

THOMAS LUNDQVIST AND LENNART SAMUELSSON

THE DIFFERENTIATION OF A DOLERITE  
AT NORDINGRÅ, CENTRAL SWEDEN



STOCKHOLM 1973

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## ABSTRACT

This study concerns modal, chemical, textural and structural variations within a flat-lying sill of Jotnian dolerite (probable age 1 100—1 300 m. y.) at Nordingrå, central Sweden. Two different units can be distinguished within the dolerite. The lower of these is slightly differentiated by crystallization which started at the contacts and proceeded towards end-products in the upper part. The upper dolerite unit is strongly differentiated, mainly by crystal settling. Rhythmic and cryptic layering and igneous lamination occur here.

## INTRODUCTION

At present, reconnaissance work for a petrographical map (scale 1:200 000) of Västernorrland County, central Sweden, is in progress. During the field work it was noted that the Precambrian anorogenic, more or less flat-lying dolerite sheets and sills of this region in numerous localities display the characteristic features of layered intrusions.

The present study was made in order to investigate the structural, textural, modal and chemical variations upwards from the lower contact of a dolerite sill at Nordingrå, on the coast of the Bothnian Sea. This locality was chosen because it offered good possibilities of sampling (well-exposed bedrock) and of calculating the position of the lower dolerite contact. Thus, the present work concerns a particular section through the dolerite. Another study of the same dolerite (the Ulvö dolerite) is in progress, and is carried out by fil. mag. S. Å. Larson, Göteborg. That investigation deals mainly with the

rhythmically layered dolerites and their structural and textural features as well as mineralogical and chemical variations.

The work of the present study has been shared by the two authors in the following way. One of us (T. L.) is responsible for the regional geology and the laboratory investigation. He has also written the main part of the paper. The second author (L. S.) has carried out the major part of the local field study, the sampling and the evaluation of the Ringkallen profile (Table 1 a).

## REGIONAL GEOLOGY

Within the Precambrian of Västernorrland County metagreywackes of varying metamorphic grade predominate. In the early stages of the Svecokarelian (Svecofennian) orogeny the metagreywackes were intruded by a suite of synorogenic (primorogenic, synkinematic) igneous rocks, ranging in composition from ultrabasic to granitic. During the serorogenic (late-kinematic) stage, ending c. 1 800 m. y. ago (Magnusson 1960; Welin and Blomqvist 1964), the synorogenic intrusions and the metasupracrustals were in part migmatized, with the concomitant formation of anatectic magmas producing granites and pegmatites. The rocks involved in the above evolution together constitute the Svecokarelian fold belt.

During the anorogenic stage following after the Svecokarelian orogeny, some essentially igneous complexes were formed in this part of Sweden. The Nordingrå and Ragunda massifs and the Rödö granite (cf. Magnusson et al. 1960) belong here.

The older part of the Nordingrå massif, the whole Ragunda massif and the Rödö granite and associated dikes have been referred to the sub-Jotnian, a term introduced by Högbom (1909 a). It is at present not known whether these sub-Jotnian intrusions took place synchronously or whether they represent different episodes of magmatic activity. A radiometric age determination of the Nordingrå granite yielded  $1\ 440 \pm 30$  m. y. (Welin and Lundqvist, in preparation).

At Nordingrå the sub-Jotnian igneous complex, including granite, gabbro and anorthosite, is overlain by a formation of sandstone with intercalations of shale. These sedimentary rocks belong to the Jotnian formations of Fennoscandia (cf. Magnusson et al. 1960). The sandstone shows a maximum thickness of 60 m, and a gentle southeasterly dip (cf. Lundbohm 1899 and Sobral 1913). At the base of the sandstone, especially where the latter rests on granite, *in situ* arkoses are found, which define the erosion surface below the Jotnian (the sub-Jotnian non-conformity).

The youngest rock of the Nordingrå region is an olivine dolerite sill or sheet of alkali basalt type (the Ulvö dolerite), which is also included in the Jotnian (cf. Magnusson et al. 1960). The dolerite rests more or less con-

formably on the sandstone formation, having protected the latter from removal by erosion. In detail the contact may be irregular, and the dolerite sends apophyses into the sandstone. Dense, chilled margins are characteristic of the dolerite along its contacts with sandstone and other wall-rocks.

The sandstone roof overlying the dolerite intrusion has been removed by erosion, no upper dolerite contact towards sandstone being found in the region. In the easternmost parts of the Nordingrå area (Bönhamn—Rävsön), where one would expect a sandstone roof to occur, anorthosite is found on top of the dolerite (cf. Sobral 1913). The cause for this is evidently pre-dolerite movements along approximately north-south or north-northeast trending faults, leading to a relative upward displacement of the eastern block.

The Ulvö dolerite in part occurs as a sheet within the sub-Jotnian igneous complex, as e. g. on Ulvöarna. It continues towards the northeast to Skagsudde and, finally, to the vicinity of Husum (c. 60 km northeast of Nordingrå; cf. Fig. 1), where its further extension is hidden below sea level. From the Skagsudde area it also branches off towards the north (Fig. 1). In the Skagsudde—Husum region the roof and floor rocks are synorogenic intrusions (granites and granodiorites) and metagreywackes in various stages of metamorphism and migmatization.

Within the folded and metamorphosed Svecokarelian complex surrounding the Nordingrå massif occurs another flat-lying dolerite, petrographically similar to the one at Nordingrå (Fig. 1). The intersection with the present erosion level has the shape of a semicircle with a diameter of approximately 100 km. In the north (near Köpmanholmen), this dolerite has intruded at the contact zone between the sub-Jotnian Nordingrå granite and Svecokarelian metagreywackes, below the former and thus presumably at a deeper level than the Ulvö dolerite (cf. also map of Sobral 1913). It continues with minor breaks to the region north and west of Kramfors, to Viksjö and, after a major break, to the northern shore of Ävikebukten, c. 15 km southwest of Härnösand. There is a probable connection with dolerite occurrences immediately south of Ävikebukten and on some small skerries southeast of Sundsvall. Although important breaks occur, the dolerite may be considered to continue further south, to Björköfjärden (c. 25 km southeast of Sundsvall) and to the region of Gnarp in Gävleborg County (cf. Lundegårdh 1967).

The dolerite between Köpmanholmen and Ävikebukten has an approximate thickness between ten and a few hundred metres. The shape is probably that of a lopolith, the contacts generally dipping gently towards the centre of the semicircle. Such a dip is especially well demonstrated c. 10 km northeast of Viksjö, where the upper marginal parts of the dolerite have been exposed by erosion in an area where dolerite is normally covered by

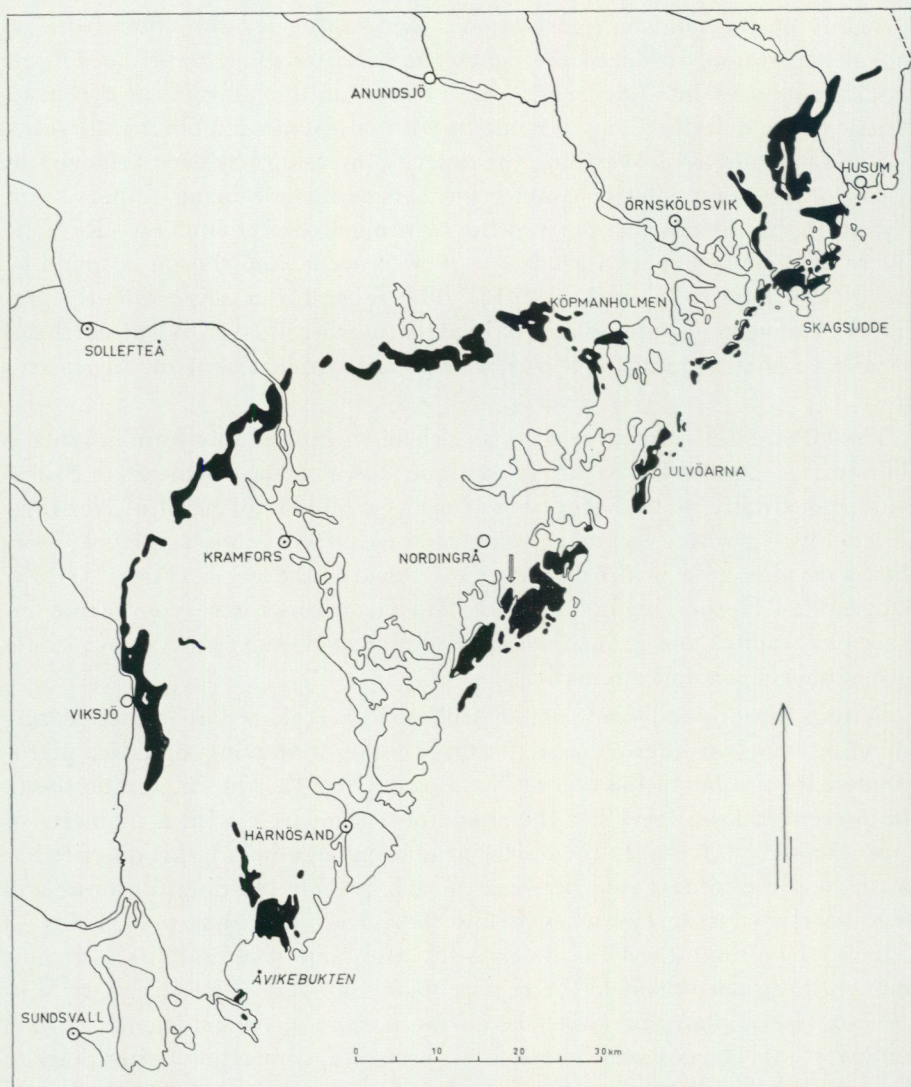


Fig. 1. Dolerite sheets (black) in the eastern part of Västernorrland County. From the preliminary petrographical map of Västernorrland. Arrow (near Nordingrå) indicates the position of the Ringkallen hill.

*Diabastäcken (svarta) i östra delen av Västernorrlands län. Från den preliminära berggrundskartan över Västernorrland. Pilen (nära Nordingrå) anger läget för Ringkallen.*

Svecokarelian rocks. Direct field observations of relationships between dolerite outcrops and topography also strongly suggest gentle dips roughly towards the centre of the semicircle. It must, however, be stated that field observations of dolerite contacts have indicated that the latter are often ir-

regular and thus not suitable for extrapolations. An investigation by geophysical methods is desirable to prove or disprove the above three-dimensional lopolith model.

The orientation of the Ulvö dolerite and the dolerite lopolith between Köpmanholmen and Ävikebukten suggests that the magmas forming these intrusions ascended along major crustal fractures striking north-northeast, i. e. subparallel to the coast line of the Bothnian Sea. These fractures may have been reactivated later, when the Alnö alkaline and carbonatitic intrusions occurred (von Eckermann 1948; von Eckermann and Wickman 1956). Alkaline dikes are also found near Kalix and Luleå, along the northernmost part of the coast line of the Gulf of Bothnia (Geijer 1928; W. Larsson 1943).

Sheets and dikes of dolerites ascribed to the Jotnian and similar to those mentioned also occur in other parts of central Sweden: in central and western Medelpad, and in Jämtland, Västerbotten, Gävleborg and Kopparberg Counties (Magnusson et al. 1960; Högbom 1894; Gavelin 1955; Stålhös 1958; Lundegårdh 1967; Gorbatshev 1967; Hjelmqvist 1966). Also in southern Sweden representatives of the Jotnian dolerites are found, although they are not so common. Important examples of such dolerites are found in Sörmland (the Breven and Hällefors dikes, see Krokström 1932 and 1936) and Småland (at Almesåkra, cf. Magnusson et al. 1960).

In addition to the large sheet-like dolerites there also occur numerous narrow dikes of similarly composed rocks in Västernorrland County. The width of these dikes generally does not exceed five metres. In most cases the dip is vertical or nearly so, and the strike east—west. Such narrow dolerite dikes are found in the rocks of the Svecokarelian fold belt, in the sub-Jotnian igneous rocks at Nordingrå, and in the dolerite sheet on N. Ulvön.

For a distance of 15 km along the shore north of Husum a calculation of the north—south tensional deformation of the crust that took place in connection with the intrusion of the narrow east—west striking dolerite dikes has yielded 76 m, i. e. c. 0.5 %. This should be regarded as a minimum value, as unexposed dikes may occur.

The narrow dikes of dolerite seem to be on the whole more abundant near the thick sheets of dolerite than elsewhere, and are therefore (and because of petrographic similarities) thought to be intruded in close connection with the latter. Possibly, however, there exist dolerite dikes which are unrelated to the sheets, both in genetical and chronological respects.

Narrow dolerite dikes ascribed to the Jotnian or post-Jotnian have been reported from several other regions in southern and central Sweden (e. g. Gorbatshev 1961; Hjelmqvist 1966; Lundegårdh 1967; Stålhös 1969).

The absolute age of the Jotnian sedimentary rocks at Nordingrå is not known. Other Jotnian sandstones etc. in Fennoscandia show a great spread

in K-Ar ages (cf. Lundqvist 1968, p. 168, and references given there). Most probably their true age generally falls in the interval 1 100—1 300 m. y. Lower figures may be caused by secondary argon loss. A similar age is also most likely for the Jotnian dolerites, although radiometric determinations show great variations (cf. Lundqvist 1968, p. 168). A very approximate figure of 1 300—1 400 m. y. was obtained by the Rb-Sr method for a dolerite from S. Ulvön (Welin 1966; Welin et al. 1966).

A rough estimate of the volume of doleritic magma intruded during Jotnian time in Fennoscandia indicates a figure of the order of magnitude of  $10^3$  km<sup>3</sup>. It seems natural that such great eruptions of magma were connected with considerable crustal deformation. As the probable age of the dolerites is 1 100—1 300 m. y., the latter ought to have intruded during early phases of the Dalslandian (or Sveconorwegian) orogeny in south-western Sweden and southern Norway (cf. Magnusson et al. 1960; Welin and Blomqvist 1964), and possibly as a consequence of this orogeny.

### THE ULVÖ DOLERITE

Earlier works dealing with the Ulvö dolerite include those of Lundbohm (1899), Högbom (1909 b), Sobral (1913), and Mogensen (1946). Sobral (1913) gave detailed petrographic descriptions and noted some extreme differentiation products which were analysed chemically: sodic dikes, monzonites, "peridotite" (with as much as 58 % normative olivine and 15 % light minerals), "anorthosite" (with 72 % normative feldspar) and titanium-ferrous iron ores. von Eckermann (1946, p. 414, and 1948) gave aspects on the differentiation, describing a highly oxidized, relatively iron-rich dolerite from Trysunda and late-magmatic sodic veins and dikes.

The main features of the Ulvö dolerite have been briefly accounted for above (p. 5). This dolerite thus forms a sheet or sill, gently (mostly c. 5—30°) dipping to the east, southeast or south. The floor is made up of Jotnian sedimentary rocks, sub-Jotnian intrusions or Svecokarelian metagreywackes (in part migmatites) and intrusions. In the roof of the dolerite the same rock types occur, with the exception of the Jotnian sandstones and shales.

Estimates of the thickness of the Ulvö dolerite do not give accurate results, because only few measurements of contact dips have been made, and because the contacts are generally irregular on the scale of direct field observation. At Ringkallen the minimum thickness is slightly more than 200 m. From the available data a value between 200 and 500 m seems most likely for the major parts of the Ulvö dolerite (cf. also below, p. 45). In the Skagsudde area a greater maximum thickness (between 500 and 1 000 m) is possible (cf. Lundqvist 1973).

Whereas the main parts of the dolerite are medium- or coarse-grained, the marginal zones are fine-grained, in part aphanitic. Close to the contacts the rock is usually strongly jointed. The orientation of these joints is such that a columnar structure is formed at right angles to the contact, the spacing of the joints widening away from the latter. Within the medium- and coarse-grained dolerite types at least three sets of joints are prominent: one that is subparallel with the contacts (flat-lying), and two or more dipping steeply.

The normal dolerite is subophitic (Krokström 1932, p. 199) and dark grey (or rather spotted, greyish white and black) in colour. Contact types are black, or, if the rock is uralitized, greenish black. Secondary alterations involving especially the replacement of pyroxene by hornblende, but also the formation of epidote and sericite from plagioclase, and chlorite from biotite, are particularly observed at the contacts and along fissures. Especially noteworthy is the crystallization of hornblende and other Ca-rich minerals in fissures, giving a central dark green zone, a few centimetres wide, which is surrounded by zones of bleached dolerite. The central hornblende is accompanied by prehnite, epidote, calcite, sphene etc. The bleaching of the dolerite involves a uralitization of pyroxene along with saussuritization of plagioclase. Olivine is altered to colourless amphibole and chlorite, iron-titanium oxide(s) to sphene (in part leucoxene), and biotite to chlorite. The bleaching also seems to be caused by a rise in plagioclase (albite) content, which involves a migration of femic constituents towards the hornblende-rich central zone. This bleaching and the crystallization of hornblende etc. should be ascribed to deuteric alterations within the cooling dolerite.

Other manifestations of late- or post-magmatic activity are formed by thin (maximum c. 1 m wide) dikes of pink or white, fine-grained albite microgranite or granophyre, and secondary alterations in the surrounding dolerite. Within the dikes hypidiomorphic albite and xenomorphic quartz predominate. Often the two minerals form a granophyric intergrowth. In generally subordinate amounts occur a usually green hornblende, epidote (with orthite and piemontite), chlorite, sphene, oxide(s), augite (in part as remnants in hornblende), calcite, zeolite (?), muscovite and apatite. In some dikes garnet has also been observed (Sobral 1913, p. 166; von Eckermann 1938, pp. 418—422). In the immediate vicinity of the sodic dikes the dolerite shows the same alterations as along the hornblende-filled fissures (uralitization etc.).

von Eckermann (1938) gave aspects on the differentiation of basic rocks (Jotnian dolerites etc.) leading to sodic dikes of the above type. Such dikes are not uncommon in the Jotnian dolerites, and occur, e. g., on the skerries east of Sundsvall (Holmquist 1899, p. 83).

In addition to the sodic rocks, similar, fine-grained (aplitic) dikes, carry-

ing potash feldspar, also occur. Such a dike from the southern part of the dolerite lopolith (p. 5) has been described by von Eckermann (1947, p. 165).

In several localities all over the region of the Ulvö dolerite a conspicuous feature is the occurrence of more or less rounded or irregular bodies of a very coarse-grained dolerite pegmatite. The volume of these is usually of the order of 0.1—10 m<sup>3</sup>.

The essential constituents of the dolerite pegmatites are plagioclase and augite in crystals which may approach 10 cm in length. The plagioclase, which is mainly a labradorite or andesine, is in part strongly altered to sericite, prehnite and epidote, with concomitant albitization. Brown or green hornblende and brown biotite are secondary after augite. Oxide minerals show alteration to leucoxene. Accessories are apatite and sphene. In some types of dolerite pegmatite a reddish, perthitic potash feldspar is a conspicuous constituent. It forms replacement textures with plagioclase, and occurs as antiperthitic patches within the latter. By an increased content of perthitic potash feldspar and by the introduction of quartz, often as granophyre, the rocks grade into coarse-grained monzonites and granites, which occur as mostly irregular schlieren within the dolerite.

In addition to the monzonitic and granitic schlieren just mentioned, there are also similarly composed, medium- to coarse-grained differentiates occupying large areas especially in the easternmost, upper parts of the Ulvö dolerite. Such rocks are well exposed e. g. on the skerries east of N. Ulvön and on Ällön (Ellön) and Gråskär east and southeast of Trysunda (cf. map of Sobral 1913). They also occur in the upper parts of the dolerite lopolith mentioned above, and are particularly well developed north of Ävikebukten (at Häggdånger) and south of Köpmanholmen.

Granitic and monzonitic differentiates in Jotnian dolerites have been reported from several other regions in Sweden, e. g. Sörmland (the Breven dike; see Krokström 1932; Gorbatshev 1961) and Kopparberg and Gävleborg Counties (von Eckermann 1936; Hjelmqvist 1961 and 1966; Lundqvist 1968). As to the genesis of these granites and monzonites, two main views exist. The first involves a formation by differentiation of basaltic magma. The acid material should then derive its origin mainly from the mantle. As a second possibility the granites etc. were formed by remelting of crustal rocks caused by the heat of the basaltic magma, perhaps followed by differentiation of the contaminated magma. It seems clear that the second mode of origin is valid in some cases. Hjelmqvist (1966, p. 150) states that assimilation of granite and porphyry material is the cause of the appearance of monzonitic differentiates. Gorbatshev (1967, pp. 42—43) describes micrographic veinlets from the Gävle area, which were formed by partial remelting of wall-rock sandstone. Unpublished observations by one of the authors (T. L.) and his co-workers in western Medelpad, Västernorrland



Fig. 2. Rhythmic layering in the Ulvö dolerite. Långroudden, 5 km NE of Skagsudde.  
*Ritmisk lagring i Ulvödiabasen. Långroudden, 5 km NO om Skagsudde.*

County, point in the same direction. Here granites etc. of the above types occur in the uppermost parts of dolerite sheets. Corroded xenoliths of wall-rocks (migmatites etc.) and contacts transitional to the latter strongly suggest that the acid rocks originated by remelting.

The perhaps most interesting products of differentiation of the Ulvö dolerite magma include rocks displaying the characteristics of layered intrusions. Especially conspicuous in the field are those parts of the dolerite that are rhythmically layered (cf. Wager and Brown 1967). Numerous examples of such structures are found in excellent exposures along the shores of the Bothnian Sea (Fig. 2). Naturally, the layering is not so easily detected in outcrops covered by lichens etc. In spite of this the structure has been recorded also in other, less well-exposed Jotnian dolerites of Väster-norrland County.

The layering of the Ulvö dolerite mainly dips gently (up to  $30^\circ$ ) in directions between east and south. It is thus approximately conformable with the dolerite contacts and with the bedding of the Jotnian sandstone formation. Occasionally, however, higher dips and other directions of dip have been observed.

The rhythmical structure is formed by an alternation of layers characterized by different contents of dark minerals. A doleritic (or gabbroic) com-

position has, however, on the whole been retained in spite of these variations. The different layers are generally between c. one centimetre and one metre in thickness. Discordant and graded layering and slumping structures have been observed.

Especially within those parts of the dolerite that display a distinct rhythmical layering an igneous lamination (cf. Wager and Brown 1967, p. 23) has frequently been developed, manifested through the orientation of tabular plagioclase, in part also prismatic augite crystals, subparallel with the plane of layering.

The rhythmic layering ("banding") of the Ulvö dolerite was already observed by Lundbohm (1899, pp. 21 and 46), Högbom (1909 b, p. 369) and Sobral (1913, pp. 96 and 99, Plate V Fig. 1). Högbom (*loc. cit.*) noted the similarities with the Tertiary Skye gabbros, and considered the band-like alternation of different dolerite varieties and the lamination to represent a fluidal structure. Sobral (1913, p. 96) thought that the banded rocks indicated a great heterogeneity of the dolerite magma.

Occasionally the Fe-Ti oxide content rises so much as to produce minor iron ore horizons within the rhythmically layered dolerites. Such concentrations occur especially on Ulvöarna, but also further northwards, on Trysunda and in the Skagsudde region (cf. Lundbohm 1899). Mogensen (1946, p. 581) concluded that these iron ores originated by "gravitational concentrations of the first crystallized apatite, olivine and ore, in which process the concentration of ore dominated owing to its high specific gravity". This interpretation is in agreement with modern views on the genesis of layering.

In addition to the rhythmic layering readily seen in the field, another type, termed cryptic layering (Wager and Brown 1967, p. 25), also occurs in the Ulvö dolerite, as shown by the present investigation. It arises from the variation in chemical composition of certain minerals, notably olivine, plagioclase, and augite.

## THE RINGKALLEN HILL

### GENERAL FEATURES

The present investigation concerns a vertical profile through the Ulvö dolerite at Ringkallen, a hill of table-mountain type situated c. 5 km SSE of Nordingrå church (cf. Fig. 1) and rising 275 m above sea level. See Figs. 3 and 4. The main geological features of this hill were presented by Lundbohm (1899, pp. 17—18). At lower levels sub-Jotnian intrusions (gabbro, anorthosite) are exposed (cf. Figs. 5 and 6). They are overlain by the Jotnian sandstone—shale formation, which here attains a maximum thickness of 50—60 m (Sobral 1913, p. 47) and dips gently towards southeast.

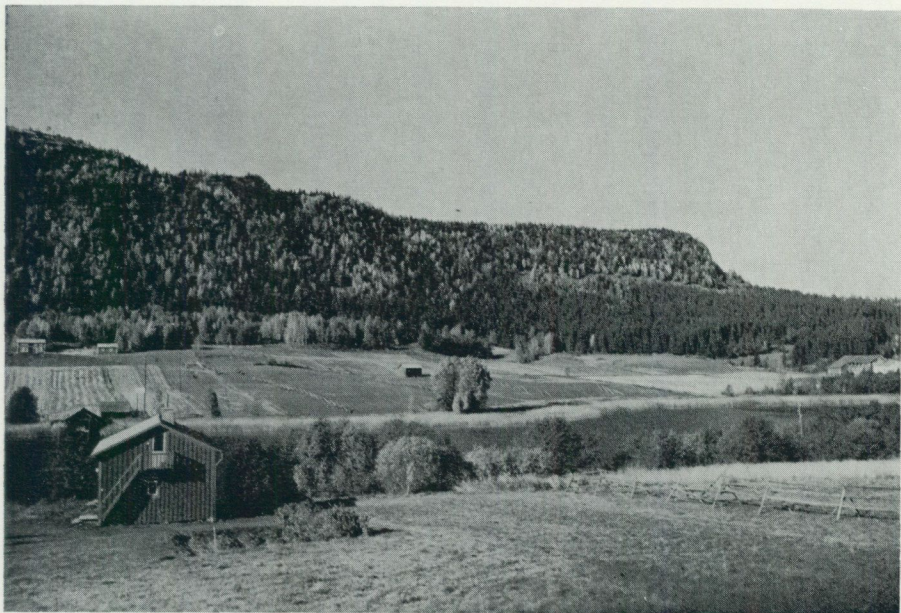


Fig. 3. The northern part of Ringkallen, viewed from ESE. Sandstone occurs near the foot of the steep slope to the right.

*Norra delen av Ringkallen, sedd från OSO. Sandsten förekommer vid foten av stupet t. h.*



Fig. 4. Ringkallen from the east (from the road 1.5 km NW of Näsänget).

*Ringkallen från öster (från vägen 1,5 km NV Näsänget).*

On top of these sedimentary rocks rests the Ulvö dolerite sill, which is found all the way up to the highest point. Thus, the sandstone roof has been removed by erosion.

The topography of Ringkallen is strongly influenced by the lithology of the bedrock. This is even more evident in other profiles through the hill than that of Fig. 6. Cf. also below, p. 19.

As the sandstone formation can be followed along the western, northern and northeastern slopes of the hill, it is possible to calculate with a good degree of accuracy the position of the lower dolerite contact (cf. below, p. 16). The height above this contact can thus be determined for samples taken from outcrops on the hill slopes, and the variations in dolerite composition, texture etc. with height can be established.

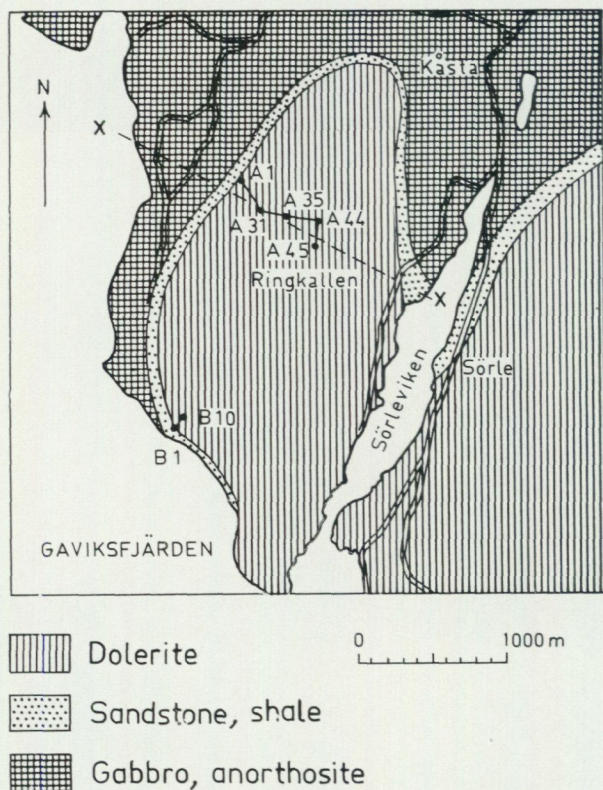


Fig. 5. Schematic petrographical map of the region around Ringkallen. X — X indicates the position of the vertical section in Fig. 6. A 1—A 45 and B 1—B 10 give the positions of sampling points (see Tables 1 a and 1 b).

*Schematisk berggrundskarta över området kring Ringkallen. X — X anger läget för vertikalsnittet i fig. 6. A 1—A 45 och B 1—B 10 utvisar provlägen (se tab. 1 a och 1 b).*

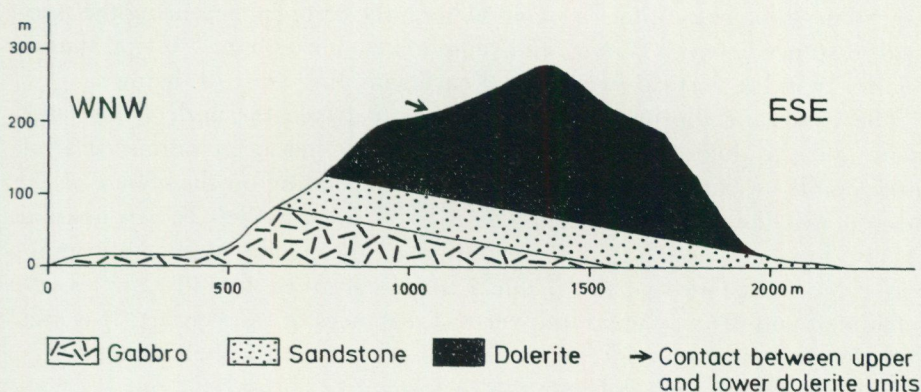


Fig. 6. Vertical section showing the rock units of the Ringkallen hill. (For position, see Fig. 5.) Vertical scale in metres a. s. l.

*Vertikalt snitt genom berggrunden i Ringkallen. (Läget för profilen ges i fig. 5.)  
Den vertikala skalan anger meter över havet.*

#### SAMPLING

The main sampling profile was placed where the maximum thickness of the dolerite was to be expected. These samples have been designated A 1 to A 45 (see Fig. 5). The profile runs approximately parallel to and near the section in Fig. 6, at a maximum distance of 150 m. Due to the lack of outcrops the contact towards the underlying sandstone and the lowermost 10–15 m of the dolerite could not be included in this profile (A). A sampling site containing the sandstone—dolerite contact was found c. 1.5 km SSW of profile A. The contact is here well exposed in an almost vertical cliff. Samples from this locality have been designated B 1 to B 10 and represent the lowermost 16 m of the dolerite (see Fig. 5).

Individual sampling points along profile A were mostly located with a levelling-instrument, but in the steepest parts of the profile a measuring-tape was used. The vertical distance between adjacent samples can in this way be determined with an accuracy better than  $\pm 0.1$  m.

Profile A starts on an outcrop of sandstone, which is easily recognized on aerial photographs. The first exposure of dolerite is seen 45 m to the east and 19 m above this point. Judging from the occurrence of dolerite boulders and the details of the topography, the sandstone—dolerite contact is probably situated 20 m to the east and 10 m above the starting point on the sandstone. This means that the measuring of vertical distances between the contact surface and the individual samples involves an error which can be estimated at  $\pm 5$  m, provided that the contact is a reasonably smooth surface, an assumption which is supported by field observations.

The samples of profile B were located with a measuring-tape. As the

sandstone—dolerite contact is exposed here, the error in measuring the (vertical) distance between contact and sample is no more than  $\pm 0.1$  m, that is, smaller than the vertical extension of each sampling area (cf. below).

The strike and dip of the contact surface between the underlying sandstone and the dolerite in the area of profile A has been estimated from three points of fairly well known altitudes. Depending on the choice of the three points the dip varies from  $4.7^\circ$  to  $5.3^\circ$  towards  $S40^\circ E$ . An average of  $5.0^\circ$  has been used for the calculation of the height of the A samples above the sandstone contact. Table 1 a (p. 49) gives, for all samples, the calculated and directly measured vertical distances to this contact. It is seen that the investigation concerns a vertical section of somewhat more than 200 metres through the dolerite.

When the position of the different points had been established, the sampling was made with a steel hammer. Chips of fresh rock were usually obtained within an area of 0.5 m vertical and 2.0 m horizontal extension. The uppermost 30 percent of the dolerite sill is in part strongly weathered. Here it was not always possible to get completely fresh rock pieces. The weight of each sample is between 0.3 and 1.0 kg.

The locations of some sampling points are given in Table 1 b (p. 49), in coordinates of the Swedish National Coordinate System. The sampling profile may be considered to run as straight lines between these points (cf. Fig. 5).

#### STRUCTURAL AND TEXTURAL VARIATIONS WITHIN THE DOLERITE

At the contact towards the sandstone the texture of the dolerite is fine-grained, and grades upwards into medium- and coarse-grained. The variations in maximum length of tabular plagioclase crystals (measured in thin sections) are shown in Fig. 7. It is seen that a sudden increase takes place near the contact, and after that a slower increase is noted. Above 80 metres from the contact great variations occur, but on the whole the dolerite becomes more coarse-grained.

In the immediate vicinity of the contact there occur phenocrysts of plagioclase together with olivine(?) pseudomorphs in a uraltized and biotitized groundmass where small tabular plagioclase crystals predominate. In Fig. 7, the maximum length of plagioclase in phenocrysts and groundmass is indicated by P and G, respectively.

Textural variations within the dolerite are properly described by the relationships between plagioclase and augite (Krokström 1932 b). Thus, the main part of the dolerite at Ringkallen is subophitic, that is, pyroxene occupies the relatively subordinate interstices between tabular plagioclase crystals, and shows a uniform orientation over large (up to c.  $10 \text{ cm}^2$ ) areas.

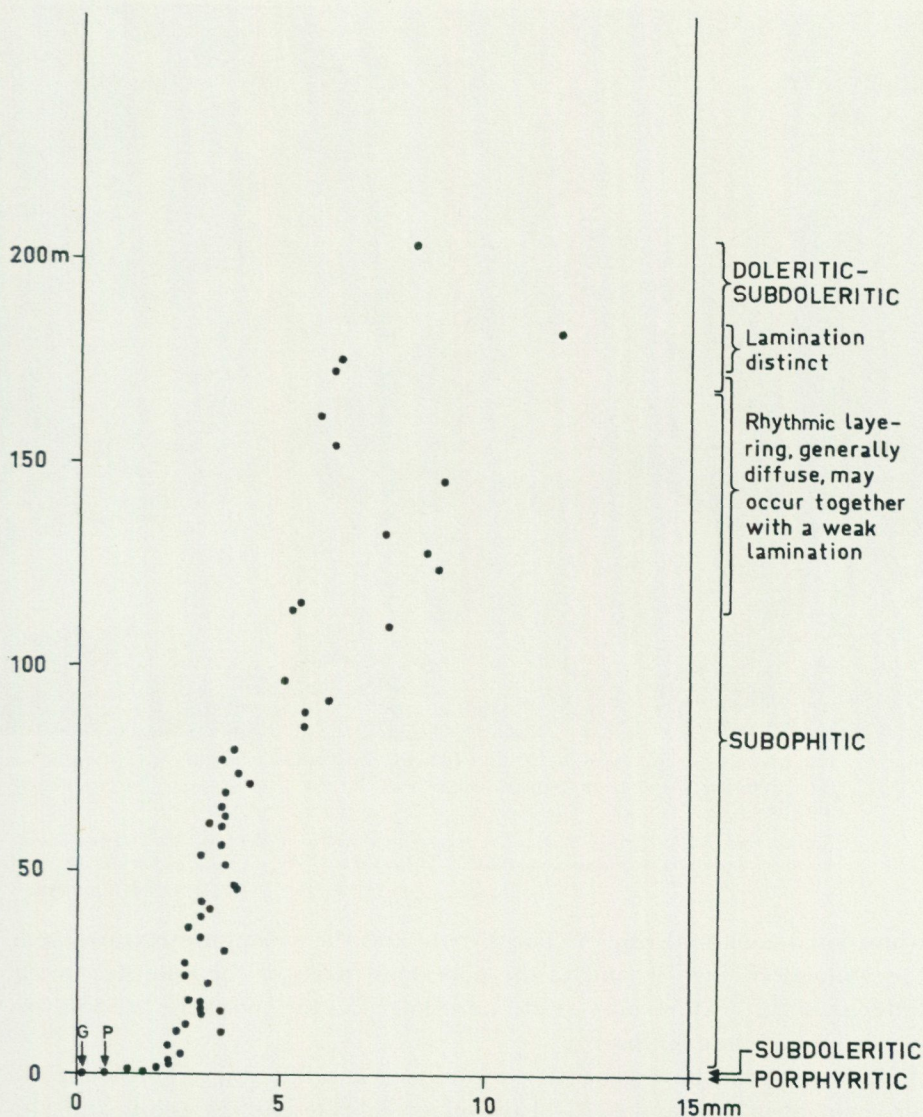


Fig. 7. Abscissa: Maximum length of plagioclase crystals in the dolerite sill of Ringkallen. (G = groundmass, P = phenocrysts.) Ordinate: Height above sandstone contact. Textures and structures are given in the right part of the figure.

*Abscissa: Maximala längden för plagioklaskristaller i diabasen på Ringkallen. (G = grundmassa, P = strökorn.) Ordinata: Höjd över sandstenskontakten. Texturer och strukturer ges i högra delen av figuren.*

Subdoleritic textures arise through the filling of interstices between plagioclase crystals with pyroxene (without uniform orientation) and the adaption of the latter to the outlines of the feldspar. They occur in the

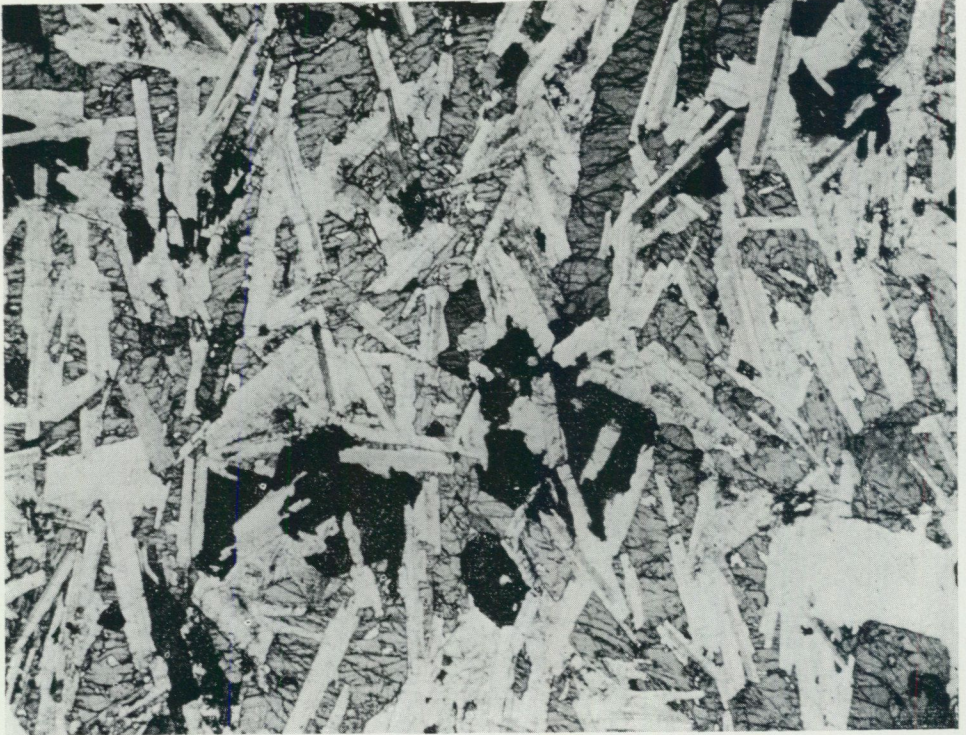


Fig. 8. Laminated dolerite (sample A 40). Tabular plagioclase crystals are oriented in the plane of lamination, which is vertical in the photograph. Nicols nearly parallel, 6 x.

*Laminerad diabas (prov A 40). Kristaller av tavelformad plagioklas ligger orienterade i lamineringsplanet (vertikalt i fotografiet). Nicoler nära parallella, 6 x.*

transitional zone between the porphyritic and the subophitic textures near the contact (cf. Fig. 7), and in the uppermost parts of the dolerite. In the latter case the texture may grade into doleritic, the pyroxene tending towards idiomorphic outlines.

Oxide minerals have generally crystallized at a late stage. This is especially evident in the basal parts of the upper dolerite unit (cf. below and Fig. 6), where these minerals fill interstices between plagioclase and olivine crystals.

Olivine usually forms more or less rounded crystals, but a tendency towards idiomorphism is often noted (cf. Fig. 10). Biotite growth has commonly occurred in rims surrounding crystals of Fe-Ti oxides. Potash feldspar is found in mesostasis intergrowths with plagioclase, which are probably indicative of replacement of the latter mineral by potash feldspar.

As a rule the fabric is non-directed, but at high levels a mostly weak plagioclase lamination is often visible (Figs. 7 and 8). In these parts of the

dolerite a diffuse rhythmical layering is also observed at places. At a height of c. 170—180 m the lamination is distinct. It is here formed by parallel orientation of tabular plagioclase and prismatic pyroxene crystals approximately in the horizontal plane.

At the sampling profile A there is a pronounced change in slope at c. 200 m a.s.l. A narrow terrace is found immediately north of the profile. Above this terrace the angle of slope is smaller than at lower levels (cf. Fig. 6). In fact, large parts of Ringkallen are characterized by a flat crest at c. 200—250 m a.s.l., from which level isolated peaks rise as much as 275 m a.s.l.

"Steps" in the topography similar to the terrace on Ringkallen also occur in other parts of the dolerite area, and may be used for a photogeological subdivision of the dolerite into two or more units (N. B. Svensson, personal communication).

As will be seen in the following chapters the terrace at 200 m a.s.l. on Ringkallen is the topographical expression of a surface separating a lower and an upper dolerite unit. From Fig. 7 it is seen that the lower unit (up to 100 m above the sandstone) is more uniform in texture and grain size than the upper. Rhythmic layering and lamination are present only in the upper unit, which is also characterized by a relatively much stronger weathering. The highest parts of the sill (near sample A 45) are at places covered with an *in situ* dolerite gravel formed by mechanical-chemical disintegration (cf. Samuelsson, in preparation).

Between the lower and upper dolerite units no indications of chilled marginal facies rocks have been found. Boulders of fine-grained dolerite, however, occur sparingly here, but may have been transported by the Quaternary ice from the northwest. Thus, it is possible that they represent a dolerite marginal facies from the sandstone contact.

#### MODAL VARIATIONS

Modal compositions of selected samples have been determined by point-counting. The results are given in Table 2.

Naturally, normal thin sections of maximum  $2 \times 3$  cm area cannot be expected to be representative of the more heterogeneous, subophitic dolerites. In the latter, the result of a modal analysis will largely depend on whether the thin section hits a large crystal of pyroxene or not (cf. above, p. 16).

Modal point-count analyses were first carried out on normal thin sections from the selected samples given in Table 2. As could be expected, the results in part showed large and unsystematic variations, unrelated to those of the chemical whole rock analyses.

Therefore, solid mounts of crushed rock material (particle size c. 0.1—

1.5 mm) were prepared from the samples used for chemical analyses. The finest fraction being omitted, it is of course possible that this method gives rise to a systematic error, as, e. g., a mineral that is easily crushed will be underrepresented in the solid mounts. A comparison between the results from normal thin sections and from solid mounts showed that the relatively greatest change (in percent of the content of a mineral) is in the figures for oxides and biotite. These minerals thus tend to be overrepresented in the solid mounts. However, as the present investigation mainly deals with the relative variations of the different minerals, a small systematic error in the modal analyses is not important. In any case the method involving analyses of solid mounts gives much more reliable figures than if normal thin sections had been used.

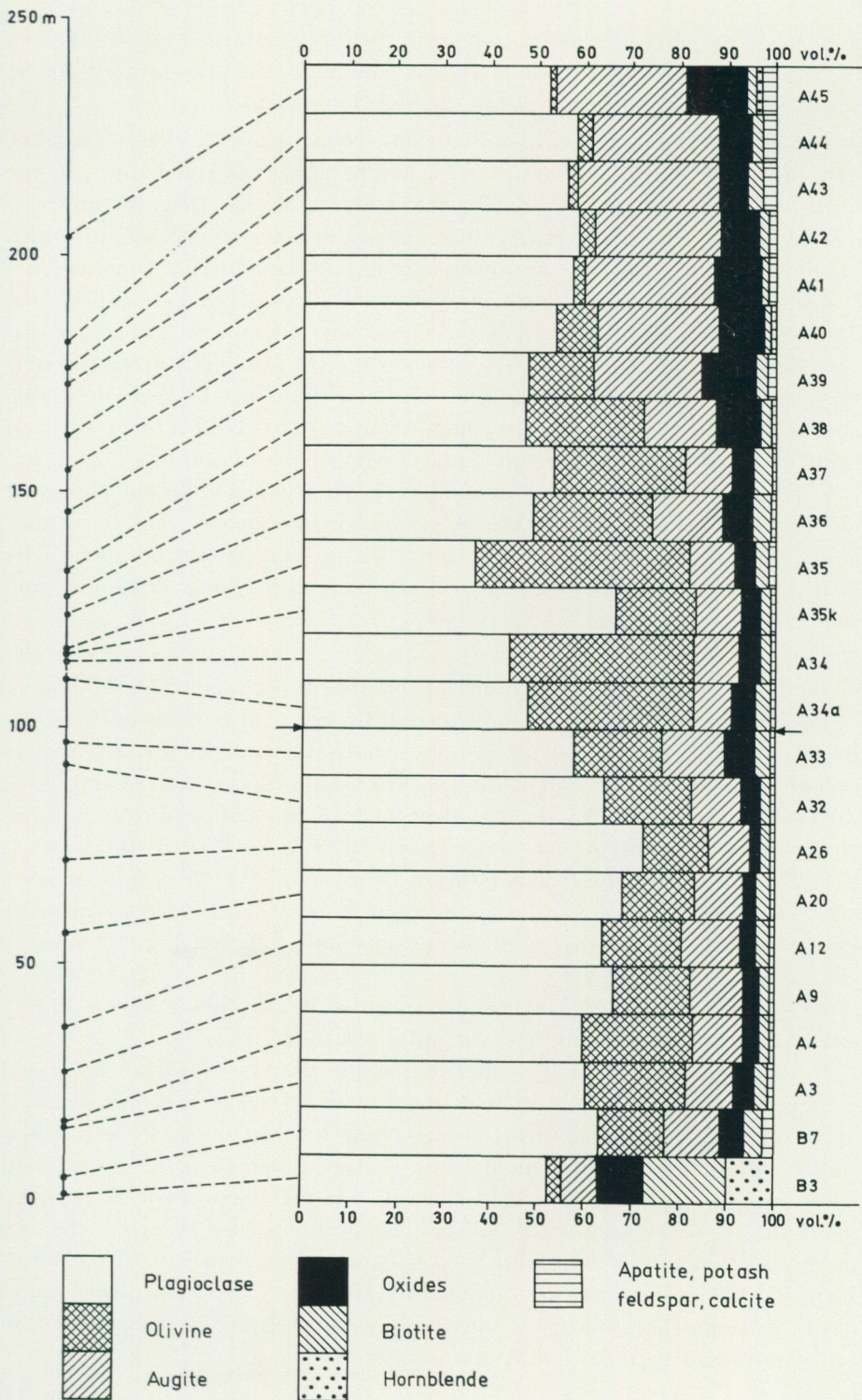
It should be noted that the agreement between modal and whole rock chemical analyses is not perfect. A contributing cause of this may be secondary alterations, the effect of which is not always possible to predict. Thus, e. g., the nature of the sericite, formed by alteration of plagioclase, is not known. In addition to muscovite, phases like paragonite and clay minerals may occur in different proportions and combinations within the aggregates termed sericite.

The most important minerals of the dolerite are plagioclase (mostly bytownite or labradorite), olivine, augite, Fe-Ti oxides (cf. p. 27) and reddish brown biotite. Apatite, potash feldspar and calcite occur in small quantities (usually less than 1 % of each mineral). Probably zeolites are also present as rare constituents. [Stilbite from a shear zone in the Ulvö dolerite has been identified by X-ray analysis (B. Lindqvist, internal report of the Geol. Survey).] Sulphides occur only in very small quantities. Thus, in many polished sections a few small crystals of chalcopyrite and pyrrhotite have been observed. In the modal analyses these sulphides, being very subordinate to the Fe-Ti oxides, have been included in the figures for the latter. Sericite (cf. above), epidote and prehnite are secondary after plagioclase. Olivine shows a usually rather weak alteration to serpentine, oxide(s), green biotite, iddingsite, and a colourless sheet silicate (talc?). Uralitic hornblende in some samples replaces pyroxene, notably near the contact with the underlying sandstone (sample B 3). In the modal analyses the secondary

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Fig. 9. Modal compositions of dolerite samples from Ringkallen. Numbers as in Table 2. The height above the sandstone contact is shown for each of the analysed samples in the left part of the figure. Arrows indicate contact between upper and lower dolerite units.

*Mineralsammansättningen för olika prover av diabas från Ringkallen. Numrering som i tab. 2. Höjden för varje analyserat prov ges i figurens vänstra del. Pilarna anger kontakten mellan övre och undre diabasenheten.*



minerals have, in case they do not form distinct crystals, been included in the figures for the minerals they replace. The main exception is hornblende, which forms rather distinct, easily identified crystals.

The diagram of Fig. 9 is based on point-count analyses of solid mounts, and shows the modal variations with height above the sandstone. In the lower dolerite unit (below arrows) the contents of the different minerals display relatively small changes, in contrast to the upper unit, in which great variations occur. In the lower unit, the highest olivine content (23.4 %) was recorded at 16.5 m level (sample A 4), whereas a maximum of 72.3 % plagioclase is attained in the upper part (sample A 26), where olivine is low (13.9 %). Sample B 3, at a distance of one metre from the contact, shows abnormally high biotite and oxide contents (17 and 10 %, respectively), and a strong uralitization. A patchy distribution of biotite and hornblende in samples near the contact suggests that assimilation of xenoliths from the underlying sedimentary rocks is responsible for the abnormal modal composition of sample B 3. A certain resemblance to the "ferric diabase" from Trysunda (von Eckermann 1946, p. 414) should be noted. The latter rock also occurs near the contact with underlying sandstone and shale.

The highest oxide and pyroxene contents (6.5 and 13.4 %, respectively) of the lower dolerite unit are noted in the uppermost sample (A 33).

The upper dolerite unit is characterized by great, in part abrupt changes in modal composition (Fig. 9). On the whole, there is an upward rise in plagioclase and augite contents and a decrease in olivine, but examples of the reverse are noted. Within the lower parts of this unit a (mostly diffuse) rhythmic layering occurs (cf. above, p. 19 and Fig. 7). This is the cause of, e. g., the abrupt change in composition from sample A 35k (light, plagioclase-rich layer) to A 35 (dark, olivine-rich layer), the vertical distance between the two sampling points being only half a metre. Fig. 10 shows a microphoto of sample A 35.

High contents of Fe-Ti oxides are recorded in samples A 38—A 42 (8.3—11.5 %), and in the uppermost sample, A 45 (12.7 %).

In the highest parts of the dolerite (samples A 41—A 45) an increased content of apatite and potash feldspar is noted. Here the apatite crystals attain greater sizes than at lower levels. Potash feldspar occurs as a mesostasis, and is often accompanied by secondary minerals, e. g. sericite and epidote, as alteration products of the surrounding plagioclase. A replacement of plagioclase by potash feldspar has probably also occurred, the two minerals often forming intimate intergrowths where potash feldspar mesostasis borders on surrounding plagioclase. The two feldspars are not always easily distinguished under the microscope, and thus the figures for potash feldspar should be regarded as approximate.



Fig. 10. Olivine-rich dolerite (sample A 35). Note the rounded or hypidiomorphic shape of olivine crystals. Nicols nearly parallel, 5 x.

*Olivinrik diabas (prov A 35). Märk den rundade till hypidiomorfa formen hos olivinkristallerna. Nicoler nära parallella, 5 x.*

#### COMPOSITIONAL VARIATIONS SHOWN BY DIFFERENT MINERALS

The most important minerals of the dolerite at Ringkallen show compositional variations with height above the lower contact. A study of these variations was undertaken by electron probe microanalysis (olivine and augite), optical methods (plagioclase) and ore microscopy combined with X-ray powder technique (oxides).

For the determination of olivine and augite compositions an electron probe microanalyser of type ARL (AMX) was used. The accuracy depends on the analytical error of the instrument and on the accuracy of chemical analyses of standards. For the elements analysed (Fe, Mg, Ti, Al and Ca), the electron probe determinations have an estimated standard deviation of approximately  $\pm 3\%$ . A standard of Mg-rich olivine (Geol. Survey no. 18U52) was used for the olivine analyses. The determination of augite was made against a standard prepared from a large augite crystal occurring in a dolerite pegmatite between Husum and Skagsudde. Correc-

tions and calculations of forsterite contents of olivine have been carried out with the aid of a computer programme (MK 1 of the Geological Survey).

The electron probe analyses of olivine and augite were carried out on polished thin sections. Although optical studies generally revealed only insignificant heterogeneities (except for variations in the brownish violet colour of augite), the homogeneity was always tested by means of analyses at different points within the crystals. The variations were thereby found to be within the limits of analytical error. In one sample (A 20), five different crystals of olivine were analysed. The scatter in calculated forsterite contents (54—58 %) can also here be wholly ascribed to the analytical error.

Olivine analyses are given in Table 3 (p. 60). In Fig. 11 olivine compositions are plotted against height above the sandstone contact. Near the latter, the forsterite content is c. 61—65 %. In the rest of the lower dolerite unit it is between 52 and 58 %, but no definite trend can be detected. (For sample A 20 the mean value of the five analyses has been plotted in Fig. 11.) As the higher values (above 60 %) were received from samples along profile B, lateral variations in composition cannot be excluded.

The upper dolerite unit (with a height above the sandstone contact ex-

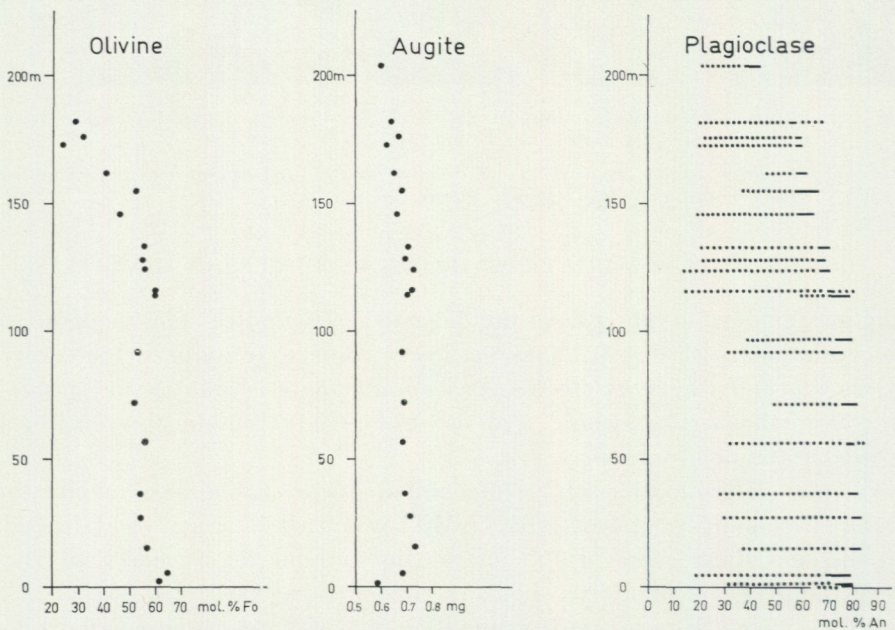


Fig. 11. Variations in chemical composition of olivine, augite and plagioclase. Dotted lines indicate plagioclase compositions within (subordinate) cores and marginal zones. Ordinate: Height above sandstone contact.

*Variationerna i den kemiska sammansättningen för olivin, augit och plagioklas. Prickade linjer anger plagioklasens sammansättning i (underordnade) kärnparter och randzoner. Ordinata: Höjd över sandstenskontakten.*

ceeding 100 m) is characterized by much stronger variations in olivine composition than the lower unit. On the whole, the forsterite content here falls from c. 60 % in the lowest parts to values between 24 and 32 % at 173—182 m above the sandstone. The most iron-rich of the analysed olivines occurs in sample A 42. (In sample A 45 the olivine is almost completely altered to iddingsite and other secondary minerals.) A reversal of the trend towards iron enrichment is noted between samples A 39 and A 40 and between A 42 and A 43. These reversed trends, involving higher forsterite contents with an increasing distance from the (lower) contact, appear to be significant with regard to the analytical accuracy. This is also supported by similar reversals shown by augite compositions. It must, however, be noted that there is not a general agreement between the variations in the diagrams for olivine and augite (cf. also below).

Augite analyses display variations similar to those of olivine (Tab. 4, p. 61, and Fig. 11). The lower dolerite unit (except for the lowermost analysed sample) is characterized by rather uniform *mg* values (0.68—0.73), a maximum appearing in sample A 3. [*mg* (mol. prop.) =  $\text{MgO}/(2 \text{Fe}_2\text{O}_3 \text{ tot.} + \text{MgO})$ .] Sample B 3, near the contact, shows a pronounced decrease in *mg* (0.58) as compared with the rest of the unit. This is a trend which is opposite to that for olivine (cf. below, p. 44). In the upper dolerite unit a distinct trend towards falling *mg* values with height is noted. Reversals similar to those for olivine occur, but are not always analytically significant. However, the increases in *mg* values from sample A 39 to A 40 and from A 42 to A 43 are in agreement with the compositional variations for olivine, and thus appear to be real.

CaO contents of augite vary between 18.4 and 20.9 %. For  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$  the analyses indicate 1.0—2.3 % and 1.6—5.4 %, respectively. A maximum in  $\text{TiO}_2$  content is noted in sample B 3 near the contact, where the augite has a relatively strong brownish violet tint. High  $\text{Al}_2\text{O}_3$  values are noted in samples A 3 (5.4 %), A 40 (4.5 %) and A 41 (5.1 %).

Plagioclase compositions have been determined by optical methods. On a 4-axis universal stage the extinction angles in albite twins have been measured in sections perpendicular to [100]. In a few cases other methods, such as measurement of maximum extinction angles, have been used. For each sample c. five crystals were studied. Anorthite contents have been obtained from the diagrams given by Tröger (1959). In some samples (A 20, A 36, A 40) measurements of the position of the indicatrix in relation to crystallographic directions have been carried out in order to determine whether low- or high-temperature optics characterize the plagioclases. No good agreement with the diagrams of Tröger (1959, Beilage 1) was obtained, but in general the plots fell closer to the low-temperature curves. It should be noted that zoning renders these measurements difficult. Anorthite con-

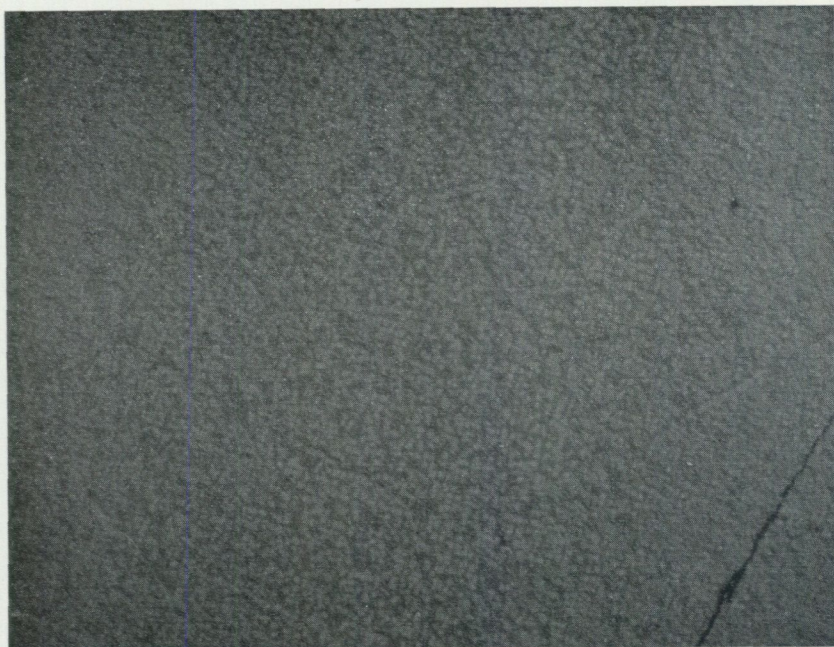


Fig. 12. Intergrowth between magnetite and ulvöspinel (sample A 37). Note the finer scale of the intergrowth in the right and left parts of the photograph. Dark areas are probably ulvöspinel. Reflected light, oil immersion. 1 nic., 1700 x.

*Sammanväxning mellan magnetit och ulvöspinnell (prov A 37). Märk att sammanväxningen är mer finskalig i högra och vänstra delarna av bilden. De mörka partierna är troligen ulvöspinnell. Reflekerat ljus, oljeimmersion. 1 nic., 1700 x.*

tents, determined by the low-temperature curves of Tröger (1959, p. 111) and given in Table 5 (p. 62) and Fig. 11 of this work, can therefore be estimated to be at best accurate within  $\pm 2-3\%$  An.

Generally the plagioclase shows a more or less pronounced zoning, which is of normal type. Reverse zoning has been found only in a few cases (samples A 9, A 33 and A 35). An estimate of the variations displayed by the main parts of the plagioclase crystals has been made in Table 5 and Fig. 11, but is necessarily somewhat subjective.

Especially near the top of Ringkallen the plagioclase often shows a strong partial alteration to sericite etc. The cores, possessing relatively high An contents, have been more easily submitted to such secondary changes than the marginal parts of the crystals. Therefore, it is possible that still higher An contents than those recorded originally existed within (subordinate) cores of plagioclase crystals, mainly at high levels in the dolerite.

No significant difference in plagioclase composition is noted between phenocrysts and matrix in the porphyritic marginal facies of the lower dolerite unit (sample B 1; cf. Table 5). Within this unit the anorthite

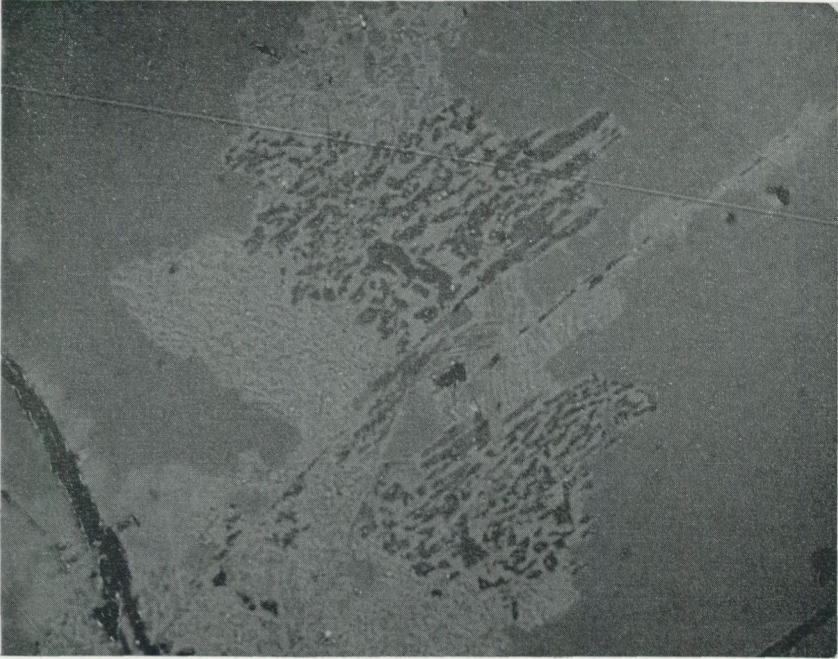


Fig. 13. Intergrowth between magnetite (light) and ilmenite (dark to light grey) within an (apparently) homogeneous titaniferous magnetite, which probably contains some ulvöspinell. Sample A 45. Reflected light, oil immersion. Nicols at low angle. 1040 x.

*Sammanväxning mellan magnetit (ljus) och ilmenit (mörkgrå—ljusgrå) i (skenbart) homogen titanomagnetit, vari ulvöspinell troligen ingår. Prov A 45. Reflekterat ljus, oljimmersion. Nicoler i spetsig vinkel. 1040 x.*

percentage mainly varies between 69 and 82, i. e. the composition is bytownite to labradorite. Cores with as much as 85 % An occur in samples A 3 and A 20. Marginal zones range from labradorite to oligoclase. No definite trend in the variations of anorthite contents can be discerned. In the upper dolerite unit, however, it is clear from Fig. 11 that the plagioclase becomes increasingly sodic towards the highest levels. At the base of this unit the anorthite percentage mainly varies between 71 and 79. It decreases to 58—60 in samples A 42 and A 43, and further to 56—58 in sample A 44 and 38—44 in the uppermost sample. Marginal zones may be as sodic as An<sub>13</sub>.

Thus, plagioclase as well as olivine and augite display the same pattern of variation: a relatively constant (main) composition in the lower dolerite unit (except for samples taken close to the contact), and a pronounced change with height in the upper unit.

Finally, the variations of the Fe-Ti oxides have been studied. Three main phases are present: ilmenite, magnetite (as titaniferous magnetite) and ulvöspinell. Two varieties of titaniferous magnetite can be distinguished by

ore microscopy. The most important of these is a fine-scale (c.  $1 \mu$  or less) intergrowth approximately along cubic planes of two isotropic phases with only small differences in reflectivity and relief (Fig. 12). One phase is greyish, the other light brown. The (integrated) colour of this intergrowth is pale brown. This texture is especially well developed in the lower parts of the upper dolerite unit. Here the two phases occur in subequal amounts. In other samples the intergrowth may be on a scale which is near the limit of detection of ore microscopy. The titaniferous magnetite then appears almost homogeneous, but retains its pale brown colour (e. g. in sample A 45). Within this variety of titaniferous magnetite there occur thin lamellae of ilmenite along octahedral planes. Ilmenite also forms more irregular intergrowths with the cubic phases (up to c. 50 % of the total aggregate). These intergrowths are sometimes in crystallographic continuity with the lamellae.

The second variety of titaniferous magnetite is always intimately intergrown with the first. Also in this case a fine-scale two-phase texture is visible at high magnifications, but it is often coarser than in the first variety. However, the second type of intergrowth is not isotropic but displays anisotropy and bireflection similar to those of ilmenite but weaker (cf. Lundqvist 1968, pp. 127—128). The coarser types of this variety of titaniferous magnetite are seen to consist of ilmenite and an isotropic phase (magnetite). See Fig. 13. The orientation of the anisotropic mineral (ilmenite) varies between irregularly contoured, but sometimes roughly lamella-shaped, areas, giving rise to a patchy pattern of anisotropy colours. In several cases the texture surrounds microscopic fissures. The thin ilmenite lamellae along octahedral planes are also present. More irregular intergrowths with this mineral occur more frequently than in the first type of titaniferous magnetite.

As it could be suspected that one of the two isotropic phases in the fine-scale intergrowths is ulvöspinel, X-ray Guinier powder photograms were prepared from the magnetic fractions of six samples (A 12, A 20, A 34, A 35, A 43, A 45) from Ringkallen. One sample (T. L. 65:38a) of a titaniferous iron ore from the old Grundham mine at Marviksgrunnan on the southern part of S. Ulvön (cf. Mogensen 1946) was also included. Of the samples from Ringkallen, nos. A 12, A 20, A 34 and A 35 represent the first variety of titaniferous magnetite described above. In the two former samples the second variety occurs subordinately. Also the Marviksgrunnan ore sample is of the first type. In samples nos. A 43 and A 45 the second variety of titaniferous magnetite is the predominant one.

An examination of the 220 line of magnetite ( $d = 2.97$ ) showed that in the photograms of samples A 12, A 20, A 34 and A 35 it is accompanied by another line representing a slightly higher  $d$  value. This is the 220 reflection of ulvöspinel ( $d = 3.00$ ; cf. Vincent et al. 1957). Also for the Marviksgrunnan ore this line is obtained. In the photograms of samples

A 43 and A 45, however, the 220 line of magnetite is not accompanied by that of ulvöspinel. All samples give ilmenite reflections, but the latter are particularly strong in nos. A 43 and A 45.

The X-ray and optical studies thus indicate the following. In the variety characterized by fine-scale intergrowths of two isotropic phases the latter are magnetite and ulvöspinel. Probably the former is grey, and the latter, light brown (cf. Ödman in Mogensen 1946, p. 582). Ilmenite occurs as lamellae along octahedral planes of magnetite and as more irregular intergrowths with the cubic phases. Similar intergrowths of magnetite, ilmenite and an unknown cubic mineral have been observed by Hjelmqvist (1950) in coarse-grained magnetite-olivinite from Smålands Taberg, southern Sweden. In addition, spinel lamellae here occur parallel to the cubic planes of magnetite. Hjelmqvist is at present inclined to consider the unknown mineral to be ulvöspinel (S. Hjelmqvist, personal communication).

In the second variety of titaniferous magnetite the presence of ulvöspinel has not been verified by X-ray investigation, and magnetite and ilmenite are the only important phases of the magnetic fraction. However, small amounts of ulvöspinel probably occur here, according to microscopic observation. It is likely that the ulvöspinel in the uppermost parts of the dolerite has been largely eliminated by oxidation to give ilmenite and magnetite (cf. Buddington and Lindsley 1964). The fine-scale intergrowths of magnetite and ilmenite which predominate in these samples are probably in part relict after an earlier magnetite-ulvöspinel texture, which in turn arose by exsolution from a homogeneous solid solution of these two minerals. In part, however, the ilmenite-magnetite intergrowths are much coarser than those between magnetite and ulvöspinel (cf. Fig. 13). The magnetite then clearly shows a lighter (brownish grey) colour than that of the associated, more or less distinct two-phase, intergrowths with ulvöspinel.

It should also be noted that in the uppermost four samples from the upper dolerite unit a bleaching to greyish white colours along microscopic fractures and grain boundaries of (light brownish) titaniferous magnetite is sometimes observed. The product of this bleaching is an isotropic mineral with a somewhat higher reflectivity than magnetite and ilmenite. Probably the secondary mineral is maghemite, but no further study of it has been undertaken.

On the basis of the above observations the following may be concluded. The lower dolerite unit and the lower part of the upper unit (up to a level between samples A 36 and A 37) is characterized by fine magnetite-ulvöspinel intergrowths, and ilmenite in lamellae etc. as stated above. Weak oxidation has in several samples produced small amounts of the patchy ilmenite-magnetite intergrowths of the second variety of titaniferous magnetite. Between samples A 37 and A 45 (with the exception of A 38) the

oxidation of ulvöspinel is as a rule very strong, and in the uppermost three samples the patchy ilmenite-magnetite intergrowths predominate, and ulvöspinel is sparse (or absent). As mentioned above, in samples A 42—A 45 the magnetite shows an alteration to a secondary mineral which is probably maghemite.

Four different modes of occurrence are noted for ilmenite. Firstly, the mineral is found as independent crystals, above all in the lower dolerite unit but also, although much more sparingly, in the upper unit. The second mode of occurrence is formed by ilmenite more or less irregularly intergrown with magnetite (and ulvöspinel), and sometimes in crystallographic continuity with ilmenite lamellae. Irregular intergrowths between ilmenite and magnetite occur especially in the uppermost parts of the upper dolerite unit. The third type is regular, thin lamellae along octahedral planes in magnetite. In the basal parts of the lower unit the lamellae are mainly broad and somewhat irregular in outline, thus grading into ilmenite of the second type. The fourth mode of occurrence is in the patchy, intimate intergrowths between magnetite and ilmenite, which, mainly at high levels in the dolerite, have probably arisen through oxidation of ulvöspinel. From the study of Buddington and Lindsley (1964) it is likely that also ilmenite of the third type was formed by oxidation of ulvöspinel. Ilmenite of the second type may have similarly been developed by oxidation, although part of it possibly originated as independent crystals like those of the first type.

#### WHOLE ROCK CHEMICAL VARIATIONS

Whole rock chemical analyses of the dolerite samples are given in Table 2 (p. 50). They include, in addition to the standard oxides of rock analyses (except H<sub>2</sub>O), the following trace elements: V, Cr, Co, Ni, Cu, Pb, Ba and Sr. In Figs. 14—18 the contents of each oxide or element have been plotted against height above the lower dolerite contact.

The analytical accuracy for the above elements and oxides is that given by Lundqvist (1968, p. 223). Figures refer to the standard deviation of the determinations.

As already mentioned, the Ulvö dolerite is characterized by the presence of only one pyroxene (augite), which displays no reaction relationship with olivine. This is a characteristic feature of alkali olivine basalts, whereas tholeiites show a reaction relationship between Ca-poor pyroxene and olivine (Tilley 1950). (In the Jotnian dolerites of Västernorrland County orthopyroxene has been found only in one sample, taken from the dolerite lopolith at Viksjö. Cf. Fig. 1.) An alkali olivine basaltic magma type is also indicated by plots of whole rock compositions in (Na<sub>2</sub>O + K<sub>2</sub>O)/SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>/(Na<sub>2</sub>O + K<sub>2</sub>O) diagrams (Kuno 1960, 1968, Figs. 1 and 2). It

should be noted that no fresh sample of the chilled marginal facies of the dolerite at Ringkallen could be obtained. However, all analyses from the relatively weakly differentiated lower dolerite unit (esp. samples B 7—B 8, cf. p. 43) fall within the alkali olivine basalt fields of the above diagrams. Compositions in the upper unit generally fall within the same fields. Exceptions are found in the lowermost parts of this unit, where crystal settling has produced rocks of extreme compositions (cf. below).

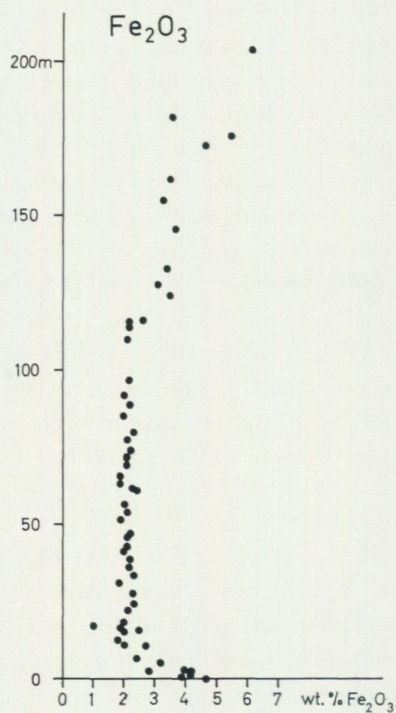
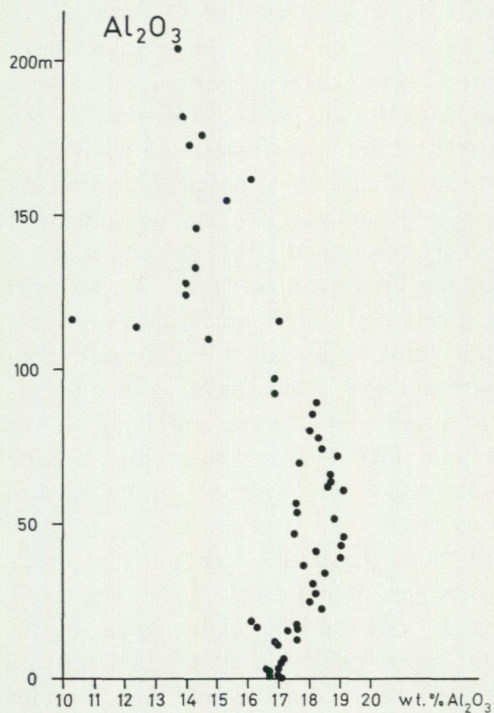
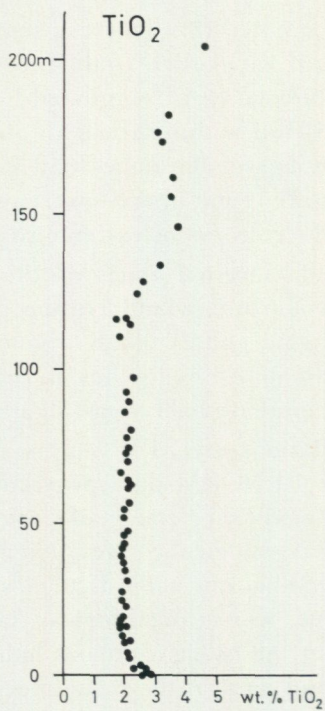
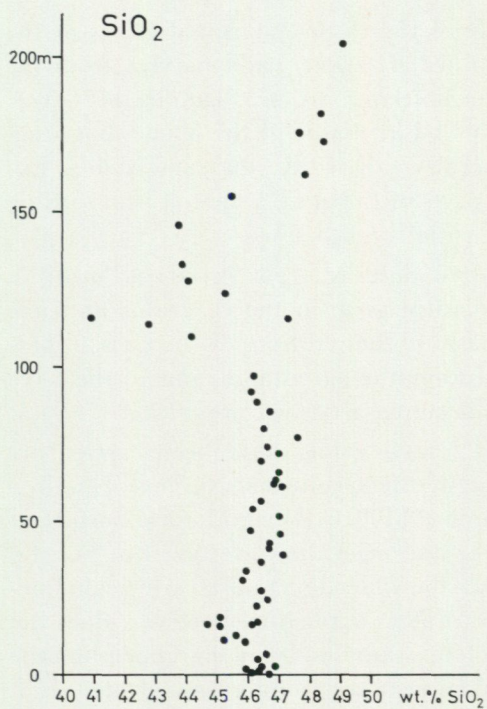
Chilled marginal zones of the Ulvö dolerite from different localities between Nordingrå and Husum generally give, in the diagrams of Kuno (1968, Figs. 1 and 2), alkali olivine basaltic compositions (S. Å. Larson, personal communication). Thus, in conclusion, the parental magma of the Ulvö dolerite most probably was alkali olivine basaltic in composition.

Calculations of CIPW norms and Niggli values have been carried out with the BENORM data programme of the Geological Survey. This is a slightly modified version of programme M0016 (General rock norms) of the U. S. Geological Survey. Niggli  $w$  and  $mg$  values are given in Fig. 18. The CIPW norms show that most of the dolerite samples are nepheline-normative, with a maximum of c. 3 % Ne. Nepheline, however, does not appear in the norms of about half of the samples from the upper dolerite unit and of most of the B samples taken near the contact towards the sandstone.

Near the lower dolerite contact,  $\text{SiO}_2$  is between 46 and 47 % (Fig. 14), but then falls to a minimum of 44.7 % at 16.5 m above the contact. After that, a slow rise in  $\text{SiO}_2$  is noted up to 77.5 m, where the content is 47.6 %. Then a slight decrease occurs to c. 46 % at the top of the lower unit. In the upper unit a great spread in  $\text{SiO}_2$  is seen in the lower parts, and from there an increase to 49.1 % in the uppermost sample (A 45) is noted. This increase is in agreement with the rise in plagioclase contents (Fig. 9). A pronounced break in  $\text{SiO}_2$  contents and trends occurs between the two dolerite units.

$\text{TiO}_2$  is between 2.5 and 3 % near the lower contact (Fig. 14), but falls at c. 5 m to values around 2 %, with a relatively small variation in the rest of the lower dolerite unit. In the upper unit an overall trend from c. 2 to 4.5 % is seen in Fig. 14. Between 146 and 182 m this trend is in part reversed, but variations are relatively small.  $\text{TiO}_2$  varies similarly to the modal content of Fe-Ti oxides. The main  $\text{TiO}_2$ -bearing phases are ilmenite and ulvöspinel. Some  $\text{TiO}_2$  also enters augite (Table 4), probably also biotite.

$\text{Al}_2\text{O}_3$  shows a maximum of c. 19 % in the middle parts of the lower dolerite unit, whereas the content is between 16 and 17 % in the uppermost and lowermost parts of the unit (Fig. 14). At the base of the upper unit a great spread is noted, and above that (samples A 36—A 45) the contents mainly vary between 13.7 and 14.5 %. Higher values are noted in samples



A 40 and A 41 (15.3 and 16.1 %, respectively). The most important carrier of  $\text{Al}_2\text{O}_3$  is the anorthite component of plagioclase. As noted above, plagioclase on the whole increases upwards in the upper dolerite unit, but at the same time the anorthite content falls. The secondary alterations of plagioclase at high levels will also influence the total  $\text{Al}_2\text{O}_3$  content, although the effect is hard to estimate, as it depends on the proportions and combinations of the alteration products (epidote, sericite, prehnite; cf. also p. 20). Variations shown by  $\text{Al}_2\text{O}_3$  can be explained as a complex function of the above factors. The highest  $\text{Al}_2\text{O}_3$  values are recorded where the combination of high plagioclase contents and high anorthite percentages of this mineral occurs.

$\text{Fe}_2\text{O}_3$  is high (between 4 and 5 %) near the sandstone contact (Fig. 14). In the main part of the lower unit the content of this oxide is c. 2—2.5 %. Similar values are recorded near the base of the upper unit, but with increasing height the  $\text{Fe}_2\text{O}_3$  content rises rapidly, and attains a maximum of 6.2 % in the uppermost sample (A 45). The main  $\text{Fe}_2\text{O}_3$ -bearing mineral is magnetite, but also augite and biotite will contain minor amounts of trivalent iron. For this reason, and/or because of varying proportions between magnetite, ulvöspinel and ilmenite,  $\text{Fe}_2\text{O}_3$  contents are not directly related to the modal percentages of oxides as given in Fig. 9 and Table 2. The oxidation of ulvöspinel to magnetite and ilmenite (p. 29) and of magnetite to maghemite (?), which has been most pronounced at high levels in the upper dolerite unit, is, however, an important cause of the relatively high  $\text{Fe}_2\text{O}_3$  contents in these samples.

$\text{FeO}$  is, contrary to  $\text{Fe}_2\text{O}_3$ , low at the sandstone contact (Fig. 15). The content rapidly rises to maximum values around 12 % at c. 15—20 m level above the contact.  $\text{FeO}$  then falls to minimum contents of c. 9.5 % in the middle parts of the lower unit. At the top of the latter  $\text{FeO}$  is c. 11—12 %. The upper dolerite unit on the whole shows falling  $\text{FeO}$  contents with increasing height, but in detail the trend may be reversed. Strong variations are especially noted in the lower parts, due to rhythmical layering. The trend of  $\text{FeO}$  in the upper dolerite unit mainly arises from the decrease in olivine content with height (cf. Fig. 9). The upward increase in modal augite and in Fa component of olivine, and the high contents of Fe-Ti oxides in some samples, only have had modifying effects on the decrease in  $\text{FeO}$  with height.

Fig. 14. Variations of whole rock  $\text{SiO}_2$ ,  $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  contents with height above sandstone contact.

*Variationerna i diabasens halter av  $\text{SiO}_2$ ,  $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$  och  $\text{Fe}_2\text{O}_3$  med höjden över sandstenskontakten.*

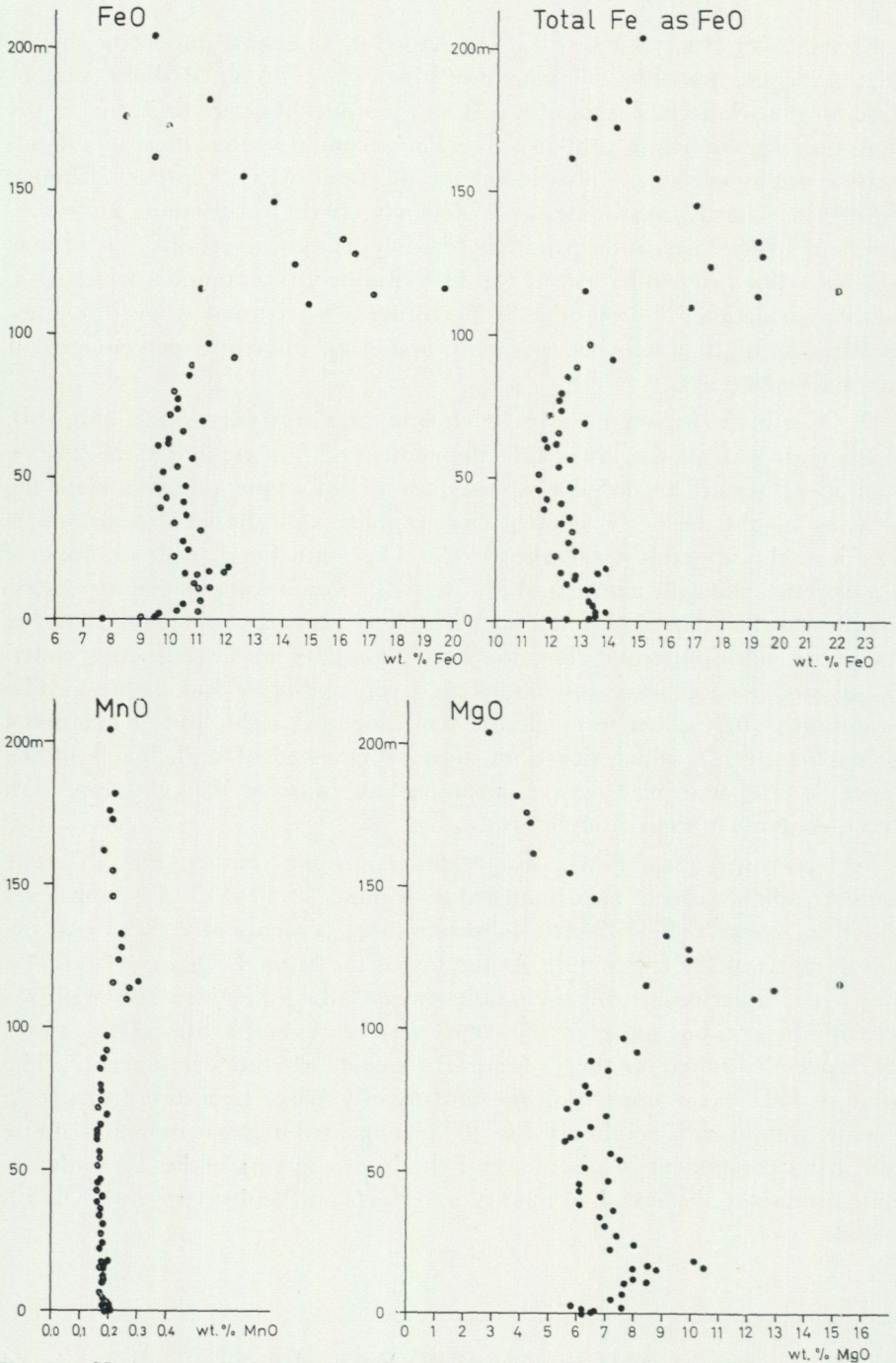


Fig. 15. Variations of whole rock FeO, total Fe (as FeO), MnO and MgO contents with height above sandstone contact.

*Variationerna i diabasens halter av FeO, totaljärn (som FeO), MnO och MgO med höjden över sandstenskontakten.*

Total iron (as FeO) shows similar trends and variations as FeO (Fig. 15). However, the opposite trends of  $\text{Fe}_2\text{O}_3$ , as compared with FeO, have the effect of reducing the gradients in total iron content.

The atomic ratio of trivalent iron to total iron (Niggli  $w$  value) expresses the degree of oxidation. It is between 0.1 and 0.2 in the major part of the lower dolerite unit and in the lower part of the upper unit (Fig. 18). In the uppermost parts of the latter the  $w$  value approaches 0.4. This is in agreement with the oxidation processes which have taken place here. (Cf. p. 29 and discussion of  $\text{Fe}_2\text{O}_3$  above.) A high value (0.35) is also noted close to the base of the lower dolerite unit. This is probably due to assimilation of wall-rock material.

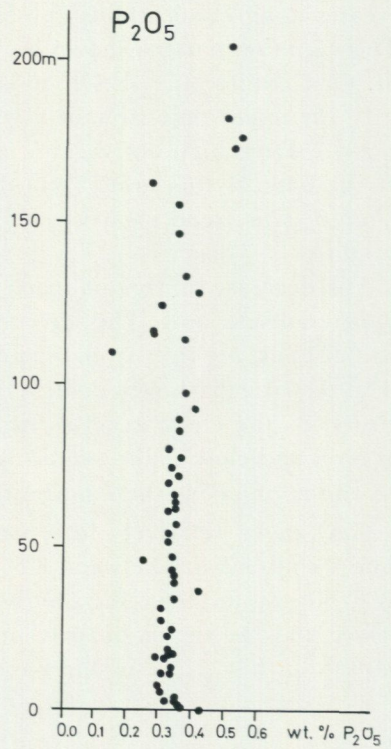
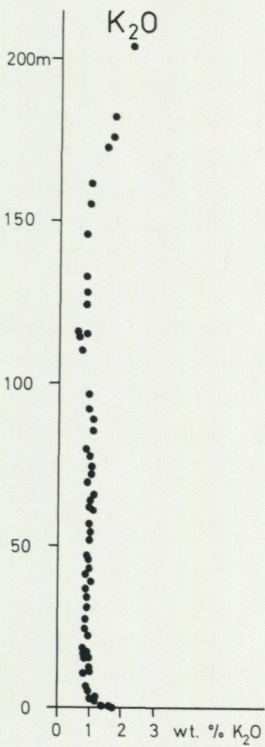
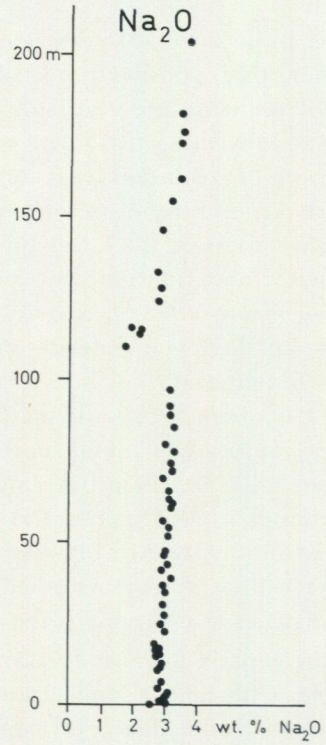
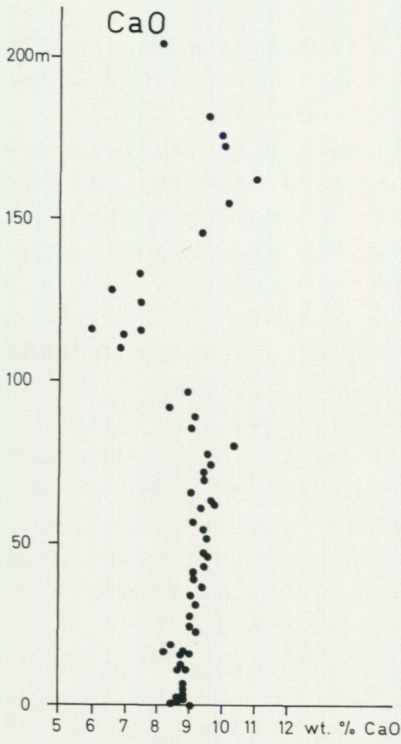
MnO is about 0.2 % in the lower dolerite unit. Somewhat higher (but varying) values are found at the base of the upper unit, but then MnO decreases to c. 0.2 % in the uppermost samples (Fig. 15). There is thus a clear change in MnO content at the contact between the two dolerite units. The distribution of Mn between different minerals (mainly olivine, augite and oxides) has not been studied. A comparison with modal analyses, however, suggests that olivine is the most important carrier of MnO.

At the contact towards the sandstone MgO is c. 6 % (Fig. 15). It rapidly increases with height, and attains a maximum of 10.5 % at 16.5 m above the contact. From that level MgO decreases, and is in some samples at c. 60–70 m height below 6 %. Towards the top of the lower unit MgO increases again, and attains values around 8 % in samples A 32 and A 33. The variation pattern shown by MgO in this dolerite unit is similar to that of other oxides (e. g. FeO), and will be discussed further below (p. 44).

In the upper dolerite unit a very pronounced MgO trend is indicated in Fig. 15. From high but varying values (max. 15.2 % MgO in sample A 35) at the base of this unit, MgO decreases to only 2.8 % in the uppermost sample. This trend clearly reflects the overall falling olivine content with height.

The decrease in MgO is more pronounced than that of (total) FeO in the upper dolerite unit. This gives rise to a distinct trend in the Niggli  $mg$  value. Thus,  $mg$  falls from 0.56 at the base to 0.24 in the uppermost sample (Fig. 18). In the lower dolerite unit the variation in  $mg$  is much smaller. However, there is a general tendency for low values to occur at c. 60–80 m level and close to the contact, and for high values to concentrate between 15 and 20 m above the sandstone (Fig. 18).

CaO shows relatively little variation in the lower dolerite unit (Fig. 16). The variations are between 8.3 and 10.4 %. Relatively high values occur at c. 60–80 m above the sandstone. A distinct break is noted between the lower and the upper dolerite units. From c. 8–9 % in the former, CaO falls to c. 6–7.5 % in the basal parts of the latter. In the upper unit a



maximum of 11.1 % CaO is recorded at 162 m (sample A 41). Above this level CaO decreases to 8.2 % in the uppermost sample. The general increase in plagioclase and augite contents with height in the upper dolerite unit causes the rise in CaO below 162 m level. Above this, the increasingly sodic composition of plagioclase and the secondary alterations of the latter give rise to a decrease in CaO. The resemblance to the variations shown by  $\text{Al}_2\text{O}_3$  (Fig. 14) should be noted.

$\text{Na}_2\text{O}$  is c. 3 % in the lower dolerite unit (Fig. 16). An indistinct maximum is noted at c. 60–85 m above the contact. Between the two dolerite units there is a pronounced break in  $\text{Na}_2\text{O}$ , the percentage of this oxide falling from c. 3 in the lower dolerite to c. 2 in the basal parts of the upper unit. From the latter level  $\text{Na}_2\text{O}$  increases to 3.7 % in the uppermost sample. This increase is caused by the trend towards higher plagioclase contents and more albitic compositions with height.

$\text{K}_2\text{O}$  is approximately constant (c. 1 %) in the lower dolerite unit (Fig. 16). Higher contents of this oxide (up to 1.7 %) occur near the contact towards the sandstone. (Cf. the high biotite content of sample B 3 in Table 2.) A slight decrease in  $\text{K}_2\text{O}$  is noted from the lower dolerite unit to the basal parts of the upper unit. Up to c. 170 m the content of this oxide is below 1 %, but at higher levels an increase is noted. A maximum of 2.20 %  $\text{K}_2\text{O}$  is shown by the uppermost sample (A 45). The high  $\text{K}_2\text{O}$  values at the top of the upper dolerite unit are in part caused by an increased content of potash feldspar (Table 2), but are probably also a consequence of secondary alteration of plagioclase to sericite. The figures of Table 2 indicate that an important part of the whole rock  $\text{K}_2\text{O}$  content is located in other minerals than potash feldspar and biotite, most probably in plagioclase.

$\text{P}_2\text{O}_5$  contents are usually between 0.3 and 0.4 % in the lower dolerite unit (Fig. 16). High values (0.4 % and more) are noted in sample B 1 at the contact towards the sandstone, and in samples A 12 and A 32. The lowest content is 0.24 % (sample A 16).  $\text{P}_2\text{O}_5$  appears to show little systematic variation within the lower dolerite unit. In the upper unit, however, a general rise in  $\text{P}_2\text{O}_5$  content with height is noted (cf. Lundegårdh 1957, p. 26), although in detail the trend may be reversed. At the base of this unit,  $\text{P}_2\text{O}_5$  shows relatively strong variations like most other oxides.

Vanadium is high (450 ppm) in samples B 1 and B 3 (of contaminated dolerite) close to the sandstone contact (Fig. 17). In the lower dolerite V contents usually vary between 200 and 300 ppm. There appears to be no

Fig. 16 Variations of whole rock CaO,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$  and  $\text{P}_2\text{O}_5$  contents with height above sandstone contact.

*Variationerna i diabasens halter av CaO, Na<sub>2</sub>O, K<sub>2</sub>O och P<sub>2</sub>O<sub>5</sub> med höjden över sandstenskontakten.*

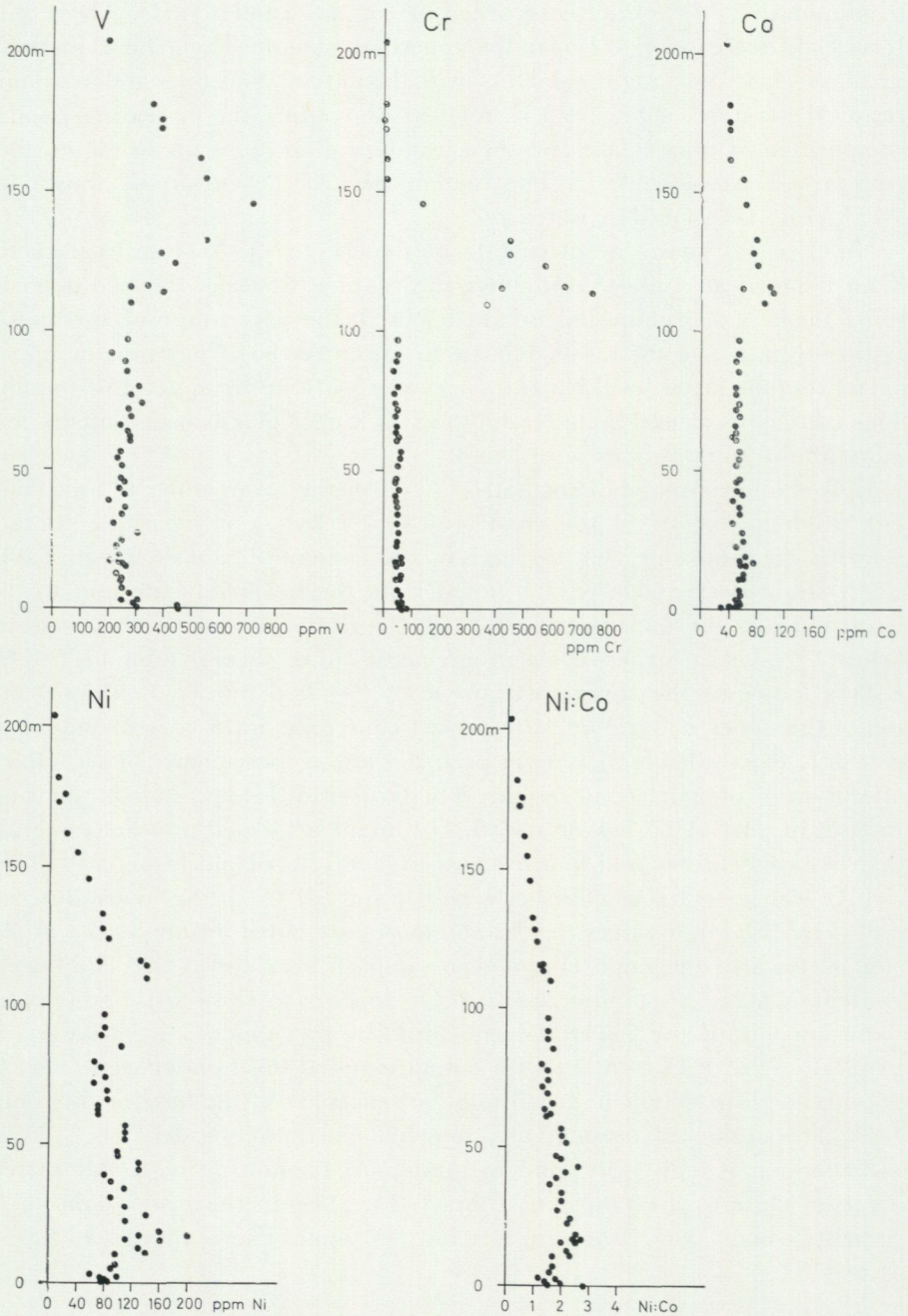


Fig. 17. Variations of whole rock V, Cr, Co and Ni contents, and of the Ni:Co ratio, with height above sandstone contact.

*Variationerna i diabasens halter av V, Cr, Co och Ni, samt i Ni:Co-förhållandet, med höjden över sandstenskontakten.*

systematic variation with height in this unit. At the base of the upper dolerite unit V contents are between 280 and 400 ppm. A maximum of 720 ppm is noted in sample A 39, 146 m above the sandstone. V then decreases to 200 ppm in the uppermost sample.

Semi-quantitative electron probe analysis (X-ray scanning microphotos) of sample A 34 indicates that V is strongly concentrated in the titaniferous magnetites. The most probable carrier of V is the magnetite phase (Ran-kama and Sahama 1952, p. 596). This is also supported by analyses of magnetic concentrates from the titaniferous iron ore on S. Ulvön (Mogensen 1946, pp. 583—584). A high V content is a very common feature of titaniferous iron ores all over the world (cf. Landergren 1948, pp. 100—101; Hjelmqvist 1950, p. 48; Lundegårdh 1957, pp. 25—32).

Analyses of minerals from the Skaergaard intrusion, Greenland, indicate that V also occurs in ilmenite and pyroxene, although the content is lower in these minerals than in magnetite (Wager and Mitchell 1951; Wager and Brown 1967). Therefore, it can be expected that also in the Ulvö dolerite a minor part of V enters ilmenite and augite.

As the proportions between magnetite, ilmenite and ulvöspinel in the Ringkallen samples are not well known, little can be said about the variations of the V content of magnetite. The enrichment in V shown by e. g. samples A 39 (720 ppm), and B 3 (450 ppm) can be wholly related to a high content of modal magnetite, assuming little variation in the proportions between magnetite, ilmenite and ulvöspinel among adjacent samples (before secondary oxidation of ulvöspinel set in). The relatively low whole rock V content combined with the high figure for modal oxides in sample A 45 (Table 2), however, may be taken to indicate that the magma at this stage of differentiation was essentially poorer in V.

In the lower dolerite unit chromium contents mainly vary between 40 and 60 ppm, and no systematic trend can be discerned. A very pronounced break occurs at the contact towards the upper unit. In the basal parts of the latter a great spread (370—750 ppm) is seen in Fig. 17. Within the four lowermost samples from this unit, Cr and V display parallel variations. From sample A 35 upwards there is a rapid fall in Cr, so that a value as low as 5 ppm is reached in sample A 41. In the five uppermost samples the content remains at c. 5 ppm (less than 5 ppm in A 43), indicating that the magma was strongly depleted in Cr.

Cr mainly enters the titaniferous magnetite, according to semi-quantitative electron probe analysis (X-ray scanning microphotos) of sample A 34. This is also supported by the strong enrichment of Cr in high-grade concentrates of the titaniferous iron ore from S. Ulvön (Mogensen 1946, p. 584).

There is no indication of high Cr contents in olivine (caused by inclusions

of chromite crystals) or in augite (cf. Wager and Mitchell 1951; Wager and Brown 1967, p. 196). However, it is of course possible that minor amounts of Cr occur in other minerals than the titaniferous magnetites, above all in pyroxene (cf. also Rankama and Sahama 1952, p. 622).

The behaviour of Cr in the upper part of the Ringkallen profile is in agreement with the tendency for this element to become enriched in early-formed magmatic differentiates (Goldschmidt 1945).

Cobalt contents are usually between 45 and 60 ppm in the lower dolerite unit (Fig. 17). Slightly lower values are recorded particularly in samples taken near the sandstone contact. No systematic variation with height is seen in Fig. 17. There is a sudden rise in Co contents between the lower unit and the basal parts of the upper unit. In the latter, Co is between 90 and 105 ppm in dark layers (samples A 34a, A 34, A 35), and 60 ppm in the plagioclase-rich sample A 35k. Above the base, Co contents fall to 40 ppm in sample A 40, from which level Co is constant up to the uppermost sample, where a slightly lower value (35 ppm) is recorded.

X-ray scanning microphotos of sample A 34, prepared with the electron probe microanalyser, indicate slightly higher Co contents in titaniferous magnetite than in ferromagnesian silicates (cf. Landergren 1948, pp 101—102). Probably, however, the latter carry the major part of the (whole rock) cobalt.

Nickel displays much greater variations than cobalt in the lower dolerite unit (Fig. 17). There is a pronounced similarity in the distribution patterns of Ni and Mg (cf. Fig. 15) in both dolerite units. This is in agreement with the tendency for Ni to replace Mg diadochically. In the lower unit, Ni contents are relatively low (c. 60—100 ppm) at the contact. A maximum of 200 ppm is noted at 16.5 m (sample A 4). Above that level Ni decreases to an (indistinct) minimum of c. 65—70 ppm between c. 60 and 80 m above the contact. At the top of the lower dolerite unit Ni contents are 75—80 ppm. In the basal parts of the upper unit higher Ni values are found: 130—140 ppm, except in the plagioclase-rich layer (sample A 35k), where the content is 70 ppm. In the rest of the upper unit Ni decreases with height to 5 ppm in the uppermost sample. Ni is thus concentrated in the early-formed differentiates of the upper dolerite unit, in agreement with the principles stated by Goldschmidt (1945).

X-ray scanning with the electron probe microanalyser reveals no great differences in Ni contents between oxides, olivine and augite. Hjelmqvist (1950, p. 48) noted the tendency for Ni (and Co) to enter olivine and titaniferous magnetite in titaniferous iron ore from Smålands Taberg, southern Sweden. With regard to the pronounced covariation of Ni with Mg in the Ringkallen samples it is likely that the major part of Ni here occurs in olivine.

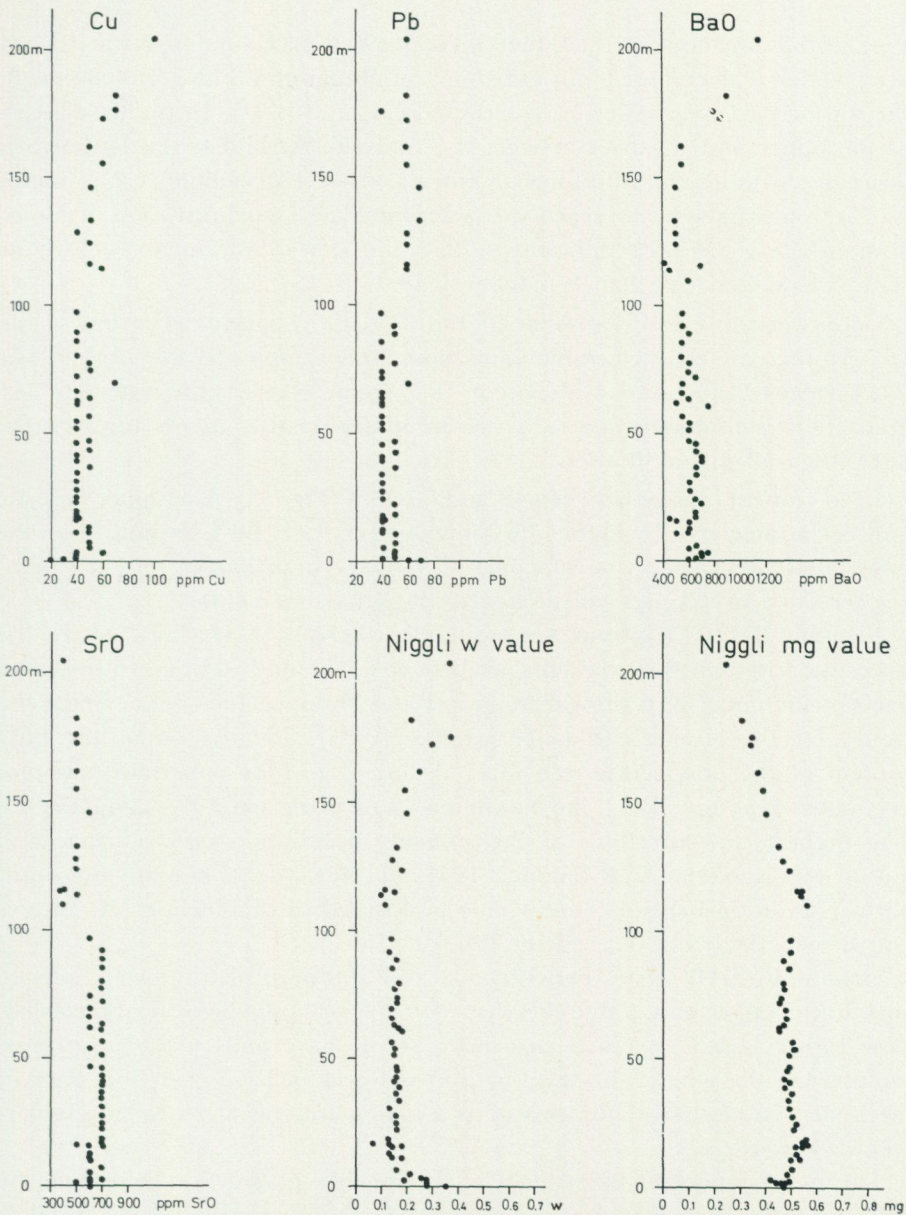


Fig. 18. Variations of whole rock Cu, Pb, BaO and SrO contents, and of the Niggli  $w$  and  $mg$  values, with height above sandstone contact.

*Variationerna i diabasens halter av Cu, Pb, BaO och SrO, samt i Nigglivärdena  $w$  och  $mg$ , med höjden över sandstenskontakten.*

The Ni:Co ratio of particular interest (cf., e. g., Lundegårdh 1946, pp. 142—143, 151, and 1949, pp. 18 ff.; Rankama and Sahama 1952, pp. 677—678 and 681—683). As seen from Fig. 17, this ratio is variable but usually

1—2 at the sandstone contact, then increases to a maximum of 2.7 at 16.5 m, after which it decreases to an indistinct minimum of 1.3 at c. 70—80 m. At the top of the lower dolerite unit the Ni:Co ratio is 1.5. In the basal parts of the upper unit it varies between 1.2 and 1.6. At higher levels the ratio decreases with height, attaining a value of only 0.1 in sample A 45. Similar Ni:Co trends have been recorded e. g. in the Skaergaard intrusion of Grönland (see, e. g., Wager and Brown 1952, pp. 198—199) and in rocks from central Roslagen, Sweden (Lundegårdh 1946, p. 151).

Copper varies mostly between 40 and 60 ppm in both dolerite units (Fig. 18). An increase is noted in the uppermost three samples (A 43—A 45). The two former of these have Cu contents of 70 ppm, whereas the latter has 100 ppm. This is probably due to a rise in chalcopyrite contents towards the later stages of differentiation.

Lead contents range between 40 and 70 ppm (Fig. 18). The upper dolerite unit is characterized by higher Pb contents (generally 60—70 ppm) than the lower unit (generally 40—50 ppm). Relatively high values (60—70 ppm) are recorded in samples taken close to the sandstone contact.

Barium (BaO) variations are similar to those of  $K_2O$  (Fig. 18). In the lower dolerite unit BaO contents are between 450 and 750 ppm. In the basal parts of the upper unit the variation is 400—700 ppm, the former being the figure for the olivine-rich layer (sample A 35), and the latter, the BaO content of the plagioclase-rich layer A 35k. The four uppermost samples give 800—1150 ppm BaO, the maximum value being valid for sample A 45. The highest concentrations of Ba probably occur in potash feldspar and biotite (cf. Rankama and Sahama 1952, pp. 471—473), but an important part of the total barium content may be located in plagioclase (cf. Wager and Brown 1967, Fig. 122; Heier 1962).

Strontium (SrO) varies between 500 and 700 ppm in the lower dolerite unit. In the upper unit, values between 370 and 600 ppm have been recorded. Low figures are here noted especially at the base and in the uppermost sample. On the whole, the level of SrO is lower in the upper unit than in the lower. In neither of the two units a systematic variation with height is seen in Fig. 18.

The most important carrier of Sr is probably plagioclase, but some Sr will also enter potash feldspar and apatite, possibly augite, too (cf. Rankama and Sahama 1952, pp. 472—473; Heier 1962, p. 443; Wager and Brown 1967, Fig. 122).

The differentiation of the two dolerite units at Ringkallen is shown in a  $(Na_2O + K_2O) - MgO - (total\ Fe\ as\ FeO)$  diagram (Fig. 19). Similar alkali-iron enrichment trends occur in both units, but the fractionation is much more pronounced in the upper one. Another difference may be stated in the following way. For a given  $MgO:FeO$  ratio the lower unit has a

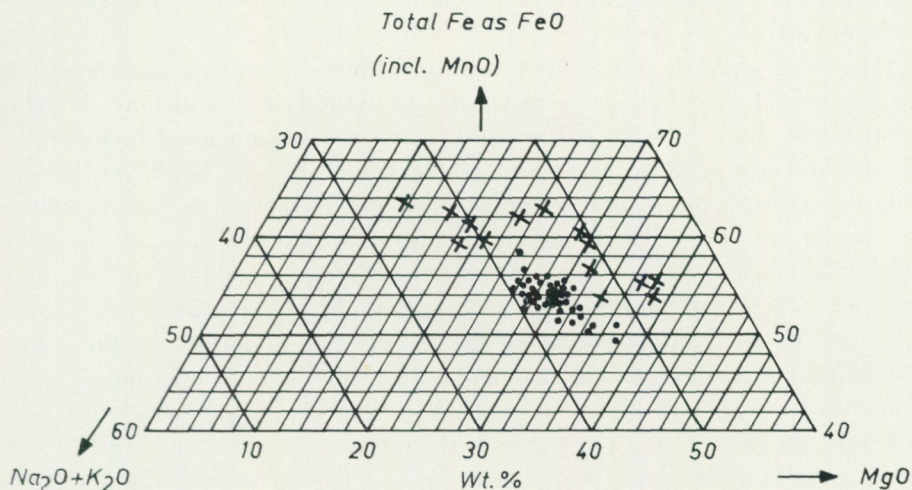


Fig. 19. Plots of whole rock chemical compositions in a  $(\text{Na}_2\text{O} + \text{K}_2\text{O}) - \text{MgO} -$  (total Fe as FeO) diagram. Dots = lower dolerite unit, crosses = upper dolerite unit.

*Variationerna i diabasens sammansättning, visade i ett  $(\text{Na}_2\text{O} + \text{K}_2\text{O}) - \text{MgO} -$  (totaljärn som FeO)-diagram. Punkter = undre diabasenheten, kryss = övre diabasenheten.*

higher content of alkali, and for a given value of total alkali the same unit has a higher MgO:FeO ratio.

The initial magma composition of the lower dolerite unit is not well known, as the chilled marginal facies is contaminated. According to the above discussed diagrams (Figs. 14—18; cf. also below, p. 44) the best approximation of this composition, expressed in terms of the components of Fig. 19, seems to be given by samples B 7—B 8 ( $\text{Na}_2\text{O} + \text{K}_2\text{O}$  c. 15 %, MgO c. 30 % and total FeO c. 55 %). For the upper dolerite unit the initial magma was in all evidence lower in alkali (somewhat below 10 % in Fig. 19) and had a slightly higher MgO:FeO ratio. This estimate takes into consideration a probable enrichment of sample A 35 in olivine with 59.7 mol. % Fo, and of sample A 35k in plagioclase, as compared with the magma from which they crystallized. This magma is thought to approximate the initial magma in composition.

## SUMMARY AND CONCLUSIONS

The results of the investigation of the dolerite sill at Ringkallen may be summarized in the following way. On the basis of modal and chemical variations two main dolerite units have been distinguished, each of them occupying about half of the observable thickness of the sill. The contact

zone between the units can in part be seen as a terrace on the western slope of Ringkallen.

The lower dolerite unit, which displays a chilled, oxidized and somewhat contaminated marginal facies towards the underlying sandstone, is relatively little differentiated. After solidification of the marginal facies rocks, which are now seen only at the lower contact (up to a height of 10–15 metres), crystallization proceeded more slowly inwards, the final products occurring at c. 60–70 m level. Here minima are shown especially by FeO, MgO, Ni, Ni:Co, olivine content, and the Niggli *mg* value, and maxima by SiO<sub>2</sub>, CaO, Na<sub>2</sub>O and plagioclase content. (Al<sub>2</sub>O<sub>3</sub> has a broad maximum at c. 40–60 m.) It should be noted that grain sizes, as defined by the greatest lengths of tabular plagioclase crystals, do not show a maximum at the same level (Fig. 7). As the final products of differentiation usually occur at a height which is  $\frac{2}{3}$  or  $\frac{3}{4}$  of the total thickness of a sill (Wager and Brown 1967, p. 534), it can be expected that the lower dolerite unit was not much thicker than 100 m.

The difference in compositional trends of olivine and augite near the sandstone contact has been mentioned above (p. 25). Somewhat high Fo contents of olivine and low *mg* values of augite are recorded in these samples. It seems likely that the difference is related to the fact that augite started crystallizing later than olivine (after emplacement).

The strong fractionation in the upper dolerite unit has resulted in late differentiation products characterized by relatively high contents of SiO<sub>2</sub>, TiO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, K<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub>, BaO, modal plagioclase and augite, and by low values of FeO, MgO, Cr, Ni, Ni:Co, *mg*, and modal olivine. The fractionation was effected mainly by crystal settling from the dolerite magma. Rhythmic layering and a weak plagioclase lamination in the basal parts and a well-developed plagioclase and augite lamination at higher levels are evidence of such a sedimentation. According to theory, rhythmic layering is produced by the settling of crystals from convection currents in the cooling dolerite magma (e. g. Wager and Brown 1967).

The first phases to crystallize (in both dolerite units) were olivine and plagioclase (see p. 16). In the basal parts of the upper unit, crystal settling of these two minerals occurred (cf. also below), whereas oxides and augite formed later. Oxides are here seen to fill interstices between plagioclase and olivine crystals. Augite encloses early-formed plagioclase (and olivine), thereby giving rise to a subophitic texture in the lower and middle parts of the upper dolerite unit. At higher levels (c. 170–180 m above the sandstone contact), however, fractionation had changed the composition of the magma so that augite settling could occur.

The strong zoning which is observed in plagioclase of the rhythmically layered and laminated dolerites within the upper unit indicates an ortho-

cumulate character of this mineral (Wager et al. 1960; Wager and Brown 1967, p. 61). Consequently, in the post-settling growth of plagioclase, material from the entrapped dolerite magma predominated.

Textural evidence of settling of olivine and oxides is lacking, because these minerals do not develop platy or prismatic crystal habits. However, high olivine contents in some layers near the base of the upper dolerite unit (esp. sample A 35), and the rhythmical layering which occurs at these levels, strongly suggest that olivine is here a cumulate mineral. It is possible that also some settling of oxides occurred in the middle and upper parts of the upper dolerite unit, where interstitial crystallization of these minerals is less common than at lower levels. (Note high contents of oxides in samples A 39 and A 45.) No crystal settling leading to high concentrations of oxides together with olivine (and some plagioclase), as in the titaniferous iron ores of S. Ulvön (Mogensen 1946), has occurred. A rise in the degree of oxidation of the dolerite magma (e. g. caused by assimilation of highly oxidized crustal material) will cause an earlier separation of magnetite, and thus makes possible the formation of layers rich in magnetite and forsteritic olivine (cf. Mogensen 1946, p. 580).

It was noted above (p. 25) that in the upper dolerite unit the general increase in Fe:Mg with height for olivine and augite was reversed between samples A 39 and A 40 as well as between A 42 and A 43. This reversal was probably caused by an influx of dolerite magma, which was for some reason at a less advanced differentiation stage than the magma originally present.

Rocks of monzonitic or granitic composition do not occur on Ringkallen. It is not known whether the small rise in potash feldspar contents observed in the highest parts of the upper unit represents the first step towards such acid differentiates. Monzonites etc., however, occur in the dolerite south-east of Ringkallen, and possibly correspond to rocks removed by erosion from pre-existing higher levels on that hill.

It is not known how much of the upper dolerite unit that has been removed by erosion. However, the grain sizes occurring at the uppermost levels of Ringkallen approximately correspond to the maximum values normally attained within the Jotnian dolerites (except for pegmatitic differentiates). This may be taken to indicate that perhaps 50 m have been removed (cf. Wager and Brown 1967, p. 534). Taking into consideration the possible existence (before erosion) of some tens of metres of monzonitic etc. differentiates, and adding the thickness of the lower dolerite unit (p. 44), a total thickness between 250 and 300 m seems probable (cf. also p. 8).

The question may be raised why the differentiation of the upper dolerite unit proceeded much further than in the lower unit. The strong fractionation (by crystal settling) of the magma of the former unit as compared

with that of the latter may have been caused by a slower cooling of the upper unit. A slow cooling could, in turn, be due to an incomplete cooling of the lower dolerite at the time when the magma of the upper unit intruded. It may thus be supposed that the lower unit is older.

As mentioned earlier (p. 11), layered intrusion structures have been found mainly in the Ulvö dolerite, but also in other flat-lying dolerites in Västernorrland County. It seems likely that layering occurs also in other Jotnian dolerite sills and sheets in Sweden (cf. p. 7). In addition, the hyperites of Värmland and other regions in southwestern Sweden (Magnusson et al. 1960, p. 9) may display similar features.

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TABLE 1 a. Heights of the different dolerite samples, given as the vertical distances to the sandstone contact.

*Höjden för de olika diabasproverna, angiven som det vertikala avståndet till sandstenskontakten.*

Sample no.	Vertical distance (metres)	Sample no.	Vertical distance (metres)
A 1	11	A 30	85.5
A 2	12.5	A 31	89
A 3	15.5	A 32	92
A 4	16.5	A 33	97
A 5	17	A 34a	c. 110
A 6	18.5	A 34	114
A 7	22.5	A 35k	115.5
A 8	24.5	A 35	116
A 9	27.5	A 36	124
A 10	31	A 37	128
A 11	34	A 38	133
A 12	36.5	A 39	146
A 13	39	A 40	155
A 14	41	A 41	162
A 15	43	A 42	173
A 16	46	A 43	176
A 17	47	A 44	182
A 18	51.5	A 45	204
A 19	54		
A 20	56.5	B 1	0— 0.1
A 21	61	B 2	0.5
A 22	62	B 3	1.0
A 23	63.5	B 4	2.0
A 24	66	B 5	2.5
A 25	69.5	B 6	3.2
A 26	72	B 7	5.2
A 27	74	B 8	7.2
A 28	77.5	B 9	10.8
A 29	80	B 10	16.0

TABLE 1 b. Location of samples of dolerite from Ringkallen (Swedish National Coordinate System).

*Lägen för diabasproverna från Ringkallen, givna i Rikets Näts koordinatsystem.*

Sample no.	Coordinates
A 1	697764/162733
A 31	697748/162747
A 35	697743/162761
A 44	697741/162785
A 45	697720/162782
B 1	697593/162695
B 10	697598/162700

TABLE 2. Chemical and modal analyses as well as Niggli  $w$  and  $mg$  values of dolerite samples from Ringkallen.  $\text{SiO}_2$  to  $\text{P}_2\text{O}_5$  are given in weight percent, V to Ni and Cu to SrO, in ppm. Modal composition in volume percent.

*Kemiska och volumetriska analyser samt Niggli värdena  $w$  och  $mg$  för diabasprover från Ringkallen.  $\text{SiO}_2$  till  $\text{P}_2\text{O}_5$  är givna i viktprocent, V till Ni och Cu till SrO i ppm.*

Sample no.	A 1	A 2	A 3	A 4	A 5	A 6
SGU lab. no.	P 1097	P 1098	P 1099	P 1100	P 1101	P 1102
$\text{SiO}_2$	45.2	45.6	45.1	44.7	46.3	45.1
$\text{TiO}_2$	1.99	1.95	1.87	1.86	1.85	1.95
$\text{Al}_2\text{O}_3$	16.9	17.6	17.3	16.3	17.6	16.1
$\text{Fe}_2\text{O}_3$	2.0	1.8	2.0	1.9	1.0	2.0
FeO	11.4	10.9	11.0	11.9	11.4	12.1
MnO	0.18	0.18	0.18	0.18	0.18	0.20
MgO	8.5	8.0	8.8	10.5	8.5	10.1
CaO	8.7	8.8	8.8	8.3	8.9	8.5
$\text{Na}_2\text{O}$	2.83	2.89	2.77	2.69	2.80	2.64
$\text{K}_2\text{O}$	0.98	0.96	0.87	0.80	0.89	0.76
$\text{P}_2\text{O}_5$	0.33	0.33	0.31	0.32	0.33	0.32
Sum	99.0	99.0	99.0	99.5	99.8	99.8
V	250	230	260	240	210	240
Cr	55	60	45	60	40	60
Co	60	60	65	75	55	65
Ni	140	130	160	200	130	160
Ni:Co	2.3	2.2	2.5	2.7	2.4	2.5
Cu	50	50	40	40	40	40
Pb	50	40	40	40	40	50
BaO	600	600	600	450	650	650
SrO	600	600	600	500	700	700
$w$	0.14	0.13	0.14	0.13	0.07	0.13
$mg$	0.53	0.52	0.54	0.57	0.54	0.56
Plagioclase			60.1	59.4		
Olivine			21.2	23.4		
Augite			10.4	10.7		
Oxides			3.9	3.4		
Biotite			3.4	2.2		
Apatite			0.5	0.2		
Potash feldspar			0.4	0.6		
Hornblende			0.0	0.0		
Calcite			0.0	0.0		
Sum			99.9	99.9		
Number of points counted			1173	1245		

Sample no.	A 7	A 8	A 9	A 10	A 11	A 12
SGU lab. no.	P 1103	P 1104	P 1105	P 1106	P 1107	P 1108
SiO <sub>2</sub>	46.3	46.6	46.4	45.8	45.9	46.4
TiO <sub>2</sub>	2.01	1.92	1.95	2.09	2.03	1.98
Al <sub>2</sub> O <sub>3</sub>	18.4	18.0	18.2	18.1	18.5	17.8
Fe <sub>2</sub> O <sub>3</sub>	2.1	2.3	2.3	1.8	2.3	2.2
FeO	10.2	10.7	10.5	11.1	10.2	10.6
MnO	0.17	0.18	0.17	0.18	0.17	0.17
MgO	7.2	8.0	7.4	7.0	6.8	7.3
CaO	9.3	9.1	9.1	9.3	9.1	9.5
Na <sub>2</sub> O	2.95	2.80	2.91	2.89	3.00	2.88
K <sub>2</sub> O	0.97	0.84	0.81	0.90	0.89	0.84
P <sub>2</sub> O <sub>5</sub>	0.32	0.33	0.30	0.30	0.34	0.41
Sum	99.9	100.8	100.0	99.5	99.2	100.1
V	230	250	310	220	250	260
Cr	45	45	50	45	45	45
Co	50	60	60	45	55	55
Ni	110	140	110	90	110	90
Ni:Co	2.2	2.3	1.8	2.0	2.0	1.6
Cu	40	40	40	40	40	50
Pb	50	40	40	40	40	50
BaO	700	650	600	600	650	650
SrO	700	700	700	700	700	700
<i>w</i>	0.16	0.16	0.16	0.13	0.17	0.16
<i>mg</i>	0.51	0.52	0.50	0.49	0.49	0.50
Plagioclase			66.2			63.5
Olivine			16.1			16.8
Augite			11.3			12.7
Oxides			3.3			3.1
Biotite			2.5			2.7
Apatite			0.3			0.5
Potash feldspar			0.3			0.7
Hornblende			0.1			0.0
Calcite			0.0			0.0
Sum			100.1			100.0
Number of points counted			1189			1353

Sample no.	A 13	A 14	A 15	A 16	A 17	A 18
SGU lab. no.	P 1109	P 1110	P 1111	P 1112	P 1113	P 1114
SiO <sub>2</sub>	47.1	46.7	46.7	47.0	46.1	47.0
TiO <sub>2</sub>	1.88	1.94	1.98	1.98	2.13	1.98
Al <sub>2</sub> O <sub>3</sub>	19.0	18.2	19.0	19.1	17.5	18.8
Fe <sub>2</sub> O <sub>3</sub>	2.2	2.0	2.1	2.1	2.2	1.9
FeO	9.7	10.5	9.9	9.6	10.6	9.8
MnO	0.16	0.18	0.16	0.16	0.17	0.16
MgO	6.1	6.8	6.1	6.1	7.1	6.3
CaO	9.2	9.2	9.5	9.6	9.5	9.6
Na <sub>2</sub> O	3.17	2.83	3.02	2.94	2.98	3.04
K <sub>2</sub> O	1.01	0.86	0.95	0.91	0.89	0.97
P <sub>2</sub> O <sub>5</sub>	0.34	0.34	0.33	0.24	0.33	0.32
Sum	99.9	99.6	99.7	99.7	99.5	99.9
V	200	260	240	260	240	250
Cr	40	40	50	40	45	50
Co	45	60	50	50	55	50
Ni	80	130	130	100	100	110
Ni:Co	1.8	2.2	2.6	2.0	1.8	2.2
Cu	40	40	50	40	50	40
Pb	40	40	50	40	50	40
BaO	700	700	650	650	600	600
SrO	700	700	700	700	600	700
<i>w</i>	0.17	0.15	0.16	0.16	0.16	0.15
<i>mg</i>	0.47	0.49	0.47	0.48	0.49	0.49
Plagioclase						
Olivine						
Augite						
Oxides						
Biotite						
Apatite						
Potash feldspar						
Hornblende						
Calcite						
Sum						
Number of points counted						

Sample no.	A 19	A 20	A 21	A 22	A 23	A 24
SGU lab. no.	P 1115	P 1116	P 1117	P 1118	P 1119	P 1120
SiO <sub>2</sub>	46.1	46.4	47.1	46.8	46.9	47.0
TiO <sub>2</sub>	2.00	2.12	2.09	2.15	2.11	1.83
Al <sub>2</sub> O <sub>3</sub>	17.6	17.6	19.1	18.6	18.7	18.7
Fe <sub>2</sub> O <sub>3</sub>	2.1	2.0	2.4	2.3	1.9	1.9
FeO	10.3	10.8	9.6	10.0	10.0	10.5
MnO	0.17	0.17	0.16	0.16	0.16	0.17
MgO	7.5	7.2	5.6	5.8	6.1	6.5
CaO	9.5	9.2	9.4	9.8	9.7	9.1
Na <sub>2</sub> O	3.08	2.89	3.17	3.17	3.10	3.10
K <sub>2</sub> O	0.99	0.95	1.10	0.98	0.99	1.05
P <sub>2</sub> O <sub>5</sub>	0.32	0.34	0.32	0.34	0.34	0.34
Sum	99.7	99.7	100.0	100.1	100.0	100.2
V	230	240	280	280	270	240
Cr	55	55	45	50	40	45
Co	55	55	50	45	50	50
Ni	110	110	70	70	70	85
Ni:Co	2.0	2.0	1.4	1.6	1.4	1.7
Cu	40	50	40	40	50	40
Pb	40	40	40	40	40	40
BaO	600	550	750	500	600	550
SrO	600	700	700	600	700	600
<i>w</i>	0.15	0.14	0.18	0.17	0.15	0.14
<i>mg</i>	0.51	0.50	0.45	0.45	0.47	0.48
Plagioclase		68.1				
Olivine		14.8				
Augite		10.6				
Oxides		2.6				
Biotite		3.4				
Apatite		0.2				
Potash feldspar		0.2				
Hornblende		0.0				
Calcite		0.0				
Sum		99.9				
Number of points counted		1368				

Sample no.	A 25	A 26	A 27	A 28	A 29	A 30
SGU lab. no.	P 1121	P 1122	P 1123	P 1124	P 1125	P 1126
SiO <sub>2</sub>	46.4	47.0	46.6	47.6	46.5	46.7
TiO <sub>2</sub>	2.10	2.03	2.13	2.06	2.19	2.00
Al <sub>2</sub> O <sub>3</sub>	17.7	18.9	18.4	18.3	18.0	18.1
Fe <sub>2</sub> O <sub>3</sub>	2.1	2.1	2.2	2.1	2.3	2.0
FeO	11.2	10.0	10.3	10.3	10.2	10.7
MnO	0.19	0.16	0.17	0.17	0.17	0.17
MgO	7.0	5.7	6.0	6.4	6.3	7.1
CaO	9.5	9.5	9.7	9.6	10.4	9.1
Na <sub>2</sub> O	2.87	3.20	3.13	3.24	2.94	3.17
K <sub>2</sub> O	0.86	1.01	1.01	0.96	0.83	1.07
P <sub>2</sub> O <sub>5</sub>	0.32	0.35	0.33	0.36	0.32	0.35
Sum	100.2	100.0	100.0	101.1	100.2	100.5
V	280	270	320	280	310	270
Cr	40	50	40	35	50	35
Co	55	50	55	50	50	55
Ni	85	65	80	75	65	95
Ni:Co	1.5	1.3	1.5	1.5	1.3	1.7
Cu	70	40	50	50	40	40
Pb	60	40	40	50	40	40
BaO	550	650	600	600	550	550
SrO	600	700	600	700	700	700
<i>w</i>	0.14	0.16	0.16	0.15	0.17	0.14
<i>mg</i>	0.48	0.45	0.46	0.47	0.47	0.49
Plagioclase		72.3				
Olivine		13.9				
Augite		8.6				
Oxides		2.1				
Biotite		2.4				
Apatite		0.3				
Potash feldspar		0.2				
Hornblende		0.0				
Calcite		0.1				
Sum		99.9				
Number of points counted		1312				

Sample no.	A 31	A 32	A 33	A 34a	A 34	A 35k
SGU lab. no.	P 1127	P 1128	P 1129	010-5320	P 1130	010-5319
SiO <sub>2</sub>	46.3	46.1	46.2	44.2	42.8	47.3
TiO <sub>2</sub>	2.12	2.07	2.23	1.80	2.16	1.70
Al <sub>2</sub> O <sub>3</sub>	18.2	16.9	16.9	14.7	12.4	17.0
Fe <sub>2</sub> O <sub>3</sub>	2.2	2.0	2.1	2.1	2.2	2.2
FeO	10.8	12.3	11.4	14.9	17.2	11.1
MnO	0.18	0.19	0.19	0.26	0.27	0.21
MgO	6.5	8.1	7.6	12.2	12.9	8.4
CaO	9.2	8.4	9.0	6.9	7.0	7.5
Na <sub>2</sub> O	3.09	3.07	3.07	1.70	2.14	2.20
K <sub>2</sub> O	1.06	0.90	0.94	0.70	0.61	0.80
P <sub>2</sub> O <sub>5</sub>	0.35	0.40	0.37	0.14	0.37	0.27
Sum	100.0	100.4	100.0	99.6	100.1	98.7
V	260	210	270	280	400	280
Cr	45	50	50	370	750	420
Co	50	55	55	90	105	60
Ni	75	80	80	140	140	70
Ni:Co	1.5	1.5	1.5	1.6	1.3	1.2
Cu	40	50	40	n. d.	50	n. d.
Pb	50	50	40	n. d.	60	n. d.
BaO	600	550	550	600	450	700
SrO	700	700	600	390	500	370
<i>w</i>	0.16	0.13	0.14	0.11	0.10	0.15
<i>mg</i>	0.47	0.50	0.50	0.56	0.54	0.52
Plagioclase		63.9	57.6	47.9	44.1	66.6
Olivine		18.7	18.6	35.3	38.7	16.6
Augite		10.3	13.4	7.8	9.7	9.7
Oxides		3.7	6.5	5.2	4.8	3.8
Biotite		2.8	3.1	2.8	2.0	2.8
Apatite		0.3	0.4	0.4	0.3	0.2
Potash feldspar		0.4	0.3	0.5	0.4	0.2
Hornblende		0.0	0.0	0.0	0.0	0.0
Calcite		0.0	0.0	0.0	0.0	0.0
Sum		100.1	99.9	99.9	100.0	99.9
Number of points counted		1227	1400	2194	1392	1244

Sample no.	A 35	A 36	A 37	A 38	A 39	A 40
SGU lab. no.	P 1131	P 1132	P 1133	P 1134	P 1135	P 1136
SiO <sub>2</sub>	40.9	45.3	44.1	43.9	43.8	45.5
TiO <sub>2</sub>	2.04	2.38	2.55	3.14	3.72	3.50
Al <sub>2</sub> O <sub>3</sub>	10.3	14.0	14.0	14.3	14.3	15.3
Fe <sub>2</sub> O <sub>3</sub>	2.6	3.5	3.1	3.4	3.7	3.3
FeO	19.7	14.4	16.5	16.1	13.7	12.6
MnO	0.30	0.23	0.24	0.24	0.21	0.21
MgO	15.2	9.9	9.9	9.1	6.6	5.7
CaO	6.0	7.5	6.6	7.5	9.4	10.2
Na <sub>2</sub> O	1.89	2.71	2.79	2.71	2.81	3.12
K <sub>2</sub> O	0.58	0.83	0.83	0.81	0.82	0.88
P <sub>2</sub> O <sub>5</sub>	0.27	0.30	0.41	0.37	0.35	0.35
Sum	99.8	101.1	101.0	101.6	99.4	100.7
V	340	440	390	550	720	550
Cr	650	580	450	450	140	10
Co	100	80	75	80	65	60
Ni	130	85	75	75	55	40
Ni:Co	1.3	1.1	1.0	0.9	0.8	0.7
Cu	50	50	40	50	50	60
Pb	60	60	60	70	70	60
BaO	400	500	500	500	500	550
SrO	400	500	500	500	600	500
<i>w</i>	0.11	0.18	0.14	0.16	0.20	0.19
<i>mg</i>	0.54	0.49	0.47	0.45	0.40	0.39
Plagioclase	36.5	48.9	53.2	47.2	47.9	53.8
Olivine	45.5	25.0	27.7	25.0	13.6	8.5
Augite	9.5	14.9	9.8	15.3	23.0	25.6
Oxides	4.3	6.5	4.6	9.6	11.5	9.8
Biotite	3.0	3.9	4.0	2.2	2.6	1.4
Apatite	0.5	0.1	0.3	0.1	0.5	0.4
Potash feldspar	0.8	0.8	0.4	0.5	0.9	0.4
Hornblende	0.0	0.0	0.0	0.0	0.0	0.1
Calcite	0.0	0.0	0.0	0.0	0.0	0.0
Sum	100.1	100.1	100.0	99.9	100.0	100.0
Number of points counted	1454	1555	1367	1423	2429	2005

Sample no.	A 41	A 42	A 43	A 44	A 45	B 1
SGU lab. no.	P 1137	P 1138	P 1139	P 1140	P 1141	P 1142
SiO <sub>2</sub>	47.9	48.5	47.7	48.4	49.1	46.7
TiO <sub>2</sub>	3.53	3.18	3.05	3.40	4.52	2.77
Al <sub>2</sub> O <sub>3</sub>	16.1	14.1	14.5	13.9	13.7	17.1
Fe <sub>2</sub> O <sub>3</sub>	3.5	4.7	5.5	3.6	6.2	4.7
FeO	9.5	10.0	8.5	11.4	9.5	7.7
MnO	0.18	0.21	0.20	0.22	0.20	0.19
MgO	4.4	4.3	4.2	3.8	2.8	6.2
CaO	11.1	10.1	10.0	9.6	8.2	9.1
Na <sub>2</sub> O	3.42	3.43	3.48	3.43	3.71	2.50
K <sub>2</sub> O	0.91	1.42	1.60	1.67	2.20	1.71
P <sub>2</sub> O <sub>5</sub>	0.27	0.52	0.54	0.50	0.51	0.42
Sum	100.8	100.5	99.3	99.9	100.6	99.1
V	530	390	390	360	200	450
Cr	5	5	<5	5	5	60
Co	40	40	40	40	35	30
Ni	25	15	20	10	5	85
Ni:Co	0.6	0.4	0.5	0.3	0.1	2.8
Cu	50	60	70	70	100	20
Pb	60	60	40	60	60	60
BaO	550	850	800	900	1150	550
SrO	500	500	500	500	400	600
<i>w</i>	0.25	0.30	0.37	0.22	0.37	0.35
<i>mg</i>	0.37	0.34	0.35	0.31	0.24	0.47
Plagioclase	57.3	58.5	56.1	58.0	52.4	
Olivine	1.9	3.0	1.9	3.0	0.2	
Augite	27.8	26.9	30.1	27.1	28.3	
Oxides	9.8	8.3	5.9	6.7	12.7	
Biotite	1.8	1.8	3.6	2.6	2.5	
Apatite	0.6	0.6	0.9	0.9	1.0	
Potash feldspar	0.8	0.8	1.5	1.7	2.4	
Hornblende	0.0	0.0	0.0	0.0	0.5	
Calcite	0.0	0.1	0.0	0.0	0.0	
Sum	100.0	100.0	100.0	100.0	100.0	
Number of points counted	2221	1898	1805	2183	1190	

Sample no.	B 2	B 3	B 4	B 5	B 6	B 7
SGU lab. no.	P 1143	P 1144	P 1145	P 1146	P 1147	P 1148
SiO <sub>2</sub>	46.1	46.3	45.9	46.4	46.9	46.3
TiO <sub>2</sub>	2.59	2.64	2.57	2.32	2.51	2.21
Al <sub>2</sub> O <sub>3</sub>	16.7	17.0	16.7	16.6	17.0	17.1
Fe <sub>2</sub> O <sub>3</sub>	3.9	4.2	4.2	2.8	4.0	3.2
FeO	9.0	9.5	9.7	11.0	10.3	10.5
MnO	0.20	0.20	0.20	0.18	0.19	0.18
MgO	6.5	6.6	6.2	7.6	5.8	7.2
CaO	8.5	8.7	8.7	8.9	8.9	8.9
Na <sub>2</sub> O	3.00	2.86	2.93	3.00	3.00	2.75
K <sub>2</sub> O	1.57	1.38	1.19	1.00	1.19	0.94
P <sub>2</sub> O <sub>5</sub>	0.36	0.35	0.34	0.31	0.34	0.30
Sum	98.4	99.7	98.6	100.1	100.1	99.6
V	310	450	290	250	310	280
Cr	75	55	60	55	60	60
Co	50	40	55	55	50	55
Ni	75	80	75	100	60	90
Ni:Co	1.5	2.0	1.4	1.8	1.2	1.6
Cu	30	40	40	40	60	50
Pb	70	40	50	50	50	40
BaO	600	650	700	700	750	600
SrO	500	500	600	700	600	600
<i>w</i>	0.28	0.28	0.28	0.19	0.26	0.21
<i>mg</i>	0.47	0.46	0.44	0.49	0.42	0.48
Plagioclase		52				63.1
Olivine		3				13.8
Augite		8				12.1
Oxides		10				4.5
Biotite		17				4.3
Apatite		0				0.5
Potash feldspar		0				1.7
Hornblende		10				0.0
Calcite		0				0.0
Sum		100				100.0
Number of points counted		1815				2135

Sample no.	B 8	B 9	B 10
SGU lab. no.	P 1149	P 1150	P 1151
SiO <sub>2</sub>	46.6	45.9	46.1
TiO <sub>2</sub>	2.13	2.16	2.05
Al <sub>2</sub> O <sub>3</sub>	17.2	17.0	17.6
Fe <sub>2</sub> O <sub>3</sub>	2.4	2.7	2.5
FeO	11.1	11.0	10.6
MnO	0.17	0.18	0.17
MgO	7.6	7.7	8.0
CaO	8.9	9.0	9.1
Na <sub>2</sub> O	2.88	2.75	2.81
K <sub>2</sub> O	0.88	0.81	0.94
P <sub>2</sub> O <sub>5</sub>	0.29	0.30	0.28
Sum	100.2	99.5	100.2
V	250	250	250
Cr	45	45	50
Co	55	55	55
Ni	95	95	110
Ni:Co	1.7	1.7	2.0
Cu	50	40	40
Pb	50	40	40
BaO	650	500	500
SrO	700	600	700
<i>w</i>	0.16	0.18	0.18
<i>mg</i>	0.50	0.50	0.52
Plagioclase			
Olivine			
Augite			
Oxides			
Biotite			
Apatite			
Potash feldspar			
Hornblende			
Calcite			
Sum			
Number of points counted			

TABLE 3. Partial chemical analyses of olivine. Sample numbers as in Table 2.  
*Partiella kemiska analyser av olivin. Provnnummer som i tab. 2.*

Sample no.	A 3	A 9	A 12	A 20-1	A 20-2	A 20-3	A 20-4	A 20-5
Fe (wt. %)	28.7	29.1	29.7	29.5	28.0	28.9	29.4	30.3
Mg (wt. %)	16.4	15.0	15.2	15.2	16.9	16.0	16.0	15.8
Mol. % Fo	56.8	54.2	54.1	54.2	58.1	55.9	55.6	54.4
Sample no.	A 26	A 32	A 34	A 35	A 36	A 37	A 38	A 39
Fe (wt. %)	31.2	31.4	26.8	26.9	29.1	29.9	29.6	33.2
Mg (wt. %)	14.5	15.3	17.3	17.3	15.9	15.9	15.8	12.4
Mol. % Fo	51.7	52.8	59.7	59.7	55.7	55.0	55.1	46.2
Sample no.	A 40	A 41	A 42	A 43	A 44	B 4	B 7	
Fe (wt. %)	30.6	36.0	45.1	41.0	41.4	26.2	24.1	
Mg (wt. %)	14.6	10.7	6.1	8.2	7.3	18.1	19.3	
Mol. % Fo	52.4	40.5	23.6	31.5	28.8	61.3	64.6	

TABLE 4. Partial chemical analyses of augite.  $mg$  (mol. prop.) =  $MgO/(2Fe_2O_3 \text{ tot.} + MgO)$ . Sample numbers as in Table 2.

*Partiella kemiska analyser av augit.  $mg$  (mol.prop.) =  $MgO/(2Fe_2O_3 \text{ tot.} + MgO)$ . Provnnummer som i tab. 2.*

Sample no.	A 3	A 9	A 12	A 20	A 26	A 32	A 34
TiO <sub>2</sub>	1.78	1.84	1.99	1.44	1.73	1.27	1.56
Al <sub>2</sub> O <sub>3</sub>	5.37	3.39	3.97	2.86	3.07	2.43	3.41
Fe <sub>2</sub> O <sub>3</sub> <sup>1)</sup>	9.45	10.32	10.76	11.18	10.95	11.72	10.57
MgO	13.07	12.66	12.16	12.17	12.62	12.81	12.47
CaO	20.24	20.15	20.34	20.52	20.90	19.37	20.11
<i>mg</i>	0.73	0.71	0.69	0.68	0.69	0.68	0.70
Sample no.	A 35	A 36	A 37	A 38	A 39	A 40	A 41
TiO <sub>2</sub>	1.12	1.06	1.12	1.15	1.11	1.37	1.12
Al <sub>2</sub> O <sub>3</sub>	1.91	2.40	2.45	2.76	2.20	4.54	5.14
Fe <sub>2</sub> O <sub>3</sub> <sup>1)</sup>	10.40	10.41	11.09	11.14	12.43	10.87	12.09
MgO	13.31	13.45	12.65	12.96	12.16	11.44	11.17
CaO	19.91	20.32	19.99	19.81	20.46	18.41	18.36
<i>mg</i>	0.72	0.72	0.69	0.70	0.66	0.68	0.65
Sample no.	A 42	A 43	A 44	A 45	B 3	B 7	
TiO <sub>2</sub>	0.99	1.08	1.03	0.98	2.29	1.10	
Al <sub>2</sub> O <sub>3</sub>	3.52	1.97	1.63	1.86	2.75	1.87	
Fe <sub>2</sub> O <sub>3</sub> <sup>1)</sup>	11.47	12.34	13.36	14.42	14.40	12.30	
MgO	9.59	12.41	12.01	11.10	10.18	13.40	
CaO	19.40	20.32	19.63	19.78	20.50	19.80	
<i>mg</i>	0.62	0.67	0.64	0.60	0.58	0.68	

<sup>1)</sup> Total Fe as Fe<sub>2</sub>O<sub>3</sub>.

TABLE 5. Plagioclase compositions. Sample numbers as in Table 2.  
*Plagioklasens sammansättning. Provnnummer som i tab. 2.*

Sample no.	Anorthite content (mol. %) <sup>1)</sup>
A 3	(38—)80—82(—85)
A 9	(29—)80—82 <sup>2)</sup>
A 12	(27—)79—82
A 20	(32—)79(—85)
A 26	(50—)76—82
A 32	(31—)71—76
A 33	(38—)73—80 <sup>2)</sup>
A 34	(60—)71—79
A 35	(14—)71—73(—80) <sup>2)</sup>
A 36	(13—)67—71
A 37	(20—)67—69
A 38	(20—)67—71
A 39	(18—)58—65
A 40	(37—)58—67
A 41	(47—)58—62
A 42	(20—)58—60
A 43	(22—)58—60
A 44	(20—)56—58(—69)
A 45	(20—)38—44
B 1 (matrix)	(69—)76—79
B 1 (phenocr.)	(65—)76—80
B 3	(30—)73—80
B 7	(18—)69—79

<sup>1)</sup> Brackets indicate subordinately occurring compositions in cores and marginal zones.

<sup>2)</sup> Reverse zoning observed.

PRISKLASS E

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