Structure, age and formation of dykes on the island of Smøla, Central Norway

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On the island of Smøla, five different dyke phases are represented in an Ordovician, mature ensialic arc complex. With decreasing relative age these are: granitic dykes and net-veins, composite dykes, porphyritic microdiorite dykes, dolerite dykes and granophyre dykes. The granophyres have been dated by the Rb/Sr whole-rock method and yielded a 9 point isochron of $428 \pm 10$ Ma with an initial ratio of $0.70480 \pm 0.0003$ and MSWD = 2.0. From the aspect ratios of the dykes a model is proposed which suggests that the dykes were formed with a magmatic overpressure of less than 90 MPa. This indicates that the source of magma was at a maximum depth of 36 km for the basic dykes and up to 15 km for the granophyres. Theoretical results indicate that a 2 m wide dolerite dyke in the Smøla area solidified within less than about 70 days and a 10 m wide granophyre within around 5 years. Emplacement of the dyke swarms resulted in about 35% crustal extension.

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The study and interpretation of dykes constitutes an important aspect of the intrusive history of the Norwegian Caledonides. With their mutual relationships to the country rocks and to other intrusive bodies, dykes can be used as markers which separate distinct episodes in the tectonomagmatic development of an area. Most of the dyke studies in Norway, however, have been aimed at geochemical, petrological and palaeotectonic interpretations.

The objective of this paper is first to present structural data from an undeformed or very weakly deformed suite of several different dyke types and associated phenomena; secondly, to report the results of an Rb/Sr isotopic study of the dykes. Thirdly, by the application of equations from rock mechanics and heat conduction, some of the physical processes related to dyke emplacement are illustrated.

Geological background

The island of Smøla is situated 35 km NW of Kristiansund in western Central Norway (Fig. 1). The main island is surrounded by more than a thousand smaller islands and skerries, the whole archipelago covering an area of about 220 km². The bedrock is dominated by basic to acidic plutonic rocks. However, because of the presence of a Lower Ordovician fossil fauna with N. American affinity, the previous geological investigations have focused on an area with supracrustal rocks in the central-southern part of the main island (Schetelig 1913; Holtedahl 1914; Reusch 1914; Carstens 1924; Strand 1932). In recent years the supracrustal rocks have been re-investigated (Bruton & Bockelie 1979; Roberts 1980) following the publication of a 1:50,000 scale geological map (Fediuk 1975). Bruton & Bockelie (1979) established a lithostratigraphy and ascribed an Arenig to Llanvirn age for the fossiliferous limestones. Roberts (1980) investigated the geochemistry of the volcanic rocks interbedded with the Lower Ordovician sediments, and showed that the volcanites belong to a high-Al calc-alkaline group characteristic of a mature ensialic arc setting.

Apart from brief comments in the earlier literature, the plutonic rocks of Smøla have not been described in detail previously. This contribution reports some of the results from a detailed field study of the mutual relationships between the different intrusive phases in the southern part of the island (Gautneb 1987). Reconnaissance by the author and others shows that the emplacement sequence established on southern Smøla also applies to the rest of the Smøla archipelago as
well as to the plutonic rocks at the island of Hitra (Kollung 1964; Bering et al. 1986).

The southern part of the island of Smøla consists mainly of a diorite which grades inwards into quartz-monzodiorite. The dioritic rocks show well-developed inch-scale modal layering and locally display an appinitic facies characterized by large amounts of prismatic hornblende. These rocks contain enclaves of the Lower Ordovician supracrustals as well as biotite- and amphibole-bearing gneiss of uncertain age. The supracrustal rocks were polyphasally deformed prior to the emplacement of the diorites. The contact-metamorphic mineral assemblages are characteristic of low-pressure/high-temperature paragenesis with, e.g., large amounts of wollastonite in the calcareous parts of metasedimentary rafts (Gautneb 1987). This indicates a metamorphic pressure less than 0.2 GPa (Greenwood 1967) and shows that the diorites were emplaced at a shallow crustal level. These diorites are intruded by several different plutonic and hypabyssal rocks (Fig. 1).

All the plutonic rocks of southern Smøla belong to a high-K calc-alkaline suite, and, based on trace elements and Rb/Sr isotopes, all are co-genetic and probably derived from similar source regions (Sundvoll & Roberts 1977; Gautneb 1987). This also applies to the plutonic rocks of Hitra (D. Roberts, pers. comm. 1987). K-enriched calc-alkaline magmas are believed to be characteristic of very mature arcs or Andean-type continental margins (Gulson et al. 1972; LeBel et al. 1985; Meen 1987). The plutonic rocks of Smøla were thus formed in a tectonic environment simi-
lar to that of the present Andes or the southern Tyrrenian Sea.

On the southern part of Smøla the plutonic rocks are essentially unmetamorphosed and show no signs of significant ductile deformation. The diorites are unconformably overlain by coarse Devonian conglomerates. These Old Red Sandstone sediments occur in a broad syncline with ENE–WSW axial trend, the northern limb of which is overturned and steeply dipping. This fold deformation is generally considered to be of Late Devonian age (Siedlecka & Siedlecki 1972). Recent palaeomagnetic studies from Smøla (Torsvik et al. in prep.) indicate extensive block rotation of both the pre-Devonian and the Devonian rocks, such that they are probably not preserved in their initial orientation. However, the amount and direction of rotation have no influence on the following discussion of dyke relationships.

The dyke phases

Five main groups of dykes are recognized on Smøla and they are here in the order of decreasing age:

1. Granitic net-veins and solitary granitic dykes
2. Composite (acid/basic) and solitary dolerite dykes
3. Porphyritic microdiorite
4. Basic dykes (dolerites)
5. Granophyre dykes

Dykes of groups 1 and 2 intruded during crystallization of the dioritic host rock, while groups 3 to 5 entirely post-date the formation of the dioritic pluton.

Granitic net-veins and solitary granitic dykes

These intrusive bodies occur only locally and are the first intrusions seen in the diorites (Fig. 1). The rocks have a medium-grained granular texture and a modal composition which varies between granite and granodiorite.

The outcrop pattern of these intrusions is mainly characterized by very dense and random development of net-veins. Locally, the intrusion of granite veins was so intense that the diorite resembles randomly orientated xenoliths in a granitic host. Solitary granitic dykes are always associated with the net-veins and usually occur near the marginal parts of granitic net-vein areas. Since these solitary dykes are related to the formation of the net-veins and to magmatic fracturing they show variable trends and thickness distributions, but thicknesses of more than about 2.5 m have never been observed.

The diorite shows examples of both brittle and ductile failure due to variable rheological behaviour during emplacement of the granitic rocks. This has been shown to be a function of melt present in host rock (Van der Molen & Paterson 1979). The ‘hydro-’ or ‘magma-fracture’ types of net veining are the most common and indicate brittle failure and relative tension in all directions (Fig. 2).

At other localities there occur dioritic fragments partly assimilated by the intruding granitic magma and in such cases the granitic rocks may show a variable colour index and a nebtilitic structure. These field relationships show that the granites intruded during the time of crystallization of the diorites when the latter were partly consolidated and behaved in a somewhat ductile manner but intruded also when the diorite had a purely brittle behaviour.

Composite dykes and solitary dolerite dykes

The common occurrence of composite dykes on southern Smøla provides evidence of co-existence (and co-mingling) of acidic and basic magma. Most of these composite dykes are associated with the granitic net-veining and the acidic parts of the dykes have indeed the same composition as the granitic veins.

Composite dykes have been described from several regions, e.g. in the British Tertiary igneous province and in eastern Iceland (see below). Most composite dykes in these particular areas are characterized by the acidic part being in the middle of the dyke, whereas in the composite dykes from Smøla the basic part is in the middle. This implies different modes of formation for these two types of composite dykes, as discussed below.

The arithmetic mean thickness of the composite dykes from Smøla is 1.3 m, and the thickness distribution is shown in Fig. 3. The distribution is bimodal, with thicknesses of 0.75 m and around 2.0 m being the most dominant. Field obser-
Observations show that the thickest dykes belong to the NE-SW dominating direction shown in Fig. 1.

The mutual relationships between the acidic and basic parts is very variable and shows that there must have been a considerable difference in the rheological properties of the two magma types in individual composite dykes. In some dykes the acidic and basic parts appear as two separate dykes intruded within each other, always with the basic part in the middle (Fig. 4). In other dykes the basic part occurs as pillows within the acidic part, showing a crenulated cauliflower-like pattern towards the acidic portion (Fig. 5). The margins of these basic pillows are usually of finer grain size than the centre, indicating that the basic part was chilled against the acidic part. When a few composite dykes are followed along strike, the form of the basic part changes from being a regular basic dyke within an acidic dyke to being crenulated basic pillows in a granitic dyke, without any evidence of multiple intrusions. Some other composite dykes have the basic part as oblate schliren-like fragments orientated parallel to the strike of the dyke. Where the thickness of the composite dyke can be seen to vary, the shape of the basic pillows and the relative amount of basic material varies with the thickness of the conduit (Fig. 6). This indicates that the acidic and basic magmas moved together through the conduit and that the viscosity of the basic part was greater than that of the acidic. If later ductile deformation had been the cause for this, then it would have affected the whole dyke and would not be related to the width of the conduit. In other dykes this relationship is reflected in a tendency for the granitic material to disrupt the basic pillows by brittle failure. These observations show that acidic and basic magma in many cases intruded together and that difference in the rheological properties prevented their mixing.

Examples of solitary basic dykes which have intruded into partly crystallized country rock (e.g. diorite or granodiorite) are found at some localities (Fig. 7). These dykes have a very irregular...
form, as in the case of the basic part of the composite dykes, but they do not occur in a well-defined conduit.

**Porphyritic microdiorite**

These dykes occur as large mappable units with NNE–SSW strike and are volumetrically the predominant hypabyssal rocks intruding the diorites. On the western part of Breineset the microdiorite is the dominating rock type, occurring as dyke-like intrusions rather than proper narrow dykes (Fig. 1).

The microdiorite has an unambiguous porphyritic texture with rhombic or lath-shaped phenocrystals of plagioclase up to 4 cm across. In some cases the phenocrystals make up nearly 50% of the dyke rock.

The contact between the microdiorite and the dioritic country rock is always straight and sharp, which shows that the diorite behaved in a brittle manner during emplacement of the microdiorite. Field relationships indicate that the microdiorite was, at least locally, emplaced by stoping processes (Gautneb 1987). The diorites occurring on the westernmost part of Breineset are assumed to be rafts within the microdiorite. The lack of three-dimensional control makes it difficult to evaluate whether or not stoping is the dominating process. However, the diorite and quartz-mon-
zodiorite have never been seen to be assimilated by the microdiorite.

Detailed mapping has shown that the aspect ratio (the length to width ratio) of the microdiorite is comparatively low, generally from 10 to 50. In eastern Iceland aspect ratios of dykes are in the order of $10^2$–$10^3$ (Gudmundsson 1983). The significance of this unusually low aspect ratio for the microdiorite dykes from Smøla is discussed below.

**Basic dykes (dolerites)**

Dolerite dykes are the most common dykes on Smøla. In general, the dyke thickness is less than 1 m; the mean thickness is 0.82 m and the mode is 0.4 m (Fig. 8). The locations of some few dykes with thickness is in excess of 5 m are shown in Fig. 1.

The basic dykes are fine- to medium-grained and both aphyric and porphyritic. The porphyritic dykes contain phenocrysts mainly of lath-shaped plagioclase, primary amphibole or pyroxene. Most dykes contain small amounts of quartz in the groundmass. The composition is similar to basaltic andesites and the metamorphism has been equal to lowermost greenschist facies (Gautneb 1987).

The dykes strike mainly NE–SW with a subsidiary trend at ENE–WSW (Fig. 1), but cross-
Fig. 9. Subparallel dolerite dykes with screens of and xenoliths of net-veined diorite.
1 - Diorite, 2 - granite, 3 - porphyritic dolerite, 4 - porphyritic dolerite, 5 - porphyritic dolerite showing flow segregation of the phenocrysts, 6 - aphyric dolerite. Sketch after photograph.

cutting relations are rarely seen. Most of the dolerites occur as solitary dykes, although it is also common to see clusters of subparallel dykes with intervening screens of country rock, or sometimes as multiple dykes emplaced within each other (Fig. 9). None of the dolerite dykes has been observed in its entire length and the true aspect ratio is therefore unknown. However, the 1:5000 scale mapping suggests that the aspect ratio is about the same as that for the granophyre dykes, i.e. exceeds 300 (see below). The dolerite dykes commonly show evidence of emplacement in an extensional stress field with dilatation lobes and matching features on the dyke walls. The large number of dykes and their well-defined orientation indeed point to a phase of extension during their intrusion.

Granophyre dykes

The most conspicuous dyke set within the Smøla area is that of granophyre. These dykes are usually more than 5 m wide and have a mean thickness of 10.4 m and mode of 10 m (Fig. 10). Their thickness, pink colour and distinctive composition are clearly different from all other rock units on Smøla and the granophyres are easily recognized in the field.

The granophyres contain phenocrysts of quartz, plagioclase and K-feldspar in a matrix which sometimes consists of microgranophyric and spherulitic intergrowth of quartz and K-feldspar. The present texture indicates that the granophyres initially had a vitrophyric texture; later devitrification of the primary glass led to the

Fig. 10. Thickness distribution of the granophyre dykes.
formation of the microgranophyric and spherulitic intergrowth. The plagioclase and K-feldspar phenocrysts are usually fresh. The texture in the granophyres thus shows that they were emplaced at a shallow crustal level into relatively cold country rocks (Smith 1967, p. 581).

Almost all the granophyre dykes are indicated in Fig. 1. Field relations show that the granophyres cut most of the dolerite dykes. However, a few dolerite dykes intrude the granophyres. These particular dolerites show features which indicate that they intruded while the granophyres were hot and partly molten. None of these dolerite dykes have chilled margins against the granophyres and the dyke walls are very irregular. These dykes are believed to be approximately contemporaneous with the granophyres. The great viscosity contrast between the dolerite and granophyre magma is considered to be the reason for the lack of mixing of the two magmas.

The best exposed granophyre dykes at Breineset (Fig. 1) have aspect ratios of around 300. This is a minimum figure, however, since the dykes are partly covered by Quaternary deposits and some continue beneath the sea. The granophyres around Leirvikneset and south of Skjølbergvågen (Fig. 1) are not well enough exposed for their exact form and extent to be determined.

**Intensity of the Smøla dyke swarm**

The abundance of dykes on Smøla and the fact that all dyke phases have approximately the same main trends indicate that the dyke swarms were formed during a period of relative crustal tension. The amount of dilatation due to dyke intrusion can be roughly quantified as follows. Based on field measurements and mapping at the scale of 1:5000 the percentage of dilatation was calculated from the following relationship:

\[
\text{Percentage dilatation} = \frac{\text{Aggregate width of dykes in traverse}}{\text{Length of traverse}} \times 100
\]

Two traverses approximately perpendicular to the average dyke trend, one across Olderøy and Hoøy and the other across Rosvolløy, gave dilatations of 36.4% and 32.7% respectively (Table 1). These results probably represent maximum values because some of the microdiorites, which are the dominating dyke phase, may have been emplaced partly by stoping processes. Regardless of the uncertainties involved, these estimates show that the Smøla dyke swarms were emplaced during a period of considerable crustal extension. From the present orientation of the average dyke trends (Fig. 1) the direction of extension has been in a NW–SW direction.

**Radiometric age determinations**

Rb–Sr whole rock dating has been attempted on 9 samples of the dioritic country rocks and 9 samples from the granophyre dykes. These rock types are believed to represent the oldest and youngest rocks in the intrusive sequence. The analyses were done on unspiked samples with the analytical facilities at the Mineralogisk-Geologisk Museum, University of Oslo, using the methods of Pankhurst & O’Nions (1973). The \(^{87}\text{Rb}\) decay constant used was \(1.42 \times 10^{-11}\text{a}^{-1}\). The regression line was calculated according to York (1969).

**Results**

Only the granophyres yielded a meaningful isochron, this being of \(428 \pm 10\text{ Ma}\) with an initial ratio of \(0.70480 \pm 0.00003\) and MSWD of 2.0 (Fig. 11 and Table 2). The diorite and quartz-monzodiorite samples produced an errorchron of \(494 \pm 54\text{ Ma}\) with MSWD of 18.1 (Gautneb 1987).

The isochron for the granophyres seems so well defined that the devitrification observed in some samples does not seem to have disturbed the isotope system.

**Discussion**

The age of the granophyres falls within the same range as the earlier reported age \(436 \pm 7\text{ Ma}\; ^{87}\text{Sr}/^{86}\text{Sr} \text{ initial ratio} \; 0.70499 \pm 0.00006\) for the
Diorites on Smøla (Sundvoll & Roberts 1977) and indicates that the absolute age difference between the country rock and the dykes phase probably is not great. The geochemical significance of these data will be reported elsewhere, but the composition of the rocks and the low initial ratios show that the Smøla rocks are essentially mantle derived and that the crustal influence has been subordinate.

The radiometric age of the granophyres gives a minimum age on the formation of the plutonic rocks on Smøla and the ductile deformation which is mainly seen on the northern part of the island. The granophyres also give the minimum age of the phase of crustal extension represented by the Smøla dyke swarms. The maximum age is represented by the supracrustal enclaves in the diorites with their Arenig-Llanvirn age.

Two major orogenic deformational phases have been reported in the Scandinavian Caledonides, the Finnmarkian and the Scandian, in latest Cambrian to early Ordovician and late Silurian time respectively (see e.g. Sturt 1984 and Roberts & Gee 1985 for reviews). The age of the meta-sedimentary rocks on Smøla and the radiometric age reported by Sundvoll & Roberts (1977) and in this paper show that the deformation of the supracrustal rocks, the ductile deformation of the diorites and the phase of crustal extension represented by the Smøla dyke swarm are post-Finnmarkian pre-Scandian phenomena, probably between Llanvirn and Llandovery in age. This

\[ T = 428 \pm 10 \text{ Ma} \]
\[ (87\text{Sr}/86\text{Sr})_0 = 0.70480 \pm 0.0003 \]
\[ \text{MSWD} = 2.0 \]

\[ \text{Rb/Sr isochron\ diagram for 9 whole-rock samples of the granophyre dykes. Errors given at the 2-sigma level.} \]

<table>
<thead>
<tr>
<th>Sample</th>
<th>ppm Rb</th>
<th>ppm Sr</th>
<th>(^{87}\text{Rb}/^{86}\text{Sr})</th>
<th>SE</th>
<th>(^{87}\text{Sr}/^{86}\text{Sr})</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>179B</td>
<td>127.131</td>
<td>139.332</td>
<td>2.64329</td>
<td>0.02643</td>
<td>0.72104</td>
<td>0.00010</td>
</tr>
<tr>
<td>370</td>
<td>97.534</td>
<td>373.882</td>
<td>0.75488</td>
<td>0.00755</td>
<td>0.70962</td>
<td>0.00010</td>
</tr>
<tr>
<td>188B</td>
<td>118.344</td>
<td>230.094</td>
<td>1.46893</td>
<td>0.01489</td>
<td>0.71373</td>
<td>0.00010</td>
</tr>
<tr>
<td>188E</td>
<td>134.495</td>
<td>184.621</td>
<td>2.10968</td>
<td>0.02110</td>
<td>0.71746</td>
<td>0.00015</td>
</tr>
<tr>
<td>91</td>
<td>132.678</td>
<td>139.586</td>
<td>2.75387</td>
<td>0.02754</td>
<td>0.72202</td>
<td>0.00009</td>
</tr>
<tr>
<td>353C</td>
<td>83.319</td>
<td>222.066</td>
<td>1.08591</td>
<td>0.01086</td>
<td>0.71132</td>
<td>0.00008</td>
</tr>
<tr>
<td>188C</td>
<td>131.975</td>
<td>173.931</td>
<td>2.19752</td>
<td>0.02198</td>
<td>0.71806</td>
<td>0.00002</td>
</tr>
<tr>
<td>188F</td>
<td>130.325</td>
<td>216.797</td>
<td>1.74053</td>
<td>0.01741</td>
<td>0.71545</td>
<td>0.00002</td>
</tr>
<tr>
<td>124</td>
<td>109.945</td>
<td>151.003</td>
<td>2.10857</td>
<td>0.02109</td>
<td>0.71760</td>
<td>0.00002</td>
</tr>
</tbody>
</table>
tectonic deformation of the volcanosedimentary rocks was considered by Roberts (1980) to be possibly equivalent to the pre-Bala deformation in the British Caledonides, and has been equated with the Mid Ordovician Taconic orogeny (Hall & Roberts 1988).

Neither the Scandian nor the late Devonian deformation resulted in any visible ductile deformation or metamorphic effects on the pre-Devonian rocks on Smøla. However, the archipelago is considered to be in allochthonous position and to form part of the Upper Allochthon (Roberts & Gee 1985).

In recent arc-related regions, e.g. the SW Pacific, short-lived phases of crustal compression and extension can occur very locally (Mitchell & Reading 1971; Hamilton 1979). The phases of intra-Ordovician deformation within the Smøla and Hitra district, as well as the dyke swarm itself, may therefore be of comparatively local extent.

Some mechanical and thermal aspects of dyke formation

Some of the most important parameters in dyke emplacement are the following:

1. Magma pressure within the dyke; 2. elastic constants for the host rock (Young’s modulus and Poisson’s ratio); 3. magnitude of remote stresses.

Let $P$ be the total magma pressure in the dyke, $\sigma_h$ the compressive stress perpendicular to the dyke and $T$ the tensile strength of the host rock (compressive stress regarded as positive). A net-vein or dyke intrusion will occur when (Jaeger & Cook 1979, p. 444):

$$P \geq \sigma_h + T$$

It is generally accepted that a dyke will follow the pathway of minimum work, thus a dyke will propagate along the plane where the ($\sigma_h + T$) has its minimum value (Gudmundsson 1984). If the plane of minimum $T$ does not deviate much from the plane perpendicular to minimum horizontal compressive stresses a dyke will normally be emplaced parallel to a principal plane of stress at the time of formation, which is generally assumed to be the $\sigma_1 - \sigma_2$ plane.

Assuming a constant magmatic overpressure $\Delta P$ (i.e. magmatic pressure in excess of the lithostatic pressure) in the dyke, the half-width of the dyke $w$ is given by (Sneddon 1951):

$$w = \frac{2(1-\nu^2)\Delta P \sqrt{(a^2 - x^2)}}{E}$$

Where $\nu$ is Poisson’s ratio, $E$ is Young’s modulus, $a$ is the half-length of the dyke, and $x$ the x-axis of the coordinate system parallel to the length of the dyke. Gudmundsson (1983) showed that (2) can be simplified to:

$$L/W = \frac{E}{2(1-\nu^2)\Delta P}$$

where $L$ is the length and $W$ is the maximum width of the dyke. Thus given the aspect ratio of a dyke, and the (elastic parameters) $E$ and $\nu$ the magmatic overpressure during intrusion can be calculated. The observed average aspect ratio for the granophyre dyke is around 300. Let $E$ be $5 \times 10^{10}$ Pa and $\nu$ be 0.25 Pa, which are typical reasonable static values for gabbro (Jumikis 1979), then by rearranging (3) we get a magmatic overpressure during emplacement of the basic dykes and the granophyres of 89 MPa (890 bars). This pressure estimate is a maximum figure, since pressure estimates from (3) depend strongly on the aspect ratio and none of the dolerite dykes nor the granophyre dykes have been observed in their entire length. However, according to Maaløe (1987) typical overpressure values for basaltic intrusions are between 10 and 200 MPa (100 to 2000 bars), and similar estimates for dykes associated with the Skaerdgaard intrusion gave a magma overpressure of 125 MPa (Rogers & Bird 1987).

The magmatic overpressure is a function of the density difference between the magma and the country rock as well as the depth to the magma source. If $\Delta P$ is the magmatic overpressure, $\rho_m$ the density of magma ($2650 \text{ kg/m}^3$ for basalt and $2200 \text{ kg/m}^3$ for granite, Williams & Mcbirney 1979), $\rho_c$ the density of the country rock, $g$ the acceleration of gravity and $d$ the depth to the magma source, then we get:

$$\Delta P = (\rho_c - \rho_m)gd$$

If one assumes that the country rock is gabbro with an average density of $2900 \text{ kg/m}^3$, which is what Sindre (1977) found for the Smøla rocks, and if $\Delta P$ is 89 MPa, then the basaltic dykes had their source at about 36 km depth and the granophyres at ca. 15 km depth. Obviously these figures are also maximum values due to the uncertainty in the overpressure estimates.
For a typical aspect ratio of 25 for the porphyritic microdiorite the corresponding magmatic overpressure would be 1067 MPa. This is an unrealistically high figure and is probably due to the fact that part of the microdiorite magma was emplaced by stopping processes. In this latter case equations 2 and 3 above do not apply.

Other things being equal, the bimodal thickness distribution of the composite dykes may indicate that the composite dykes were emplaced in two generations formed with different magmatic over-pressure or from sources at different depths, i.e. from two different magma chambers at different depths.

The geochemistry of the Smøla rocks indicates that the rocks were formed in an arc-related environment (Roberts 1980; Gautneb 1987). The isotope analysis shows that the rocks are mantle derived. According to Gill (1981), mature arcs have crustal thicknesses of the order of tens of kilometres. Thus the pressure and depth estimates above are not in conflict with any other result from Smøla.

The occurrence of multiple dykes puts certain constraints on the possible time differences between the dolerite dykes. Since a dyke normally follows the pathway of minimum work, a dyke may follow a pre-existing dyke if the first is still partly molten and has a lower tensile strength than the host rock. A completely solidified dolerite is assumed to have approximately the same tensile strength as the host diorite. By using the approach of Gudmundsson (1984), it is possible to estimate the cooling time of basaltic dykes and the time difference between pulses in a multiple dyke.

Jaeger (1968) shows that the time \( t \) for complete solidification of a dyke is given by:

\[ t = \frac{w^2}{4\lambda^2\kappa} \]

where \( w \) is the half width, \( \lambda \) is a dimensionless constant and \( \kappa \) is thermal diffusivity of magma and country rock. The magma temperature for basaltic andesites is 1020–1110°C (Williams & McBirney 1979). If we assume that the solidification range is 1100–800°C, \( \lambda \) is 0.182 with a latent heat of magma of 4.2·10^5 J/kg (Jaeger 1968). The thermal diffusivity \( \kappa \) is given by (Jaeger 1957):

\[ \kappa = \frac{k}{\rho_c c} \]

where \( k \) is thermal conductivity, \( \rho_c \) is density and \( c \) is specific heat of the host rock (assumed equal to that of the dyke magma). If the thermal conductivity is equal to 3.2 W/(mK), which is an average value for diorite (Turcotte & Schubert 1982), the heat capacity is 835 J/(kgK) (Jumikis 1979), and the density is 2900 kg/m^3 (as in (4)), then (6) gives \( k = 1.3\cdot10^{-6} \) m/sK and (5) \( t = 5.8\cdot10^6 \) s. Thus a 2-m-wide dolerite dyke (\( w = 1 \)) will solidify within 5.8·10^6 s or 67 days and the time difference between the magma pulses in the multiple dyke (Fig. 9) will be less than around 1.2 years.

The granophyre dykes probably had an emplacement temperature of around 820–790°C, which is the range for rhyolite magma (Williams & McBirney 1979). If we assume a solidification range of 800–600°C, \( \lambda \) is 0.170 (Jaeger 1968) and other things being equal, (6) gives \( t = 6.7\cdot10^6 \) s. An average granophyre dyke with thickness of around 10 m will thus solidify within around 5.3 years.

The above mechanical and thermal considerations on the Smøla dykes carry some uncertainties. The results should not be looked at as definite, but the calculations are probably within the right order of magnitude, and demonstrate methods which have not been commonly applied to dykes in the Norwegian Caledonides.

Some comments on the formation of the composite dykes

The composite dykes in southern Smøla are so uniquely well preserved that they deserve a more thorough discussion. Detailed field descriptions of composite acidic and basic intrusions have been widely reported in the literature (e.g. Elwell et al. 1960; Blake et al. 1965; Gunn & Watkins 1969; Wiebe 1973, 1974; Vogel & Wilband 1977; Vogel 1982; Furman & Spera 1985; Mattson et al. 1986; Frost & Mahood 1987). Theoretical and experimental modelling of the formation of composite intrusions have been attempted by Yoder (1973), Koyaguchi (1985, 1987), Blake & Campbell (1986), Sparks & Marshall (1986) and Frost & Mahood (1987). Models have generally aimed at explaining the most common composite dykes within the British Tertiary igneous province and on Iceland, where in both cases the acidic part is in the middle (see Blake & Campbell 1986). It is generally assumed that acidic magma is so viscous...
that it has difficulty in intruding the host rock unless it penetrates along a still molten basic body with almost zero tensile strength. This has obviously not been the case for the Smøla dykes, because here the basic parts occupy the middle of the composite dykes. Fig. 12 shows a diagrammatic sketch of the outcrop features of the composite dykes on Smøla. It is assumed that there is a continuous transition between all the principal dyke types in Fig. 12 since some of the illustrated outcrop patterns can be observed along the same dyke when followed along strike.

Koyaguchi (1985, 1987) has proposed a model for the mixing of magmas in conduits which seems to explain some of the observed features in the Smøla composite dykes. This model assumes a stratified magma chamber with a less dense, more viscous acidic magma on top of a denser, less viscous basic magma. Koyaguchi (1987) assumed that a portion of both magmas penetrates a conduit with the stratification still preserved. When the density of the country rock is higher than the density of this composite magma the conduit will close behind the penetrating magma and open in front of the magma. Koyaguchi (1987) showed that during this process the stratification was reversed several times with gradually more and more mixing of the magmas. If the model proposed by Koyaguchi (1987) provides a viable mechanism for the different dyke types illustrated in Fig. 12, then the depicted patterns are a function of intrusion rate and the differences in viscosity, density and proportion between acidic and basic magma. For instance, a slow rate of intrusion and a relative large viscosity contrast could form a dyke such as shown in Fig. 4, while a faster intrusion rate, more extensive mingling and a lower viscosity contrast would assist in forming features like those depicted in Fig. 5.

Summary and conclusions

In the southern part of Smøla, five different types of dyke intrude undeformed diorites and form a well-preserved dyke swarm. All the dykes are believed to belong to the same mature arc plutonic complex and the absolute age differences between the dykes are probably not very great.

The length/width ratios of the dykes make it possible to estimate the maximum depth to the

![Fig. 12. Diagrammatic sketch of the different outcrop features seen in composite dykes intruding a dioritic host rock. It is considered that the development from a to d is due to an increased rate of intrusion, more mixing and less viscosity contrast between the acidic and basic melts.](image)
magma sources as 36 km for the dolerite dykes and 15 km for the granophyres.

The cooling time for an average dolerite was in the order of several months of days, while the cooling time for an average granophyre was of the order of years.

Rb–Sr dating of the youngest granophyre dykes together with the faunal evidence in the meta-sedimentary rocks show that the dyke swarm was emplaced in post-Llanvirn to Llandovery time. The dyke swarm followed a period of polyphased deformation of supracrustal rocks on Smøla and was associated with about 35% crustal extension.

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