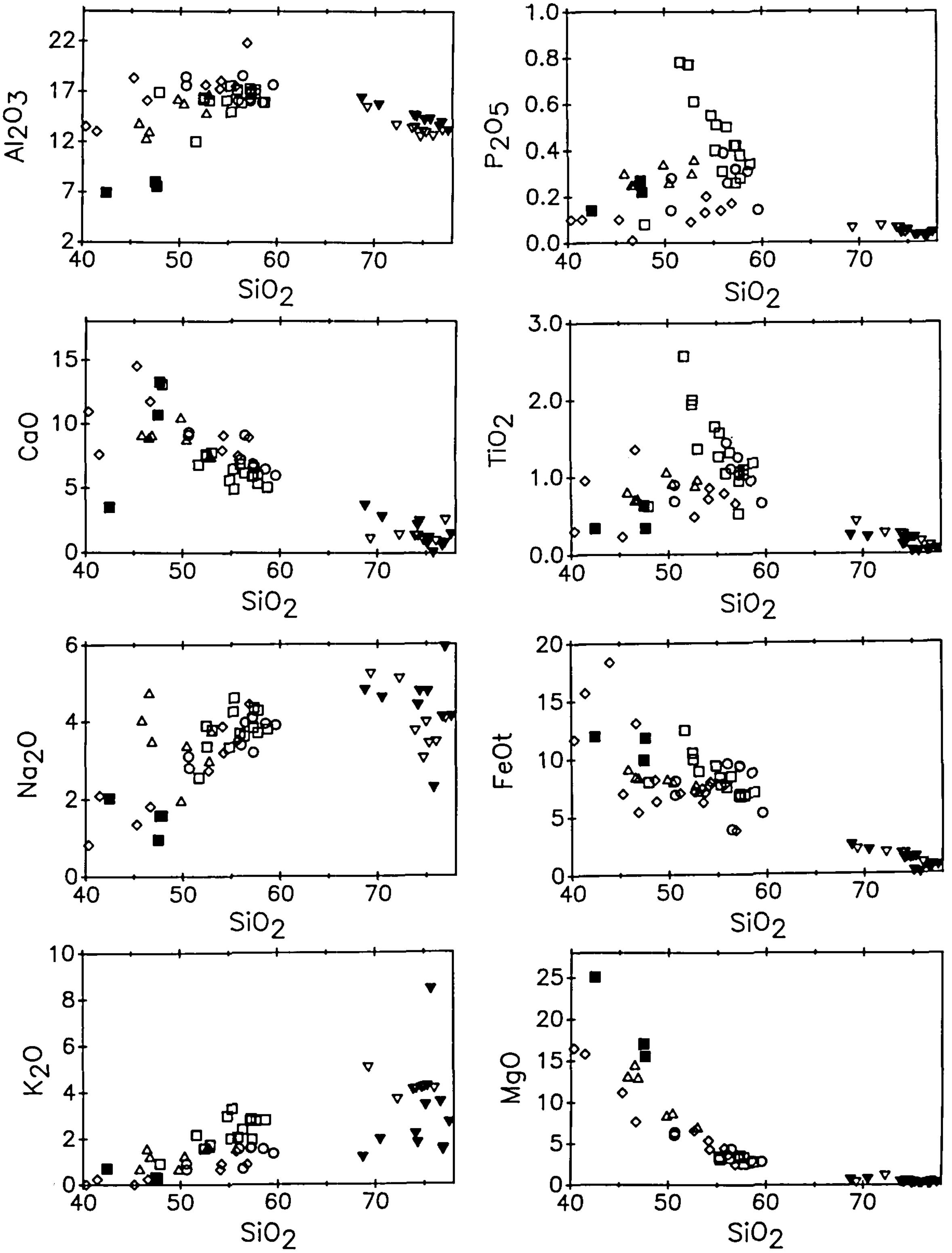

Fig.10 Harker diagrams of major elements from the batholith. Filled squares - appinites; open triangles - dolerite dykes; open squares - monzodiorite; open circles - diorites; open inverted triangles - granophyre dykes; filled inverted triangles - granites; open diamonds - gabbros.

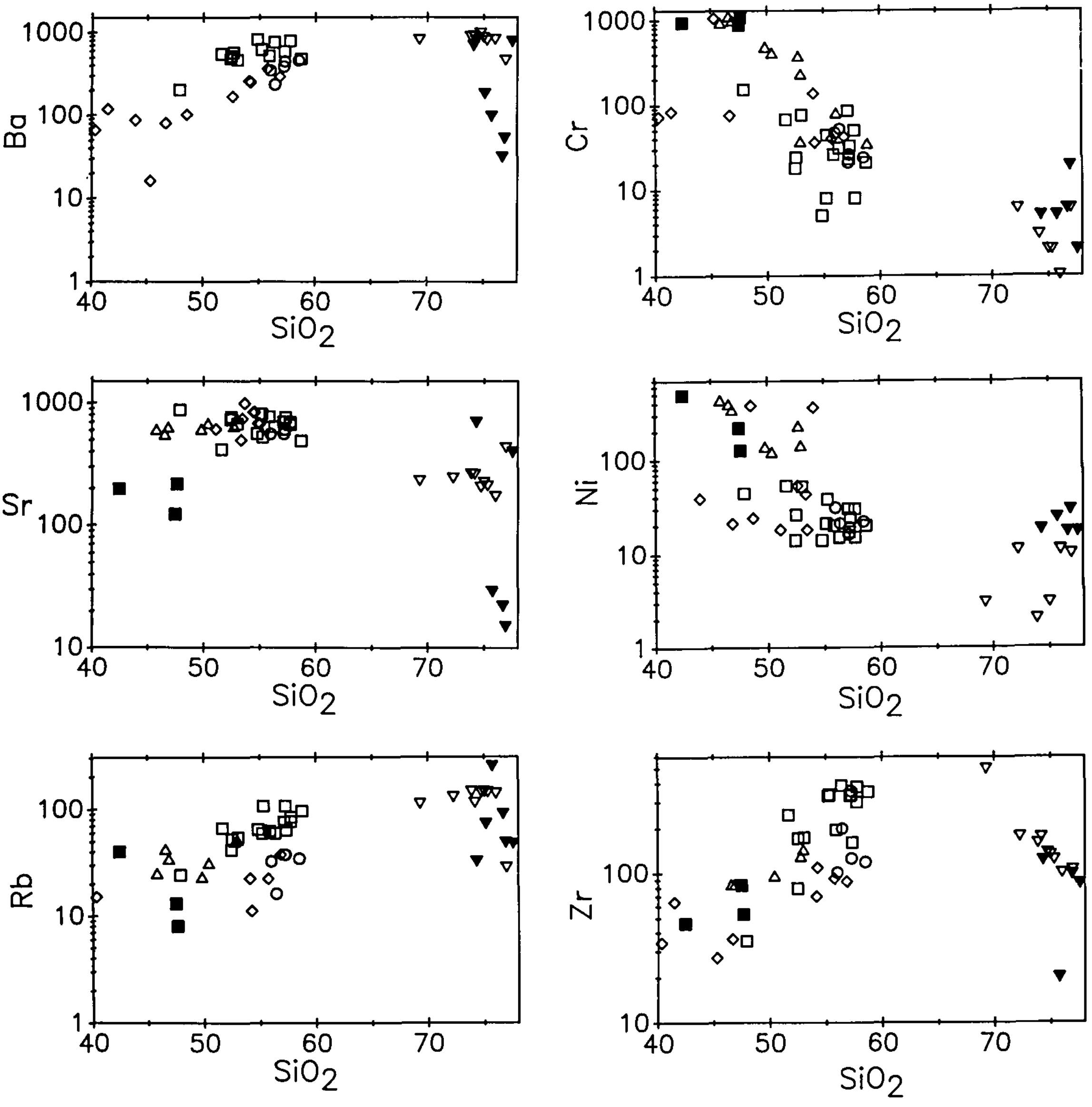

Fig. 11. Harker diagram of selected trace elements from the SHB. Symbols as in Fig. 10.

the higher contents of K-feldspar, apatite and zircon in these rocks.

The gabbros show a variation in SiO_2 from 40% to about 57%. Their overall chemical variation is characterised by some scatter, particularly in CaO, Al_2O_3, TiO_2 and FeOt; this is mainly due to a variable mafic/felsic mineral content, probably as a result of cumulate effects. The gabbros also have distinctly lower concentrations of incompatible elements than the dioritic rocks. The granitic rocks show very smooth trends for all elements except the alkalies, probably related to variations in the plagioclase/K-feldspar ratio. Some trace elements (Rb, Ba and Sr) show different trends within the groups of granitic rocks (Table 3). This has been ascribed to two different fractionation paths for these rocks (see below).

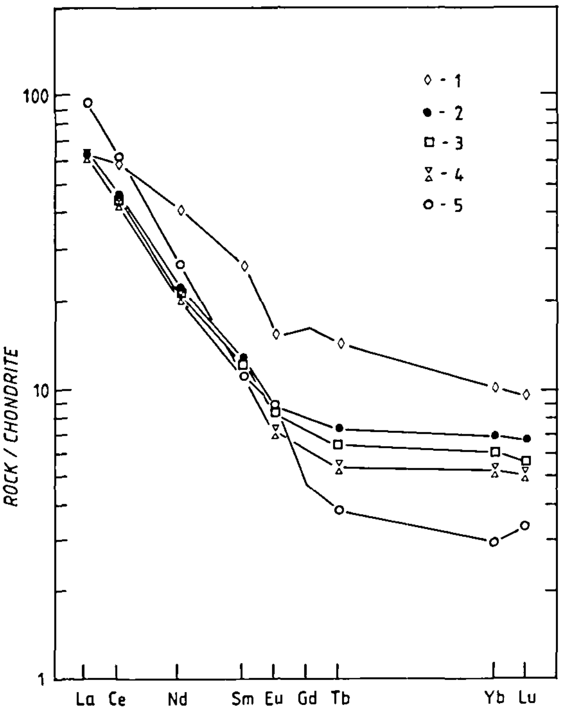

Fig. 12. REE patterns of some selected SHB rocks. 1 - Diorite, Hitra; 2 & 3 - granite, Lerberen, Ørlandet; 4 & 5 - granite,granodiorite, Hitra.

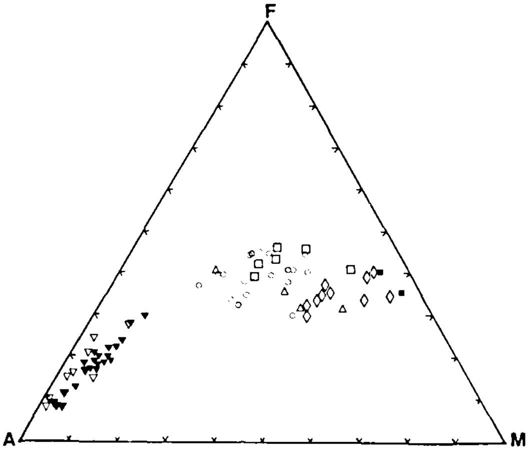

Fig. 13. AFM diagram for selected rocks from the SHB. Symbols as in Fig. 10.

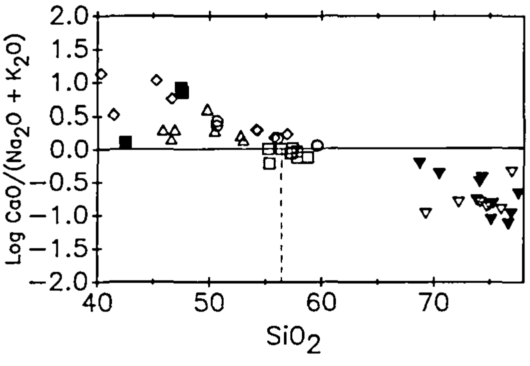

Fig. 14. Log $(CaO/(Na_2O+K_2O))$ versus SiO_2 for samples of the SHB. The rocks of the SHB have an alkali-lime index of c. 56, which lies on the transition between calc-alkaline and alkali-calcic rocks. Symbols as in Fig. 10.

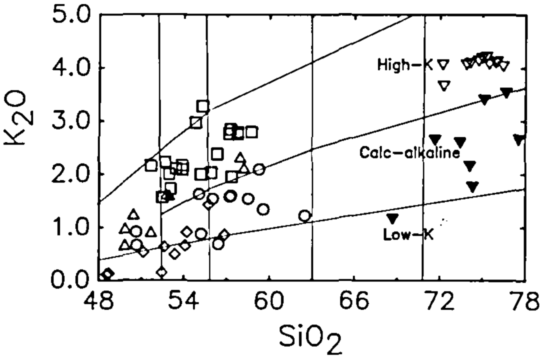

Fig. 15. K_2O versus SiO_2 for selected rocks from the SHB, grid after Peccerillo & Taylor (1976). The monzodiorites belong to a high-K suite, while the diorites show more normal calc-alkaline compositions. Symbols as in Fig. 10.

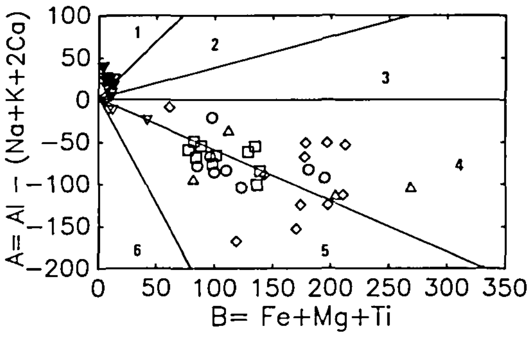

Fig. 16. Characteristic minerals (after Debon & LeFort 1983). Symbols as in Fig. 10. The sectors indicate the following characteristic minerals: 1 - muscovite › biotite; 2 - biotite › muscovite; 3 - biotite; 4 - hornblende ±biotite, orthopyroxene, olivine, clinopyroxene, epidote, sphene; 5 - clinopyroxene ± hornblende, epidote, sphene; 6 — rare rock composition. See Debon & LeFort (1983) for details.

The dolerite dykes have SiO_2 levels varying from about 45% to about 55% and they seem to define a single distinct group particularly with respect to Al_2O_3, Na_2O, P_2O_5, Cr and Ni. For other elements they show variations similar to those of the gabbros.

The late-stage granophyres have SiO_2 concentrations above 70% and deviate somewhat from the main-stage granites and granodiorites with respect to Al_2O_3, Na_2O, K_2O, TiO_2 and most of the trace elements.

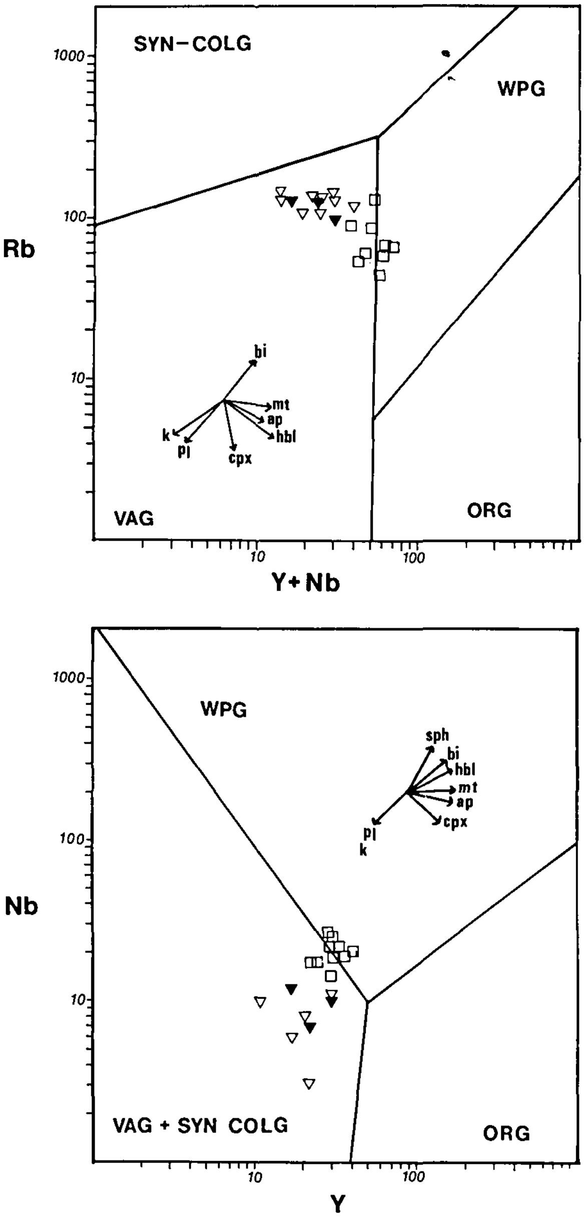

Fig. 17. Trace element classification of granites after Pearce et al. (1982). Symbols as in Fig. 10. ORG - Ocean ridge granites; VAG - Volcanic arc granites; WPG - Within-plate granites; SYN-COLG - Syn-collision granites.

The chondrite-normalised REE patterns for selected SHB rocks are characterised by comparatively high total REE abundances (Fig.12), and relative enrichment in the light rare earths (LREE) with La_n in the range 60-95 and Lu_n from c. 3 to 10. The sample with the lowest La_n/Lu_n ratio is that of the diorite, which also has the highest enrichment in HREE and the only detectable, though weak, negative Eu anomaly. The REE patterns are compatible with derivation from a source with an eclogitic residual (Henderson 1984).

In terms of general chemical classification the AFM diagram has been widely used as a discriminant for igneous rocks. In Fig. 13 this is shown for selected rocks from the SHB. The gap is again apparent between the acidic and basic rocks. The AFM plot provides a rough estimate of arc maturity. Tholeiitic rocks of primitive island arcs commonly show a well-defined Fe enrichment whereas rocks from mature arcs lack this feature. The trend of the SHB rocks does not indicate any Fe enrichment and is similar to that of mature island-arc or continental-arc plutonic rocks (Brown 1982). The SHB has an alkali-lime index of 56 (Fig.14), which corresponds to the transition between calc-alkaline and alkali-calcic rocks. Thus, the SHB shows a somewhat more alkaline affinity than typical calc-alkaline rocks. This tendency is also seen in the K_2O versus SiO_2 plot (Fig. 15), where over 50% of the SHB rocks define a variation typical for that of high-K calc-alkaline rocks.

Debon & LeFort (1983) proposed a classification system which is able to distinguish between different magmatic associations, namely cafemic, aluminous and alumino-cafemic. The aluminous and cafemic associations correspond to the S- and I-type granites, respectively, of Chappell & White (1974). In the mineral plot of Debon & LeFort (1983), the rocks of the SHB show a trend corresponding to the meta-aluminous, cafemic association (Fig. 16). Pearce et al. (1984) have devised discrimination diagrams for the tectonic environment of granitic rocks using some common trace elements. In this diagram (Fig.17) selected granitoids of the SHB all plot in the field of volcanic-arc granites (VAG) while the quartz-monzodiorites are transitional from VAG to within-plate granite (WPG). However, these particular element ratios are sensitive to various magmatic and post-magmatic processes (e.g. crystal accumulation or alteration) which may effectively increase the spread and move the rocks out of their proper field. The quartz monzodiorites are, for example, probably deflected towards the WPG as a consequence of the content of pyroxene, hornblende and apatite (see Pearce et al. 1984, p. 977, for details).

In summary, the plutonic rocks of the SHB show features of high-K calc-alkaline rocks characteristic of mature magmatic arcs. With an alkali-lime index of 56 the analysed rocks are transitional between calc-alkaline and alkali-calcic character and belong to the cafemic (I-type) group of granitoid rocks. Cafemic (I-type) granitoids are usually associated with subduction (Debon & LeFort 1983) and the alkaline nature of the diorites is similar to that of the Linga Group within the Peru Batholith (LeBel et al. 1985) or the Transhimalaya plutonic belt in Tibet (DeBon et al. 1986). Compared with other Caledonian intrusive complexes, the SHB shows some similarities with the high-K rocks of the Kilmelford area of western Scotland (Zhou 1987). Of particular interest is the coexistence of calc-alkaline and high-K calc-alkaline rocks which show similarities with recent magmatism in the Aeolian archipelago of southern Italy (Ellam et al. 1988) where a transition from calc-alkaline to potassic volcanites has been observed. This transition has been interpreted to be associated with island arc magmatism during abating subduction (Barberi et al. 1974, Ellam et al. 1988). A comparable tectonic interpretation was also adopted by Zhou (1987) for the magmatic rocks from Kilmelford in Scotland.

Tentatively, we suggest a similar tectonic setting for the SHB, which is considered to represent the fairly deep plutonic part of an evolved magmatic arc complex, reflecting magmatism during the terminal stage of subduction prior to major collision. The major and trace element variations as well as the high chondrite-normalised LREE/HREE ratios in the SHB rocks are the natural consequence of the evolving magmatic processes in such a tectonic environment. The geochemistry of the Arenig-Llanvirn volcanic rocks from Smøla, also of mature-arc calc-alkaline character (Roberts 1980, 1982b), lends support to this overall paleotectonic interpretation.

Petrogenetic evolution

In this section we will discuss briefly possible processes which can explain some of the chemical variation detected in the batholith. We purposely limit our discussion to those rocks from which most data are available, namely the diorites (including monzodiorites), granites and granophyre dykes. The discussion must therefore be regarded as a preliminary attempt to describe the petrogenesis of the SHB plutonic rocks.

In attempting to interpret trends in plutonic rocks, as described above, it is important to emphasize the fact that the compositions may not represent liquid compositions. This is particularly important for the gabbroic rocks which at least locally show modal layering. To what degree these modally-layered rocks crystallised as orthocumulates or adcumulates is not known. The trends discussed above, in spite of the compositional gap and some scatter, can be interpreted in terms of a general decrease in compatible elements (Ni, Cr, Mg, Fe) and an increase in the incompatible elements (K, Rb, Zr and Ba) during evolution of the crystallising magmas. Sr behaves compatibly at high SiO_2 levels, which is a common feature in high-K calc-alkaline rocks in particular and granitoids in general (Gill 1978). By using the approach of Tindle & Pearce (1981) and Tindle et al. (1988), these trends can be interpreted as a result of fractionation of plagioclase, ortho- and clinopyroxene, amphibole and K-feldspar. The scatter in Zr contents for some of the granites is most easily explained by fractionation of accessory minerals such as zircon. In Fig. 18 which illustrates this further, several trends are apparent. The gabbros, diorites and monzodiorites show an increase in Ba and some decrease in Sr (Fig. 18a), an increase in Rb at fairly constant Sr contents (Fig. 18b) and an increase in both Ba and Rb (Fig. 18c) with fractionation. The granites show a decrease in both Ba and Sr (Fig. 18a), a decrease in Sr together with a constant or slight increase in Rb (Fig. 18b), and a decrease in Ba together with a slight increase in Rb (Fig. 18c). The granophyres show a decrease in Sr at almost constant Ba contents (Fig. 18a), a decrease in Sr at almost constant Rb contents (Fig. 18b) and a contant level of both Ba and Rb (Fig. 18c).

The fractionation vectors illustrate the trend directions during crystallisation of the particular minerals. Partition coefficients are taken

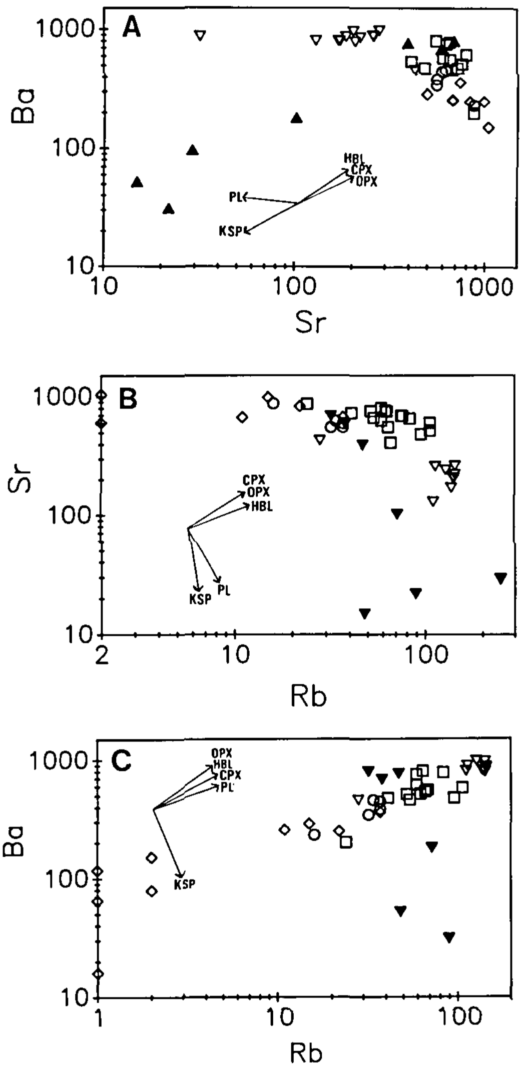

Fig. 18. Log-log Ba, Sr and Rb distributions with crystallisation vectors indicated showing the direction of Rayleigh fractionation trends for particular minerals. See text for discussion. The crystallisation vectors are based on partition coefficients from Gill (1978) and Arth (1976). Symbols as in Fig. 10.

from Gill (1978) and Arth (1976). These trends can be interpreted in terms of fractionation of plagioclase and mafic phases such as clinopyroxene, orthopyroxene and amphibole in the gabbros, diorites and monzodiorites. The granophyres seem to have evolved through mainly plagioclase fractionation; while fractionation of both plagioclase and K-feldspar seems to be necessary to explain the variation among the granites. It is also evident that the compositional gap at about 60% SiO_2 also represents a step-like change in the composition of the fractionating assemblages, i.e. from mainly pyroxene, hornblende and plagioclase to mainly plagioclase and K-feldspar. (Tindle et al. 1988). However, it must be emphasized that we do not believe that these trends represent true liquid lines-of-descent from a common parental magma, but merely illustrate the approximate composition of the fractionating mineral assemblages which can explain the trends.

The absence of tonalits from the differentiation sequence raises the possibility that the granites and granophyres may have originated from another source rather than by fractionation from the monzodiorites. However, consideration of the differentiation patterns from the REE (Fig. 12), Rb, Sr and Ba (Fig. 18), and the isotopic data (p. 15), does not support the concept of an alternative source.

Granitoid petrogenesis may be the result of many different processes, some of the most important of which are: partial melting, crustal assimilation, diffusion-controlled crystallisation and volatile transfer, and crystal and liquid fractionation. In the light of the data currently available, some of these processes are rather unlikely in the case of the SHB. For instance, partial melting would have resulted in early formation of low-temperature acidic magma, corresponding to the composition of the granophyres, whereas they were emplaced at a late stage in the magmatic history. The $^{87}Sr/^{86}Sr$ ratios of less than 0.705 also rule out any substantial contamination by old crust or by sedimentary rocks from an old provenance area. The slightly elevated initial Sr ratios are probably best explained by the addition of very small amounts of lower crustal melts to a mantle-derived magma.

Until more detailed data are available, particularly REE and isotope data, we believe that the general models outlined above provide a reasonable interpretation of the data at hand.

Summary and conclusions

The geological setting and evolution of the Smøla-Hitra Batholith can be summarized as follows:

1. Polyphasally deformed para- and orthogneisses of probable Proterozoic age, together with Arenig - Llanvirn low-grade metavolcanites and sediments constitute the envelope

and occur as enclaves within the Smøla-Hitra Batholith.

2. The SHB is a composite batholith with the following sequence of intrusions: A) Hornblende diorite, monzodiorite and gabbro. B) Tonalite, granodiorite and granite. These plutonic rocks pre-date the following sequence of dykes and minor intrusions: A) Composite dykes. B) Porphyritic microdiorite. C) Minor appinite pipe-like intrusions. D) Dolerite dykes. F) Granophyre dykes. The dyke rocks post-date a phase of weak deformation, the structures of which are seen only locally in the diorites and granites. Geobarometric estimates from hornblende indicate a pressure of solidification of about 0.26 ± 0.1 GPa (2.6 ± 1.0 kb) for the main-stage diorites.

3. Zircon from the main rock-type in the batholith has been dated by the U/Pb method to 450 +5/-3 Ma (Tucker 1988). The youngest granophyre dykes have yielded a fairly reliable Rb-Sr whole-rock isochron age of 428 ± 10 Ma. Thus, the entire batholith was emplaced and cooled over a time interval of about 30 Ma.

4. The rocks of the SHB and its immediate country rocks and enclaves show little sign of Scandian deformation and metamorphism, and they are unconformably overlain by Old Red Sandstone deposits of Late Silurian to Middle Devonian age.

5. The rocks of the SHB are characterised by high-K calc-alkaline compositions. Comparison with similar plutonic complexes suggests that the SHB was formed in a well-established, mature-arc setting, probably during the terminal stages of a subduction cycle . The chemical variations in the diorites and granites can be explained by fractionation of the common minerals plagioclase, hornblende, pyroxene and K-feldspar. The age and composition of the SHB are similar to those of several other Caledonian plutonic complexes in central and southern Norway, e.g. the Sunnhordland batholith (430 ± 10 Ma, 435 ± 6 Ma, Andersen & Jansen 1987, Fossen & Austrheim 1988) and the Heilhornet pluton (444 ± 11 Ma, Nordgulen & Schouenborg 1989). The nature and occurrence of these plutonic complexes and their similar late Mid Ordovician to Early Silurian ages provide substantial proof for an important tectonomagmatic event prior to the Scandian continent - continent collision.

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THE SMØLA - HITRA BATHOLITH AND ADJACENT ROCKS

COMPILED BY
HÅVARD GAUTNEB & DAVID ROBERTS
1988

MAJOR ROCK-TYPES (DYKES OMITTED)

- * EXPLOSION BRECCIA
- ▨ OLD RED SANDSTONE SEDIMENTS (LATE SILURIAN TO DEVONIAN AGE)
- A MINOR APPINITIC BODIES
- △ INTRUSIVE BRECCIATION
- ▌ ULTRAMAFIC APPINITIC ROCKS
- ▨ GABBRO
- ▩ QUARTZ MONZODIORITE
- ▨ GRANODIORITE/GRANITE
- ▨ TONALITE
- ▦ HORNBLENDE DIORITE
- ▨ ACIDIC TO BASIC VOLCANIC ROCKS } SKJØLBERG FORMATION
- ▤ MARBLE } SKJØLBERG FORMATION
- ▨ CONGLOMERATE, LEIRVIK FORMATION
- ▨ UNDIFFERENTIATED PARAGNEISSES
- ▤ UNDIFFERENTIATED ORTHOGNEISSES
- ▧ HIGH-GRADE GNEISSES OF VESTRANDEN, UNDIFFERENTIATED

SCALE
0 10 20 km