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DOLERITES OF THE ESKILSTUNA REGION

Eastern Central Sweden

BY

R. GORBATSCHEV

STOCKHOLM 1961

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ABSTRACT

A system of east-westerly trending dolerite dikes is described from the Eskilstuna region 60 miles W of Stockholm. The main rocks are olivine dolerites, pyroxene dolerites, and dolerite porphyrites, all believed to belong to a single evolutionary sequence. Minor rocks include anorthosites found as fragments in the dolerites, granophyric dolerites, leucodolerites, and granophyres. The petrology and field geology of the rocks are described and their alignment with faults discussed. A comparison with other dolerites of the province of Södermanland shows that the rocks of the central Hällefors series are consistently lower in al and mg and higher in fm and potassium than the rest of the basic Södermanland hypabyssals.

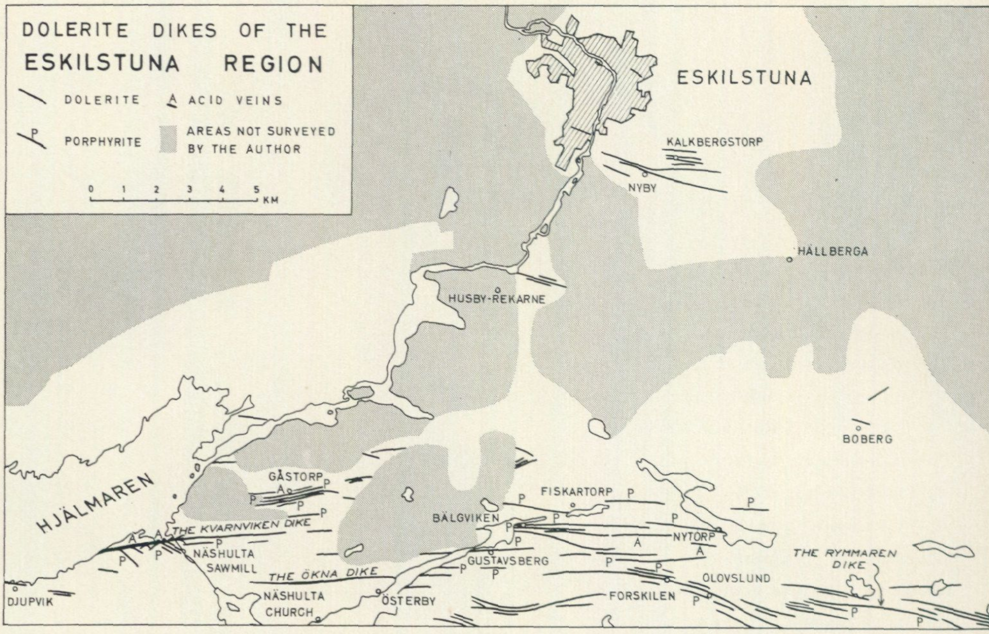

Fig. 1. General map of the dolerites in the Eskilstuna region.

Introduction

In the neighbourhood of Eskilstuna a great number of dolerites[1] pierce the Svecofennian gneisses and granites to form steep-dipping dikes, which strike predominantly E—W to ESE—WNW. These dikes are part of the dolerite belt stretching from the eastern coastal parts of the province of Södermanland to the western environs of Lake Hjälmaren and including, besides a considerable number of small dikes, the two large hypabyssal bodies of Breven and Hällefors(näs), described in detail by T. Krokström (1932a, 1936a). Other dikes belonging here have been mentioned in a great number of geological mapsheet descriptions and have also been the subject of more detailed special investigations by among others B. Asklund (1923), H. von Eckermann (1934), and E. Åhman (1956).

In a valuable pioneer paper A. E. Törnebohm (1877) established a comprehensive classification of Swedish dolerites. Amongst the dolerite types occurring in Södermanland and the adjoining areas Asklund (1923) distinguishes a system of often porphyritic "bronzite"-dolerites (cf. A. Gavelin 1907) from the olivine rocks of Törnebohm's Åsby-Hällefors types. The "bronzite"-dolerites are by Asklund considered to be sub-Jotnian and related to the uralite diabases

[1] Dolerite is here used in the British sense of the word (Harker 1908, Holmes 1928, Krokström 1936b), and is thus equivalent to the term diabas(e) of Swedish use and the recommendation of the US. Geological Survey.

of Småland, S. Sweden. The latter rocks, previously described by F. Eichstädt (1882) and H. Hedström (1906), are often associated with acid dike porphyries. Similarities of dike orientation (NW—SE to N—S strikes), mineralogical features and the presence of plagioclase-porphyritic varieties of both are regarded to prove this hypothesis. A younger system is, according to Asklund, that of the olivine-bearing and related dolerites. These Jotnian or post-Jotnian rocks in the province of Södermanland generally trend east-westerly.

The Eskilstuna map-sheet has lately been reinvestigated by the Geological Survey of Sweden. This project, the petrographical part of which was directed by P. H. Lundegårdh (Lundegårdh and Lundqvist 1959, Lundegårdh 1960), resulted in the discovery of a considerable number of dolerite dikes not found on the previous Survey map of the region (Karlsson 1863).

Petrographically these and associated rocks of the Eskilstuna region comprise the following types:

1. olivine dolerites and dolerites with abundant olivine pseudomorphs
2. pyroxene dolerites with or without pseudomorphosed olivine
3. dolerite porphyrites
4. leucodolerites, granophyres, and related acid vein rocks

Very often there is a gradual transition between these types, which also may constitute the different parts of composite dikes. In spite of this a general sequence of intrusion can be established, in which series the olivine rocks are the oldest and the acid varieties the youngest members.

The size of the hundred-odd dikes mapped or inspected by the author ranges from insignificant veins a fraction of an inch across to dikes or systems of dikes traced over several miles and attaining a width of a hundred yards and more (the Kvarnviken and Ökna dikes, cf. the map, Fig. 1). About twenty of the dikes are broader than 30 metres. In addition, many small occurrences must be reckoned either to be completely covered by Quaternary deposits, or to have evaded attention during the mapping of the area.

As regards topography the dolerites either follow depressions, then often occupying the southern (lee-) sides of glacier-sculptured outcrops, or rise to form prominent hills, the latter *inter alia* applying to the Kvarnviken dike, which occupies the summit of Bråtthatt hill and other heights E and W of Näshulta sawmill. This inconsistent morphological habit seems essentially to be a function of the amount of fractures traversing the dolerite dikes at right angles or parallel to their contacts and, in medium-sized dikes, still more often in two oblique directions, thus splitting the rock into sets of rhombic fragments. In the Kvarnviken dike the dolerite has been subject to intense late-magmatic and post-crystallization alterations, in which process the contraction cracks have mostly been healed with micropegmatite and epidote.

Beautifully developed hexagonal and other polygonal fracturing is found in some of the smaller, massive, fine-grained dolerite occurrences.

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Fig. 2. Olivine dolerite, Gustavsberg. + nic., 35 ×. Photo R. Gorbatschev

The Olivine Dolerites

The Ökna, Gustavsberg and Olovslund-Forskilen dikes are together with some smaller dikes in the woods N and NW of Forskilen (cf. Fig. 1) the most typical representatives of the rock group treated in this chapter. The olivine dolerites of the Eskilstuna region are dark grey to brownish-grey rusty-weathering rocks of fine- and medium-sized grain: the tabular plagioclase laths attain a maximum length of about 5 mm. Slightly porphyritic types are common and form a group transitional to the dolerite porphyrites abundant in the area. Although contact-zone outcrops are not plentiful and the field relations often cannot be elucidated in detail, there generally seems to be no sharp border between the olivine-carrying and the olivine-free dolerites. Thus, for instance, both types are found in the Ökna dike, where sporadically somewhat porphyritic olivine dolerite occupies most of the extent and confines the olivine-free rock to the westernmost parts of the body. Comparatively acid dolerite varieties are also found locally in the fine-grained contact belts of the olivine dolerites, this feature in most cases being due to the interaction between the dolerite melt and its wallrock.

The texture of the olivine dolerites is beautifully ophitic to subophitic[1] (Figs. 2 and 3). The mineral assemblage consists, roughly in the order of abundance, of plagioclase, pyroxenes, olivine and olivine pseudomorphs,

[1] Regarding these terms the terminology of Krokström (1932 b, p. 199) is used throughout the present paper.

Fig. 3. Plagioclase laths ophitically enclosed in augite. The plagioclase-pyroxene boundaries are predominantly rectilinear. Olivine dolerite, Gustavsberg. + nic., 45 ×. Photo R. Gorbatschev

chlorite, serpentine, and ores. Biotite and secondary amphibole often are prominent accessories, while apatite is scarce.

The plagioclase is a bytownite or calcic labradorite (An 69—82) showing well developed albite, pericline, and Carlsbad twinning, and usually also a somewhat diffuse oscillatory zoning, which brings the An percentage of the rims downs to about 50 and often cuts across the twin lamellae. In rocks with fresh olivine the alteration of plagioclase generally is insignificant, the idiomorphy of the feldspar laths often being perfect.

The pyroxenes of the olivine dolerites are faintly greenish or brownish to colourless augite, and orthopyroxene displaying a negative axial angle of about 62 degrees, which according to Winchell (1951) corresponds to a $FeSiO_3$ mol.-percentage of 45. Although the proportions between the two kinds of pyroxene vary, augite is always the more abundant, and may, especially in the more acid rock types, be the only (unaltered) pyroxene present. The crystallization of orthopyroxene seems generally to have taken place somewhat in advance of that of the augite; the first-named mineral, however, is often speckled with drop-like rounded augite inclusions which are in optical continuity with the adjoining larger crystals of that mineral (Fig. 4). These in turn are often crystallographically coaxial with the orthopyroxenes forming the cores of composite pyroxene grains. This mode of occurrence suggests a formation by unmixing from original pigeonite (cf. Hess 1941, p. 582).

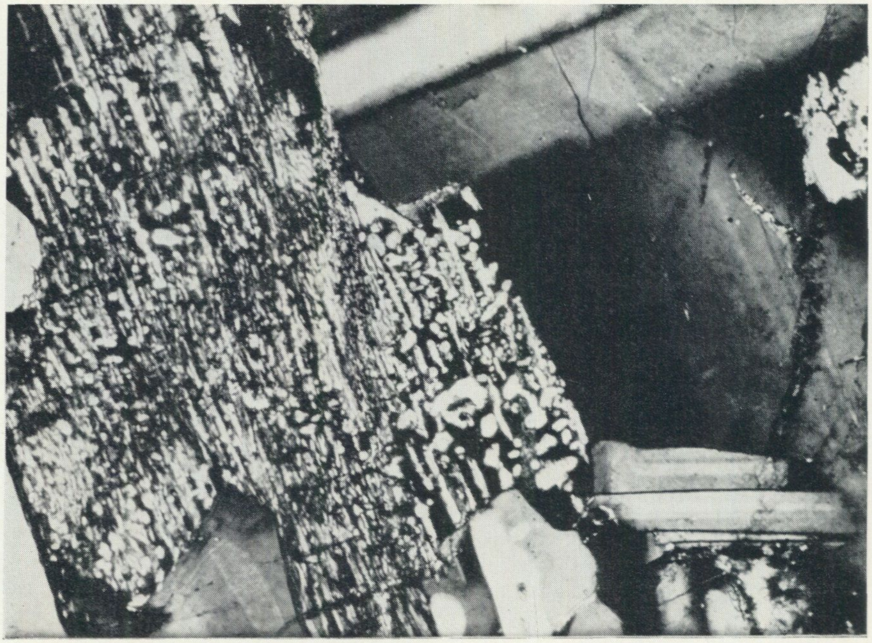

Fig. 4. Intergrowth between orthopyroxene (black) and clinopyroxene (light grey). The crystals to the right are labradorite with serpentine-filled cracks. Olivine dolerite, Gustavsberg, + nic., 180 ×. Photo R. Gorbatschev

The optical properties of the augite of the olivine-bearing rocks are $c \wedge \gamma$ 40—44° (mean value 42°), 2 V_γ 38—46° (mean 43°), distinct to weak dispersion $r > v$, and $n_\gamma - n_\alpha$ 0.022—0.026. In addition to the usual (110) cleavages (001), (100), and (010) partings are prominent, the latter two often being very well developed.

Alteration of the augite to uralite and serpentine may occur, but is not very pronounced, the orthopyroxenes generally being much more susceptible to alteration than their calciferous counterparts. Both varieties of pyroxene may also change into greenish-brown clouded pseudomorphs composed of very finely dispersed iron ore dust and an indeterminable flaky substance (chlorite?), the very fine lamellae of which follow the original (110) cleavages as well as the dome planes and are intergrown with minute layers of unaltered pyroxene.

The uralite is pale green with $c \wedge \gamma$ 16—17° and 2 V_α 80 ± 5°, and may associate with another amphibole of dark olive-green to greenish-brown pleochroism, $c \wedge \gamma$ 16°, and a negative axial angle of about 55°. The latter amphibole is often quite massive and subhedral and may partly be a late-magmatic crystallization product.

In rocks with complete olivine alteration (into predominantly ores) the clinopyroxene frequently displays smaller axial angles (2 V_γ 33—42°, $c \wedge \gamma$ 39—44°) and considerably lower birefringence (0.015—0.018), which indicates a higher content of magnesium and a lower calcium percentage.

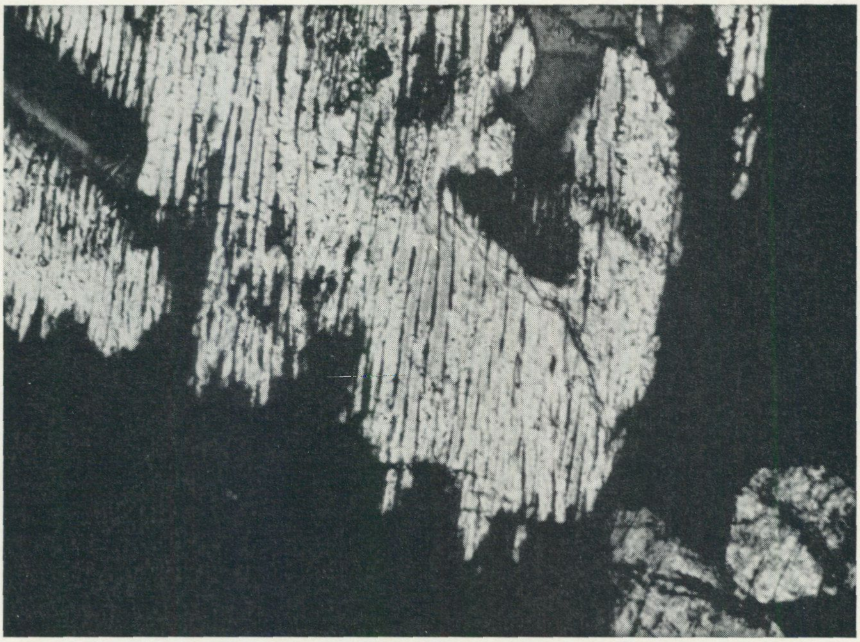

Fig. 5. Part of corroded orthopyroxene core (light grey) in augite (black). The crystal in the upper left corner is a plagioclase lath surrounded by a rim of augite. Olivine dolerite, Gustavsberg, + nic., 230 ×. Photo R. Gorbatschev

The biotite found as small flakes between the plagioclase laths is vividly pleochroic in hues of reddish-brown, its axial angle being about 12—15°.

The variations in the optics of the olivine are very considerable even within the area of a single slide (2 V_α 71—88°), the mean value in all thin-sections examined nevertheless being constant between 80.5 and 82 degrees, which according to Winchell (op. cit.) indicates a content of about 45 mol.-% fayalite. While generally occurring in the shape of subhedral or rounded grains, the olivine sometimes exhibits ophitic relations toward the plagioclase, and even completely encloses laths of the latter mineral. These laths, however, are much smaller than the common size of the plagioclase grains. Alteration of the olivine is found to range from all but imperceptible to complete and results in a number of products among which ores, serpentine, dark chlorite, and uralite are the most prominent.

Among the earliest, and in weakly altered olivine the only, pseudomorph components are ores, bowlingite, and talc, the latter mineral forming narrow rims along the ore-lined cracks of the mother crystal. In places these rims expand to embrace all of the original olivine and then intergrow with small blebs of iron ore. The process is identical with that described by Krokström (1936a, pp. 130—131) from the Hällefors dike.

A later stage of olivine breakdown is represented by the formation of colourless or faintly green to brown serpentine. Serpentinization and alteration into

Fig. 6. Pyroxene dolerite, 4 km E of Olovslund. Pyroxene is light grey, ore is black. The plagioclase-pyroxene boundaries are sinuous as contrasted with the rectilinear ones of the olivine dolerites (cf. Fig. 3). + nic., 37 ×. Photo R. Gorbatschev

weakly pleochroic green chlorite (delessite) are most prominent in rocks with considerably or completely altered olivine and are then usually found together with some uralitization and a powerful corrosion of the plagioclase by serpentine- and/or ore-filled veinlets. Still another kind of olivine alteration transforms the mineral into vividly yellow or green pseudomorphs of extremely fine-grained chlorite or "bastite" showing weak birefringence. This type of pseudomorphs has a very patchy distribution and is often coupled with the appearance of calcite-filled cracks and zones of intense plagioclase sericitization and saussuritization together with chlorite-alteration of the pyroxenes. The process affects rocks ranging in type from olivine-rich dolerites to those with almost no remains of fresh olivine and is of a late (post-solidification) time, being due to the action of circulating solutions replacing the olivine left over by the other types of alteration. Thus, naturally, this variety of pseudomorphs is not found in rocks abundant in free silica and distinguished by early and complete olivine destruction. Uralite is fairly common and in the pseudomorphs often associates with greenish-brown chlorite. The newly formed amphiboles are almost colourless or olive-green, the first named variety associating with considerably more iron ore than the second. These pseudomorphs also replace pyroxene.

In some oliviniferous dolerites small patches of micrographically intergrown quartz and alkali feldspar habitate the angular interstices between the plagioclase laths. Whenever the phenomenon is well developed, and unaltered olivine

Fig. 7. Laths of plagioclase (white), pyroxene (grey), and ore rods (black) in a groundmass of chlorite and some alkali feldspar. Pyroxene dolerite with reddish augite, 0.5 km SE of Bälgviken. || nic., 145 ×. Photo R. Gorbatschev

is a component of the rock, the crystals of this mineral are mantled by heavy rims of iron ore, ore also forming complete olivine pseudomorphs or leaving but a few minute shreds of the original mineral, talc, bowlingite or uralite in the cores of the replaced crystals. The surviving olivine is here invariably impregnated with fine ore dust giving it a dull grey appearance. The amount of ore formed secondarily is easily in excess of the iron oxides contained in the original mineral, and thus, even considering the appearance of magnesian chlorite in the peripheric parts of the replaced olivine grains, iron must have been supplied from the outside. This process presumably is of a late magmatic time.

Dark purplish red, strongly pleochroic iddingsite occurs in places in insignificant amounts marginally replacing olivine (-pseudomorphs). In the formation of iddingsite the iron ore of the cracks in the olivine and the ore rims surrounding the mother crystal are largely consumed.

A good deal of the iron oxide ore found in the rock is of a secondary origin, eu- or subhedral primary crystals nevertheless being fairly abundant. Together with titanomagnetite there locally occur interstitial small and sparse grains of pyrrhotite.

Quantitative point-counter data on the actual mineral composition of this and other dolerite types will be found tabulated on page 13. As regards the main mineral components, the last decimals of the percentages of that compilation of course lack significance.

The Olivine-free Dolerites

The different types of olivine-free rock together comprise the bulk of the Eskilstuna dolerites. Their colour is generally a deeper black than that of the oliviniferous rocks and often also shows shades of green, which are due to the occasionally very considerable content of uralite and chlorite. As has been stated in the preceding chapters, there is no well-defined border of habit, dike orientation or age separating these rocks from the olivine dolerites. The transition is effected by grades and mineralogically involves a drop in the content of olivine pseudomorphs together with an increase in quartz. The "silica saturation point" is passed while the rock still carries serpentine-uralite-ore pseudomorphs replacing olivine of early crystallization. Other differences in proceeding from olivine to pyroxene dolerite include lower An percentages in the plagioclase and a gradual change in the optical properties of augite. Simultaneously, amphibole, chlorite, and calcite become prominent indicating an enrichment of the melt in volatiles and a lower temperature of its solidification.

Microtexturally the difference between the oliviniferous and olivine-free dolerites becomes pronounced as the pyroxene gradually loses its ophitic habit and changes into aggregates of subhedral grains (Figs. 6 and 7). In transitional varieties hour-glass pyroxene structures are common, as are fans of pyroxene crystals with c-axes emanating from a common centre. In some varieties the augite forms discrete crystals embedded in intergranular green chlorite. As a matter of fact, the euhedral outlines prove that the pyroxene has never oc-

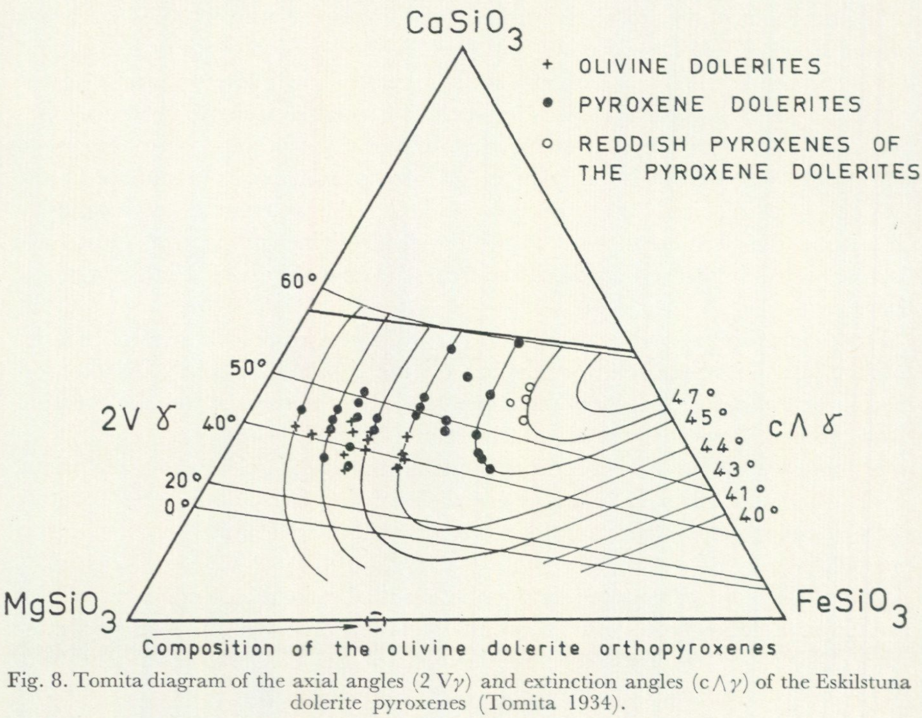

Fig. 8. Tomita diagram of the axial angles ($2\,V\gamma$) and extinction angles ($c\wedge\gamma$) of the Eskilstuna dolerite pyroxenes (Tomita 1934).

Table 1. Actual mineral composition of the Eskilstuna dolerites and associated rocks (volume p. c.)

Rock and locality / Mineral	Olivine dolerites				Porphyrites			Pyroxene dolerites					Uralite-diabase. The Gåstorp dikes	Leucodolerite. The Gåstorp dikes	Granophyre, 1 km W of Näshulta sawmill
	Gustavsberg	Olovslund	Bälgviken	The Ökna dike	1.5 km ENE Fiskartorp	The Fiskartorp dike	The Gåstorp dikes	2.2 km N of Bälgviken	The Ökna dike	2.5 km NE of Husby-Rekarne	3 km ENE of Djupvik	The Kvarnviken dike			
Plagioclase and alteration products[1]	56.2	54.8	58.8	61.5	54.9	52.5	62.6	49.8	44.5	43.7	38.9	49.9	27.5	—	[2]37.6
Alkali feldspar	0.0	0.8	0.6	1.8	2.1	1.1	0.1	4.6	1.0	0.7	0.4	0.7	10.2	[3]55.0	[4]16.5
Quartz	—	0.7	0.2	0.5	—	0.3	—	1.9	0.1	0.1	0.0	—	14.6	25.0	26.4
Olivine	10.0	5.1	—	4.1	9.3	—	—	—	—	—	—	—	—	—	—
Clinopyroxene	15.2			17.3	23.8	18.0	10.0	8.8	16.2	18.2	19.4	19.1	4.9	—	—
		18.3	7.9												
Orthopyroxene	3.0			1.7	—	—	—	—	—	—	—	0.2	—	—	—
Amphibole	0.1	1.2	0.2	0.3	3.8	2.1	23.2	24.2	31.3		33.1	6.2	19.1	8.3	4.9
Serpentine and chlorite	8.1	5.2	21.1	5.1		18.7				24.0		16.5	12.0	3.4	3.3
Talc and bowlingite	2.1	1.5	6.3	0.9	—		—	—	—		—	—	—	—	—
Biotite	0.3	3.2	0.9	1.2	0.0	0.1	0.0	1.0	—	0.4	—	—	2.8	1.8	5.3
Epidote	—	—	—	0.7	0.0	1.6	0.2	0.0	—	—	0.2	0.6	0.8	—	3.3
Sphene	—	—	—	—	—	—	—	—	0.1	0.0	—	—	0.2	1.8	0.8
Oxide ores	[5]4.8	[6]9.0	3.6	3.7	5.2	5.0	3.4	7.2	6.0	9.5	7.0	6.3	5.3	0.1	0.5
Sulphide ores	—	—	—	—	—	0.0	0.1	0.2	—	—	—	0.1	1.1	—	—
Apatite	0.1	0.1	0.4	0.7	0.9	0.6	0.4	2.6	0.6	1.0	0.5	0.4	1.5	1.1	1.1
Calcite	0.1	0.1	—	[7]0.5	—	—	—	—	0.2	2.4	0.5	0.0	—	3.5	0.3

[1] Including sericite and clinozoisite, excluding chlorite- and amphibole-rims and veins.
[2] Albite. [3] Albite > perthite. [4] Potash feldspar. [5] 4.1 % in olivine-pseudomorphs.
[6] 5.0 % in olivine-pseudomorphs. [7] 0.4 = vein calcite.

cupied all of the feldspar-lath interstices, and much of the chlorite found here must consequently be of primary formation. In all varieties of the olivine-free dolerite the boundaries between pyroxene and plagioclase are much more sinuous than in the olivine dolerites. Plagioclase crystals outwedging when partly enclosed in pyroxene were also noticed. Plagioclase and pyroxene have consequently crystallized together for a considerable time.

The crystal habit of the iron ore is often one of long rods, which, when best developed, results in a treble pattern of divergent subhedral plagioclase and pyroxene as well as ore laths and rods set in a groundmass of amphibole, ore dust, chlorite, quartz, and alkali feldspar (Fig. 7).

As regards mineralogy the composition of the most common kind of olivine-free dolerite is dominated by plagioclase, pyroxene, chlorite, and amphibole; quartz, alkali-feldspars, biotite, calcite, and apatite forming the minor and accessory constituents. The amount of apatite, frequently found in the shape of very slender long needles, is generally higher than in the olivine dolerites.

The An content of the plagioclase ranges from 40 to 65 mol.-%. The peripheric parts of the crystals of the mineral are often intergrown with quartz or pass into oligoclase with micropegmatite occupying the plagioclase lath interstices. Continuous diffuse or oscillatory zoning or undulatory extinction are the rule.

The pyroxenes grade from colourless augite ($c \wedge \gamma$ 40—44°, 2 V_γ 37—46°) over intermediary types to distinctly pleochroic brown, and finally reddish-brown, probably titaniferous pyroxene with $c \wedge \gamma$ 45—47°, 2 V_γ 52—61°

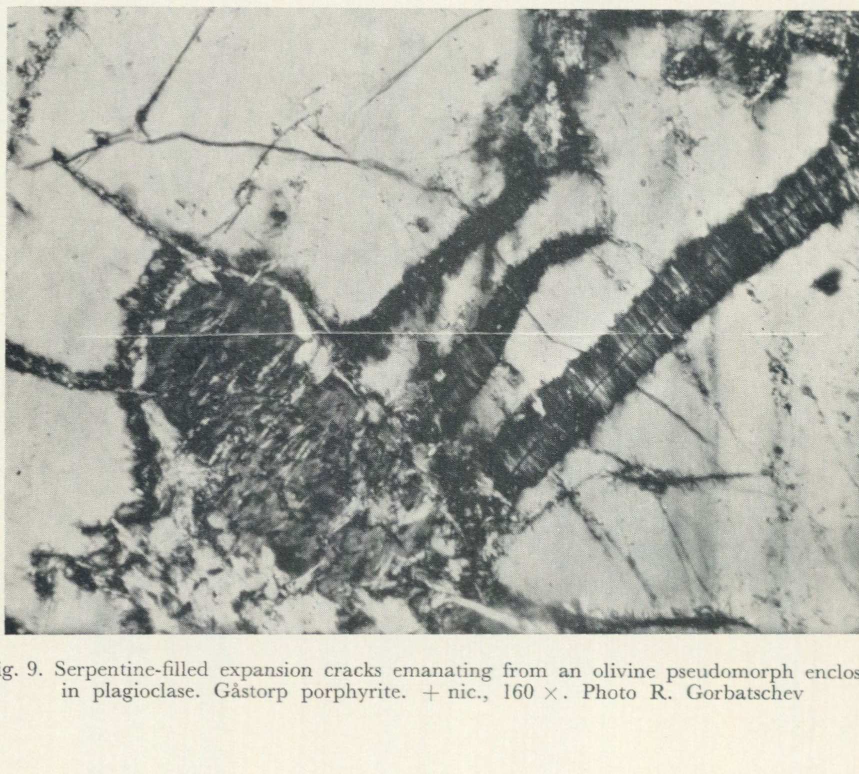

Fig. 9. Serpentine-filled expansion cracks emanating from an olivine pseudomorph enclosed in plagioclase. Gåstorp porphyrite. + nic., 160 ×. Photo R. Gorbatschev

and $n_\gamma - n_\alpha$ about 0.020. The birefringence of the pyroxene is subject to rather strong variability. The reddish brown type usually occurs in discrete dikes with very few olivine pseudomorphs, but also very little or no quartz, thus showing good crystal — melt adjustment. On the evidence of a cross-cutting dike S of Bälgviken, this dolerite type is believed to be slightly younger than the rest of the basic hypabyssals. Again, the rock occurs in the composite Ökna dike and is thus genetically related to the rest of the dolerites. Although no chemical data are available it may tentatively be suggested to correspond to the dolerites of the Hällefors central series (cf. p. 36). Fig. 8 summarizes some of the optical properties of the Eskilstuna dolerite pyroxenes. This diagram includes only pyroxenes with two directly observed optic axes.

Uralitization of the pyroxenes is fairly frequent. The secondary amphiboles are generally of a bright blue-green colour and hastingsitic optical character ($c \wedge \gamma \sim 16°$, $2\,V_\alpha$ 55 to 60°), but do also comprise other brownish-green and colourless varieties. The uralitization of pyroxene forms fringes of radiating amphibole threads around the pyroxene grains, but can occasionally be of the massive type. The spatial distribution of uralitized areas in the thin-sections is rather irregular. No unaltered orthopyroxene is found in most of the pyroxene-uralite dolerite dikes (the Kvarnviken dike is an exception), though some of the chlorite-uralite-ore clusters enclosed in augite possibly pseudomorph the former mineral. Neither is it always possible to discriminate unambiguously between olivine and pyroxene pseudomorphs.

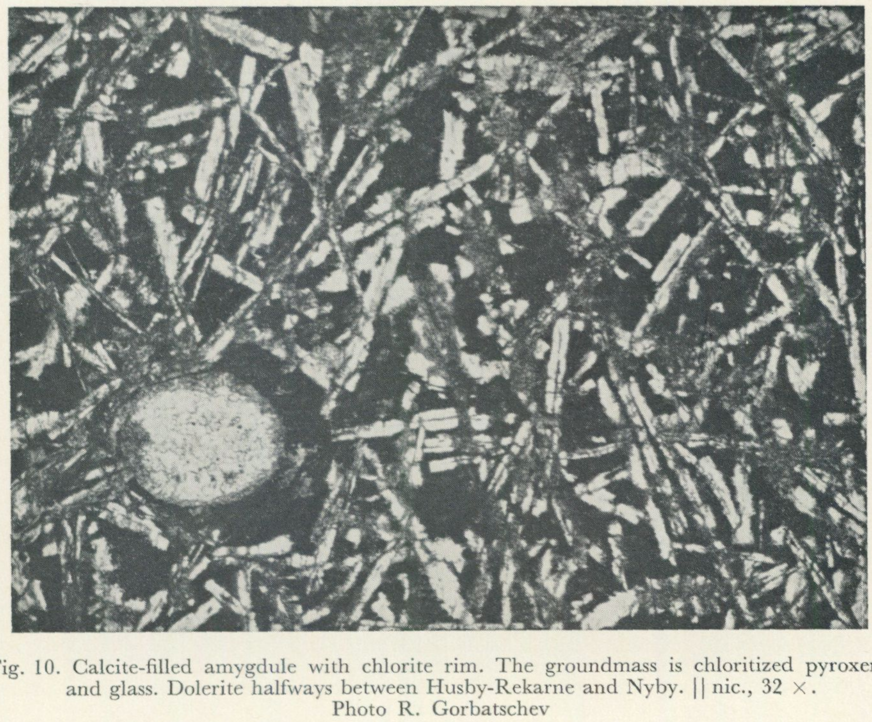

Fig. 10. Calcite-filled amygdule with chlorite rim. The groundmass is chloritized pyroxene and glass. Dolerite halfways between Husby-Rekarne and Nyby. || nic., 32 ×.
Photo R. Gorbatschev

Serpentine is of common occurrence, as also are delessite, strongly pleochroic diabantite (?) and optically negative penninite. The latter is usually clearly secondary and predominantly habitates strongly altered portions of the rock. There is intense marginal- and vein-replacement of the plagioclase by serpentine and other chlorites (Fig. 9).

Clinozoisite is found to be a saussuritization product and may associate with sericite that usually occupies the inner parts of sporadically occurring plagioclase phenocrysts.

The biotite has the general appearance and axial angle of its counterpart in the olivine dolerites.

Among the ore minerals ilmenite gains a prominent position as does pyrrhotite, whereas pyrite appears in noteworthy quantities in the more acid rock varieties and in autometamorphosed dikes. In a bluish-black fine-grained andesine dolerite found, among other places, immediately to the south of Bälgviken and at the Näshulta sawmill, this ore mineral may occupy as much as 3 % of the total volume of the rock.

Amygdules coated with chlorite and occupied by calcite, quartz, or chlorite are rather common (Fig. 10), as are calcite- and chlorite-filled fissures and cracks.

As is evident from the above description numerous features show that rest solutions rich in volatiles have played a prominent part in the formation of the rock autometamorphosing the pyroxene dolerites and generating deuteric water-

Fig. 11. Uralite dolerite, Gåstorp. The main components are uralite and ores (black), epidote, chlorite, and apatite (grey), corroded plagioclase laths and micropegmatite (white). ||nic., 140 ×. Photo R. Gorbatschev

rich minerals. The textural features and the mineralogical characteristics, however, prove that the pyroxene dolerites are not just altered olivine dolerites, but have crystallized from a magma of different composition, the properties of which melt among other things generally included an abundance of volatile components enriched by differentiation or absorbed from the surrounding rocks.

The chemical analysis on page 18, reprinted from Lundegårdh's description of the geological map of the Eskilstuna region (Lundegårdh and Lundqvist 1959, p. 13), represents a rock rather rich in free quartz, but carrying many undisputable olivine pseudomorphs.

Other compositional varieties of olivine-free dolerite include uralite dolerite with completely uralitized pyroxene and basic andesine (An 48) cutting across pyroxene dolerite in some of the composite Gåstorp dikes (Fig. 11).

Glassy development

Disregarding the marginal facies of holocrystalline dolerites, undecomposed volcanic glass is found in only two places, viz. E of Boberg (dike 15 cm across) and 5.5 km N of Österby manor (dike measuring 0.8—1.2 m in width). In parts of its course that can be traced for about 200 metres the latter dike is wholly devitrified. Under the microscope the glass of both dikes has a dark brown colour and is speckled with crystallites of pyroxene (?) and ore. There is also an intense alteration into chlorite and epidote and an abundance of hyalophitically enclosed plagioclase laths (An 50) about 0.05 mm long. Larger (greatest diameter about 1.5—2 mm), lath-shaped or rhombic phenocrysts of plagioclase and, less often, chloritized augite are also prominent. Furthermore there are amygdules of rather different size filled with quartz and calcite (Fig. 12). Some of them have been deformed prior to the crystallization of the quartz fillings.

Micropegmatitic dolerites

Monzonitic pyroxene-uralite-andesine dolerites with considerable amounts of micropegmatite are found in the Gåstorp and Kvarnviken dikes, where they are the youngest dolerite members of the hypabyssal suite (Fig. 13). The difference between these rocks and the pyroxene dolerites is mainly a matter of mineral proportions. The plagioclase of the acid kind of rock, however, is somewhat richer in Ab and the pyroxene is less magnesic (higher extinction angles). The micrographic dolerites grade in turn into the leucocratic rocks described in another chapter.

The Dolerite Porphyrites

The dolerite porphyrites are greyish-black rocks spotted with white or grey plagioclase phenocrysts. Their mineral composition corresponds either to the oliviniferous or the olivine-free dolerites. Whereas occasional plagioclase phenocrysts are found in many if not most of the dolerites, the phenocryst-rich porphyrites are restricted to a series of localities extending from the SE corner of the map to the shore of Lake Hjälmaren NE of Näshulta sawmill. Together with other occurrences this belt includes the Rymmaren, Nytorp, Fiskartorp, Bälgviken, and Gåstorp dikes. The Gåstorp dikes are a system of five dikes,

Table 2. Chemical analyses of dolerites of the Eskilstuna and Västerås regions

Weight percentages				Weight norm				Niggli values			
	Olivine dolerite, Gustavsberg	Pyroxene dolerite, 2000 m N of Bälgviken	Dolerite, Löt, Västerås map-sheet		Gustavsberg	2000 m N of Bälgviken	Löt		Gustavsberg	2000 m N of Bälgviken	Löt
SiO_2	46.62	49.47	49.14	qz	—	7.34	1.65	si	102.9	140.4	131.1
TiO_2	0.81	3.62	2.86	or	4.01	11.91	8.79	qz	−18.5	−6.5	−11.3
Al_2O_3	17.12	15.87	15.95	ab	17.41	24.85	26.32	al	22.3	26.5	25.1
Fe_2O_3	2.64	4.74	2.18	an	35.46	24.17	25.17	fm	52.7	42.5	43.5
FeO	9.45	6.96	9.88	Σ sal	56.88	68.27	61.93	c	19.6	19.2	20.8
MnO	0.17	0.16	0.17	di	3.79	0.40	4.99	alk	5.4	11.7	10.6
MgO	9.31	3.66	4.20	hy	18.80	12.00	19.59	k	0.18	0.31	0.24
BaO	n.d.	0.02	0.04	ol	12.02	—	—	mg	0.58	0.36	0.38
CaO	8.30	6.32	7.28	mt	3.82	6.88	3.17	ti	1.34	7.72	5.73
Na_2O	2.06	2.94	3.11	il	1.53	6.87	5.43	p	0.12	0.92	0.87
K_2O	0.68	2.02	1.49	ap	0.30	1.82	1.82				
P_2O_5	0.12	0.76	0.77	fr	0.05	0.48	—				
S	0.08	0.05	0.15	pt	0.15	0.10	0.29				
F	0.04	0.30	0.06	Σ fem	40.46	28.55	35.29				
H_2O^+	2.38	2.30	2.22								
H_2O^-	0.16	1.14	0.54	$+H_2O$	2.54	3.44	2.76				
Sum:	99.94	100.33	100.04	Total:	99.88	100.26	99.98				
−0 for S,F	0.04	0.14	0.08								
Total:	99.90	100.19	99.96								

All analyses have been made at the Geological Survey of Sweden. (See Lundegårdh and Lundqvist 1954 and 1959).

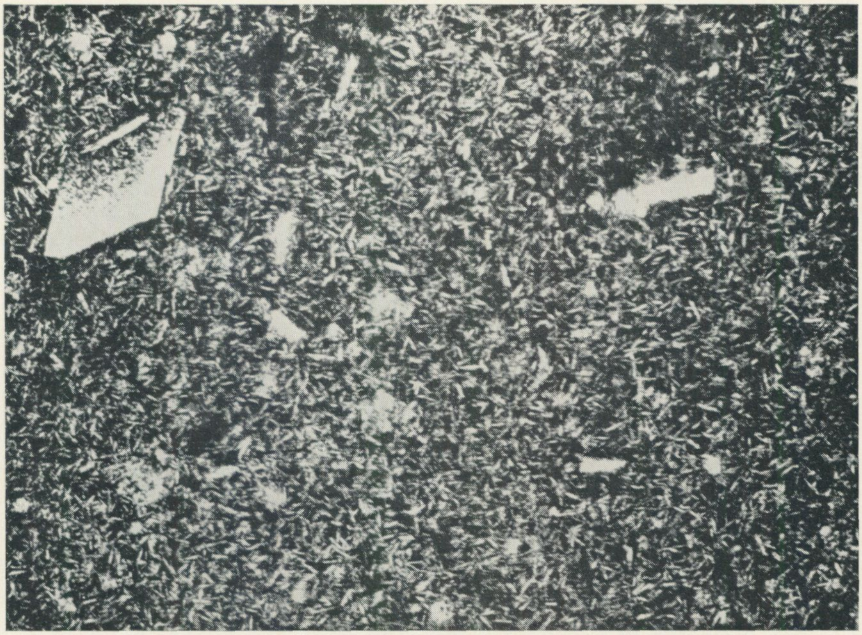

Fig. 12. Dolerite with glassy groundmass. 4 km N of Österby. || nic., 35 ×.
Photo R. Gorbatschev

each about 10 m wide, three of which are rich in plagioclase phenocrysts; the Nytorp dike is 4 m across, while the width of the rest ranges between 20 and 40 metres. In addition there are many satellite and other narrow porphyrite dikes.

Fig. 14 shows a rather characteristic porphyrite from a locality 300 m WSW of Fiskartorp in the Fiskartorp dike. The volume percentage of phenocrysts in the dikes here listed usually amounts to between 25 and 40, the most common size of the chunky feldspar prisms ranging between 0.5 and 2 cm. Larger crystals occur, the biggest on record being found in the Rymmaren dike and measuring in length about 20 cm. Crystals larger than 5 cm are, however, comparatively scarce. Continuous or oscillatory zoning is restricted to the fringes of the phenocrysts or may be altogether absent. The phenocryst cores have An percentages between 62 and 75, while the narrow rims, when most sodic, are a labradorite of about 55—60 % An, which is also the composition of the often zoned laths of groundmass plagioclase, which attain lengths of between 1 and 3 mm. Broken and crushed phenocrysts are occasionally encountered, as are contorted cleavages, translation planes etc. All these phenomena are older than the zoned rims and have thus been generated during the eruption of the magma or movements in the magma chamber.

Whereas the total percentage of plagioclase in some porphyrite dikes (notably the Rymmaren and some parts of the Gåstorp dikes) is higher than in the dolerites, numerous volumetric measurements demonstrate that this is not necessarily the case. The relative impoverishment of the groundmass in plagioclase is sometimes perceptible and is demonstrated quantitatively by the volumetric analysis of the Fiskartorp porphyrite, the data found in Table 1 being mean values of volumetric analyses from three different localities. This feature together with the absence of zoning except in narrow fringes indicates an origin of the porphyritic texture by tranquil crystallization and subsequent eruption followed by rapid cooling. The occasional olivine phenocrysts and the presence of crystals of this mineral and pyroxene as inclusions in the plagioclase phenocrysts also support this suggestion. The tranquil initial crystallization in other cases permitted an accumulation of plagioclase in the top portions of the magma thus giving rise to dolerite porphyrites extremely rich in plagioclase and the anorthositic rocks described below. There is generally no relation of size between the phenocrysts on the one and the coarseness of texture and width of dike on the other side (cf. Fig. 15). Flow textures and preferred orientations of the long axes of plagioclase phenocrysts appear in some rocks, especially in dike margins.

No recognizable orthopyroxene is present in the rocks considered here. The augite of the dolerite porphyrites is rather like that of the dolerites and has the optical properties $c \wedge \gamma$ 41—46°, 2 V_{γ} 37—45°, dispersion $r > v$, colourless or greyish to very faintly green. The textural plagioclase/pyroxene relationship is usually subdoleritic to subophitic. Ophitic textures *sensu stricto* are found only in oliviniferous porphyrites. Alteration of pyroxene to chlorite, uralite, and serpentine is common.

Fig. 13. Granophyric dolerite, the Gåstorp dikes. + nic., 58 ×. Photo R. Gorbatschev

Fig. 14. Dolerite porphyrite of the Fiskartorp dike. 300 m WSW of Fiskartorp. About $^1/_4$ nat. size. Photo P. H. Lundegårdh

Only one dike provides large quantities of unaltered olivine. This is the fine-grained porphyrite ENE of Fiskartorp, not very rich in plagioclase phenocrysts. The olivine is here only weakly altered, the textural relations are similar to those of the normal olivine dolerites. In addition this porphyrite carries olivine phenocrysts measuring 2—4 mm across.

Olivine pseudomorphs of the kind described in a previous chapter (p. 10) are, as a rule, common in the rest of the porphyrite dikes. Quartz is rather sparse and often occurs in the shape of interstitial micrographic intergrowths with alkali feldspar. No rocks warranting the name of quartz-rich porphyrites were encountered. As mentioned before, however, there are occasional feldspar phenocrysts in the quartziferous dolerites of the preceding chapter.

The minor and accessory minerals of the porphyrites are those given for the normal dolerites described above.

Anorthositic rocks

Anorthosites and anorthositic dolerites are found in some of the Gåstorp dikes, where the rock-type ranges from glomeroporphyrites very rich in phenocrysts (Fig. 16) to compact anorthosites. The latter form fragments that vary in size from a few cm to a metre or more, and are enclosed in porphyrite and dolerite. The rock consists of about 90 vol.-% euhedral or broken euhedral, short chunky plagioclase crystals measuring between 0.5 and 2 cm in diameter and compacted by a sparse intergranular mass of clinopyroxene and olivine or pseudomorphs of these minerals. The An percentage of the plagioclase ranges from 69 to 73, dropping to between 60 and 65 in the narrow oscillatorily and sometimes normally zoned rims surrounding some of the broken as well as unbroken crystals. The plagioclase may be altered to clinozoisite and sericite, but this alteration is never very complete. Inclusions of olivine pseudomorphs and pyroxene crystals are occasionally found inside the feldspars. There is also some serpentine veining of the latter mineral as well as narrow uralite-chlorite rims at the contact between the plagioclase and the marginally often uralitized interstitial augites (Fig. 17). The augite is a colourless one, optically equivalent to the clinopyroxene of the olivine dolerites. Accessories are ore, biotite, and apatite, the latter being very scarce.

While some of the anorthositic rocks are merely glomeroporphyric accumulations of plagioclase phenocrysts, others form a breccia in the often quartziferous slightly granophyric surrounding dolerite. The contact relations and outlines of the anorthosite fragments and their mineral composition show that the rock had completely solidified previous to being intruded, broken, and carried into its present position by the dolerite. Also, in this Gåstorp dike the dolerite is thoroughly uralitized whereas the anorthosite is only very slightly so.

The anorthosites must be considered to be early differentiates of the dolerite magma, since their field relations prove them to be older than any of the other dolerite types of the Gåstorp dikes. Also their paragenesis of calcic plagioclase, olivine, and clinopyroxene qualitatively equals that of the olivine dolerites and assigns the anorthosites to an earlier stage of differentiation than that of the rest of the Gåstorp dolerites. The anorthosites have apparently formed by gravitative accumulation of early crystallized plagioclase in the top portions of the magma chamber, where parts of the crystal mush had opportunity to solidify trapping some pyroxene and olivine between the plagioclase crystals before being disrupted and displaced by several succeeding surges of the dolerite magma, which gradually, by differentiation and wall-rock absorption, evolved toward granophyric types. The occurrence of anorthosites in the Eskilstuna dolerite suite is important, since it demonstrates that gravitative differentiation processes previous to extrusion were prominent in the development of the different dolerite types. The mineral composition coupled with the field association of the anorthosites further links the olivine dolerites to the quartziferous members of the basic dike series, thus providing evidence of an unbroken evolutionary development and a single original magma of the succeeding melts.

Composite dikes

Dolerite dikes embracing several rock types number about half a dozen, the Kvarnviken and Gåstorp dikes being the largest and most diversified.

In addition to the anorthosite described above the Gåstorp dikes are composed of porphyrite of the common type, dolerite with abundant olivine pseudomorphs, olivine-free slightly quartziferous dolerite, granophyric dolerites, and a light rock here described as leucodolerite. The porphyrite and the olivine-pseudomorph-bearing dolerite are the two main early rocks passing into each other via slightly porphyritic varieties with an unhomogeneous distribution of feldspar phenocrysts. The quartziferous and granophyric dolerites are clearly younger than these rocks, forming either small veins with chilled borders fil-

Fig. 15. Fine-grained porphyrite with aphanitic rim and coarse feldspar phenocrysts. The Gåstorp dikes. Photo R. Gorbatschev

ling cracks in the two earlier varieties, or constituting the bulk of some dikes, then containing fragments of anothosite and porphyrite (Fig. 18). The leucodolerite, which is petrographically described in another chapter, outcrops SW of Gåstorp, where it is found to be younger than the quartziferous dolerite, the field relations of these two rocks toward the porphyrite at the locality near Gåstorp in other respects being similar (Fig. 19). The total amount of leucodolerite is very small, this rock forming a few crack-filling veins in the other members of the intrusive suite.

The Kvarnviken dike is composed of dolerite-porphyrite of the customary olivine-pseudomorph-bearing type and of a somewhat quartziferous non-porphyritic variety of pyroxene-uralite-dolerite in addition to which there are numerous, rather small dikes of granophyre. The Kvarnviken dolerite differs from the rest of the olivine-free dolerites in carrying a subordinate amount of macroscopically sorrel orthopyroxene. The An percentage of the plagioclase is in unaltered varieties about 60; there are generally but very few or, in large portions of the rock, no olivine pseudomorphs. The porphyrite occupies all the

Fig. 16. Dolerite porphyrite very rich in phenocrysts. The Gåstorp dikes. One division of the scale is 1 mm. Photo G. Andersson

offbranching apophyses and the margins of the main dike leaving the central parts of this body to the non-porphyritic dolerite. Except for one single poorly exposed locality of not very conclusive field relations, no sharp border is found to separate these two rocks. The ground is, however, heavily moss- and thicket-covered and large portions of the rock are affected by later alterations, but even so there apparently were no two separate intrusions, the ascending magma instead gradually changing composition so as to produce later non-porphyritic quartziferous types in the central portions of the dike, where the flow of the melt presumably continued for a longer time. Immediately thereafter and still before the rock had time to solidify completely, there followed a surge of silica-alkali-rich emanations and volatile-rich rest-melt effecting very thorough uralitization, epidotization, and some albitization of the dolerite, also producing innumerable veinlets and microscopic patches of micropegmatite. While this alteration predominantly affected the central non-porphyritic dolerite, it did not halt at the transitional borders with the contiguous porphyrite, but locally also inoculated that rock with secondary minerals. The situation in the Kvarnviken dike is further complicated by the proximity of large faults accompanied by zones of brecciation and retrograde epidote-chlorite metamorphism in the dolerite accompanied by the introduction of additional migratory potassium and silica. The outcrops by Kvarnviken Bay thus almost exclusively consist of a heavily crushed and altered reddish-green uralite-epidote-chlorite-micropegmatite-ore rock with very few remains of the original minerals of the dolerite.

In addition to diffuse impregnation and veinlet occurrence, micrographically intergrown quartz and feldspar also form comparatively large (more than 0.5 m across), persistent dikes filling cracks and often aligned to zones of dislocation in the dolerite (Fig. 20). The predominant direction of strike is at right angles to the trend of the Kvarnviken dike, the dip is varying, but mostly steep. Occasionally the granophyre dikes continue for some distance into the wallrock.

Contacts and Inclusions

The contacts between the dolerites and the country rocks (gneisses) are usually quite sharp and distinct. Low-grade contact influence is macroscopically perceptible as zones of hornfels or discoloration some centimetres broad. For medium-sized (5 to 20 metres broad) olivine dolerite and porphyrite dikes the width of the contact belts is about 1 % of the width of the dikes. Microscopic examination demonstrates an enrichment of the contact belts in quartz and the formation of clinozoisite and chlorite at the expense of the original minerals of the gneiss. In the macroscopically intact gneisses adjoining the low-grade contact belts, quartz is the first mineral to show signs of contact influence. The quartz grains are granulated and recrystallized, losing the strain shadows abundantly present in the wallrock. The accumulation of the quartz

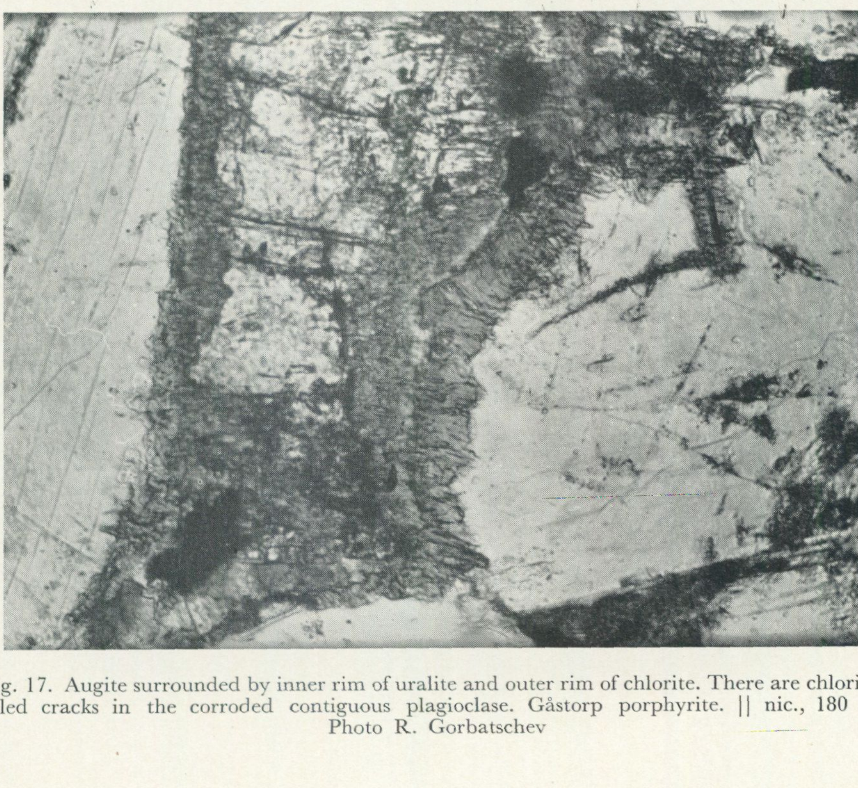

Fig. 17. Augite surrounded by inner rim of uralite and outer rim of chlorite. There are chlorite-filled cracks in the corroded contiguous plagioclase. Gåstorp porphyrite. || nic., 180 ×. Photo R. Gorbatschev

into distinct streaks and the heavy corrosion of feldspars indicate an early mobilization of the silica. In the immediate neighbourhood of the dolerites there usually are narrow zones composed of quartz enclosing clinozoisite prisms and radiating clinozoisite clusters. In parts of the hornfels zone the arrangement of the clinozoisite crystals reproduces the original shape of the destroyed plagioclase grains, this texture disappearing as the dolerite dikes are approached. In the plagioclase of the gneiss there is first a general development of sericitic mica followed by the formation of clinozoisite and the recrystallization of the sericite into fairly large muscovite flakes. New albite is formed in some cases, but never in any great amount. Twinning and perthitic structures are destroyed and there may or may not be complete granulation of the plagioclase grains. The content of potash feldspar in the gneisses starts diminishing early in the process of contact metamorphism; the microcline of the gneisses was never found to be appreciably sericitized, but the formation of sericite in the plagioclase accounts for part of the potash derived from the destroyed microcline, especially the microcline of the ancient perthite lamellae. In most investigated specimens, the potash feldspar had recrystallized to develop untwinned microcline rims at the border between plagioclase and quartz, in some cases enveloping the former mineral in complete, though narrow, mantles of potash feldspar. The potash of these rims seems partly to be derived from the ancient perthite lamellae or by unmixing from the plagioclase. In contact belts of this low-grade type micrographic intergrowths are absent or very scarce. The ferromagnesian minerals of the gneiss have altered into chlorite in the distant, and into iron ore plus epidote in the proximal parts of the contact metamorphic zones. This type of contact did not involve a complete remelting of the wallrock, but the migrations of the elements were considerable and, as far as can be judged from mineralogical data, of the order potassium > sodium >silica > calcium. This represents the apparent net displacement of the chemical constituents which depends on diffusion constants, concentration gradients, bond-breaking energies, solubilities etc., and should not be confused with the migration abilities or velocities of the elements replaced. Iron and probably also some calcium and sodium were introduced from the dolerite melt. Optical data show that the iron content of the clinozoisite is highest at the contact and diminishes both in more distant parts of the wallrock and in the clinozoisite formed at the expense of the plagioclase of the dolerite. Chlorite is always found some distance away from the dolerite contact and this being so, the formation of chlorite from the dolerite pyroxenes must, in the cases investigated, be subsequent to the cessation of chlorite formation in the contact metamorphic zones of the wallrock. The dolerite in the immediate vicinity of the contacts is often contaminated with micropegmatite or quartz. Biotite is not produced by this type of contact alteration. The following compilation gives the mineral composition and order of alterations in a typical section through the contact belt of the Fiskartorp porphyrite 300 m N of Bälgviken:

1. 30—35 cm away from the contact. Incipient saussuritization and considerable sericitization of the oligoclase-andesine of the gneiss. There are granulated

Fig. 18. Anorthosite fragments in dolerite, the Gåstorp dikes. Photo R. Gorbatschev

patches of plagioclase, albite, clinozoisite, and microcline inside some of the plagioclase crystals. The quartz has been considerably recrystallized and has started to replace the plagioclase. There are narrow fringes of albite and microcline at the borders between the quartz and the andesine. Biotite has altered to chlorite. Clinozoisite and quartz fill a few narrow cracks. Mineral composition (volume %): quartz 40, plagioclase 26, microcline 20, sericite 4, biotite and chlorite 6, clinozoisite 3, ore 1.

2. 20—25 cm away from the contact. The plagioclase is very considerably saussuritized and penetrated by quartz. Plagioclase twinning and perthitic structures are almost completely destroyed. There is some plagioclase granulation, the sericite recrystallizing into large muscovite grains. Sericite rims are prominent around the plagioclase patches. Most of the quartz has been displaced and has accumulated in distinct streaks and large multigrain fields. All biotite has been completely chloritized. Mineral composition: quartz 37, plagioclase and albite 20, microcline 6, sericite and muscovite 17, clinozoisite 15, chlorite 4, ore 1.

3. 5—10 cm away from the contact. The rock is now a very fine-grained quartz-clinozoisite hornfels with a few grains of chlorite and ores. All feldspar is gone, but the arrangement of the clinozoisite patches reproduces the shape of the original plagioclase grains. Original quartz areas are free from clinozoisite. There is some schistosity parallel to the contact. The rock carries numerous quartz veins. Mineral composition: quartz 70, clinozoisite 29, ore and chlorite 1.

4. Contact line. Compact quartz-clinozoisite hornfels with quartz-filled

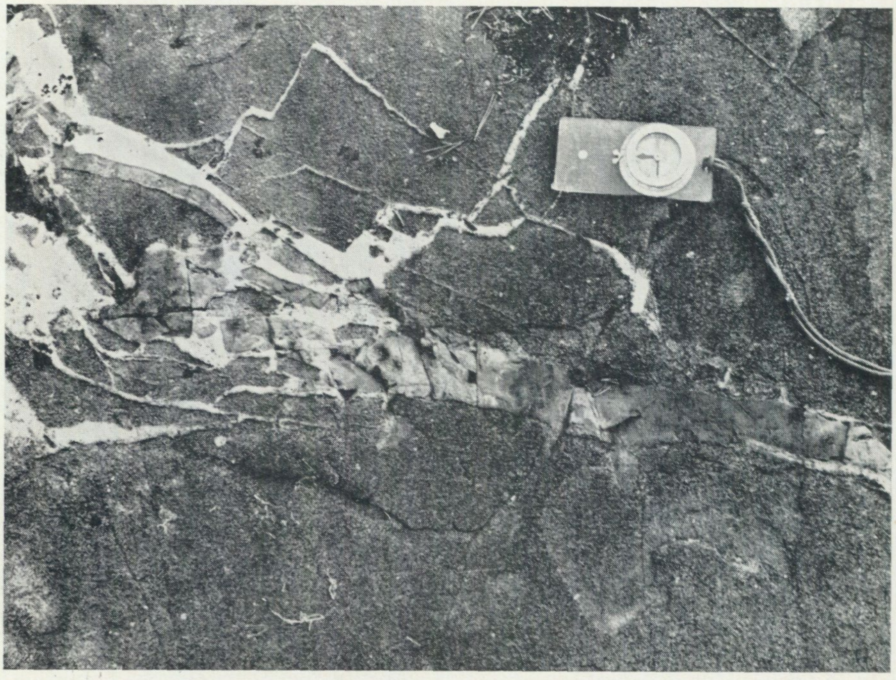

Fig. 19. Dikelets of fine-grained quartz-uralite dolerite (pale grey) and leucodolerite (white) in medium-grained somewhat porphyritic pyroxene dolerite. The Gåstorp dikes. Photo R. Gorbatschev

cracks. In the porphyrite we meet with large rectangular clinozoisite patches pseudomorphous after plagioclase phenocrysts, but there is no suggestion of an original ophitic texture. Mineral composition: quartz 16.5, clinozoisite 78, ore 5, chlorite 0.5.

5. 20 cm inside the dolerite. The porphyrite has altered to a clinozoisite-chlorite-quartz rock. The original ophitic texture is suggested by the arrangement of the clinozoisite which forms divergently radiating laths in a groundmass of chlorite. There is some interstitial micropegmatite. Mineral composition: quartz and micropegmatite 10, clinozoisite 48, chlorite 37, ore and leucoxene 5.

A somewhat more thorough type of alteration is represented by the contacts of a number of dolerites in the 30 metres and more width class and also by fragments of country gneisses included in some narrower dikes, *e.g.* one of the Gåstorp porphyrites. Here the inner parts of the fragments or the distal parts of the contact belts display the mineralogical features described above including alteration of plagioclase, recrystallization of quartz, and disappearance of microcline. In inclusions of the Gåstorp dike there are quartz droplets in the interior parts of the altered plagioclase grains. This quartz always forms groups of 4 to 20 droplets of identical optic orientation, each of the large gneiss plagioclases containing several quartz droplet groups. The transition of the country rock into dolerite is rather gradual, the mineral association of the contact belts consisting of micropegmatite, quartz, amphibole, epidote, and clinozoisite. There is almost no unaltered feldspar except in micrographic intergrowths.

Still more intense contact alteration is found in the palingenic-dikes type of contact. The best example of this is the Kvarnviken dike. Other examples are displayed by the contacts of the dolerite dike N of Djupvik, parts of the Ökna dike, and a few occurrences N of Forskilen. Here we find no hornfels zones rich in quartz, though the alterations in the gneiss are to begin with much like those described above. Between the fine-grained or aphanitic contact dolerites and the gneisses there are zones of irregularly micrographic rock some cm or dm broad and apophyses of micropegmatite projecting into the dolerite. In the aphanitic endocontact dolerites the boundaries of the acid veins are usually cleancut and sharp, but they become increasingly more sinuous and diffuse in the micropegmatitic veins extending into the central parts of the dolerite dikes. In some cases the acid veins fail to penetrate the aphanitic dolerite contacts. The thickness of the palingenic veins ranges between 0.2 and 5 cm, the grain-size is fine, and the constituent minerals are quartz, albite, perthites, orthoclase, epidote, together with some ore, apatite, sphene, biotite, and chlorite. The dolerite environment of these veins is more or less sericitized, saussuritized, and chloritized. The contact between the palingenic veins and the dolerite is often marked by large crystals of iron-rich epidote and green flakes of chlorite. The texture of the palingenic dikes is always more or less micrographic. However, the quartz-feldspar intergrowths have a patchy distribution and are likely

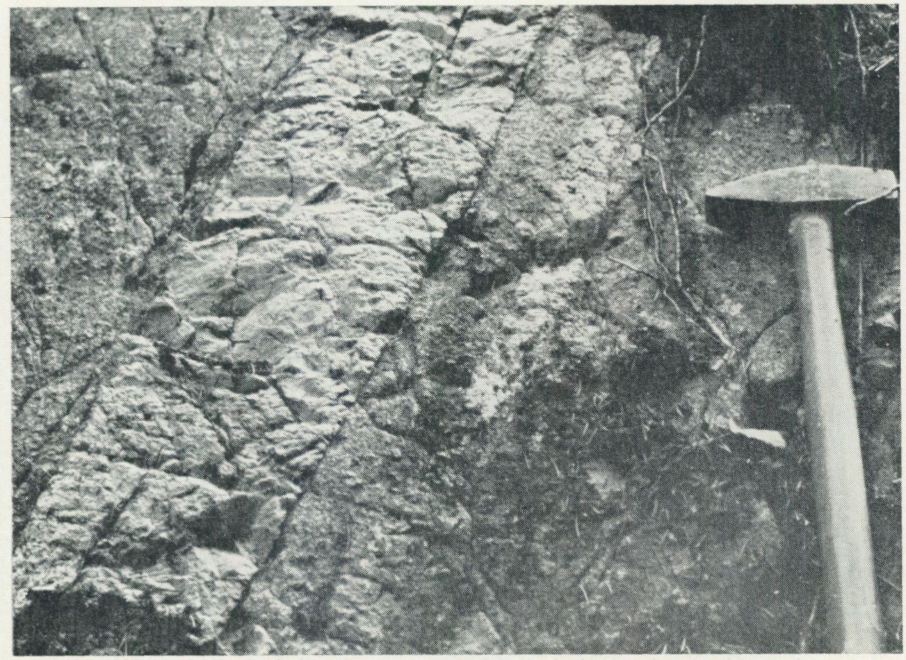

Fig. 20. Granophyre dikes in the Kvarnviken dolerite NE of Näshulta sawmill. Photo R. Gorbatschev

to be much more irregular than the micrographic texture of the granophyre dikes described in the next chapter. A hybrid-rock contact between gneiss and dolerite was found at the S boundary of the Kvarnviken dike WSW of Näshulta sawmill. The hybrid forms a belt or lens between the gneiss and a dolerite which lacks aphanitic borders. The hybrid rock is fine- to medium-grained and consists of divergently radiating or trachytoid andesine and amphibole laths set in quartz and alkali feldspar of a rudimentary and comparatively coarse micrographic texture. In the andesine laths there are groups of minute clinozoisite grains. The amphibole is somewhat chloritized and partly replaced by feldspar and quartz.

Concerning the age relations of dolerite solidification as against contact palingenesis, mixing of the two melts occurs only in narrow zones along the contacts and in some sinuous veins extending into the interior of the dolerite dikes. In the latter case, however, the mineral relations prove that much of the dolerite was partly crystallized before coming into contact with the palingenic material. The remelted gneiss could invade the interior parts of the dolerite dikes first after the development of contraction cracks in the fine-grained dike margins. This agrees well with the results of Kahma's (1951) detailed investigation of the contact relations of the Finnish Satakunta dolerites.

Palingenic action under different circumstances is indicated by the impregnating acid material in the interior parts of the Kvarnviken dolerite. Even if there are similarities with the processes evoked by the large palingenic-contact-veins, the mode of emplacement of the alkalies and silica here demonstrates an original remelting under conditions of considerable superheat, thorough mixing with parts of the dolerite melt, and enrichment with the volatiles of the dolerite rest solutions. It follows that much of this palingenic material must have been generated at greater depths under conditions eliminating the obstacle of rapidly crystallizing aphanitic dolerite rims.

Leucodolerites and Acid Vein Rocks

The rock described as leucodolerite occurs in veins 0.5 to 20 cm across, filling fractures in a pyroxene dolerite dike belonging to the Gåstorp group. The leucodolerite also cuts across dikes of uralitized fine-grained dolerite younger than the pyroxene dolerite (Fig. 19). Though there are partly resorbed inclusions of gneiss in the dolerite dike containing the leucodolerite, there exist no obvious interrelations between inclusions or contacts and the leucodolerite veins. In view of the lack of a chemical description the choice of the term leucodolerite is due to its convenience in describing the leucocratic character of the rock in question, and in marking its textural and compositional relationship with the dolerites. A rather similar term (leucodiabase) has previously been used by a number of authors for a special rock association believed to be characteristic of the Karelidic belt of Fennoscandia (cf. Padget 1959). Even if there are some mineralogical and textural similarities between these rocks and the Eskilstuna leucodolerite, no chemical, tectonic or genetic relations whatsoever are suggested to exist between the two.

The leucodolerite is a fine-grained greyish-white rock of distinct and persistent composition and texture. It is composed of divergently radiating albite laths set in a groundmass of intergrown quartz and perthitic alkali feldspar (Fig. 21). The type of intergrowth can be described as a variety of the micrographic texture, but the quartz blebs most frequently have rounded outlines and the mineral is more abundant than in the common type of granophyre symplectites. Normal micrographic texture is found in a few small patches; on the other hand the leucodolerite texture ranges to mosaics of optically independent quartz and alkali feldspar grains. The boundaries between the albite laths and the interstitial perthite are either straight or sutured, the latter being the rule. There also exist gradual transitions between the two kinds of feldspar. The dark minerals are lath-shaped crystals of green hastingsitic amphibole, biotite, green chlorite (partly an alteration product of amphibole and biotite), and some sphene. Calcite is a constant ingredient amounting to between 3 and 5 % of the volume. Apatite is a common minor mineral. A few stray oxide ore grains complete the list of leucodolerite minerals. In most dikes there are also small myaroles and vugs completely or partly filled with quartz.

Granophyre veins occur in a number of dolerite dikes, the best examples being found in the Kvarnviken dike. These are fine- to medium-grained red rocks distinguished by nicely regular micrographic quartz-feldspar intergrowths (Fig. 22). In comparison with the leucodolerites the granophyres appear to be

Fig. 21. Leucodolerite from the Gåstorp dikes. Albite and amphibole laths are enclosed in quartz-antiperthite-symplectites. + nic., 36 ×. Photo R. Gorbatschev

considerably more potassic and are characterized by richness in clinozoisite or epidote, but carry very little or no calcite. The amphibole, biotite, and chlorite are similar to those of the leucodolerite, but in addition there are rosettes of brownish chlorite emanating from the intergranular boundaries. The feldspar is commonly heavily stained with reddish hematite dust. Quartz- and chlorite-lined myarolic cavities were found in many granophyre occurrences. The mineralogical similarities between the dike granophyres and the granophyric contact veins (cf. p. 29) are considerable, the space relations in some cases definitely indicating a common origin. In other cases the granophyres may be generated by rest solutions of the dolerite magma, or there may have been an intermixing of material from the two sources. The relative abundance of sphene and apatite is rather suggestive of the latter possibility. The leucodolerite has mineral proportions persistent throughout the several veins and is on this evidence and on account of its more sodic composition not considered to be a product of dolerite-wallrock interaction, but rather a late sodic differentiate of the dolerite magma.

Age and Tectonic Relations

With the exception of the fact that the Eskilstuna dolerites are much younger than the formation of the surrounding Svecofennian bedrock, the geological features of the investigated area offer no direct clues for the determination of their exact age.

As is shown in Fig. 1, the dikes predominantly follow E—W striking zones of fissures and thus run roughly parallel to the general trend of strike in the Old Archaean rocks of the Eskilstuna region (Lundegårdh and Lundqvist 1959, pp. 46—51). The E—W fault and fissure system was formed very early and coincides with lines of mechanical failure dating back to the Svecofennian orogenic period, which is proved by the existence of migmatized east-westerly zones of dislocation. Movements along these planes of weakness have taken place both in connection with and subsequent to the emplacement of the dolerites, evidence of which statement is provided by breccias and tectonically altered zones in the dolerite dikes. The Mälarmården and Hjälmaren faults responsible for the downthrow and preservation of the Cambro-Silurian rocks of Närke (30 miles W of Eskilstuna) predominantly follow this system of fissures, though also utilizing zones of breakdown that have other directions (NW, NE) and ages of origin. The second main fault and fissure system of the Eskilstuna region trends NW to WNW, and according to systematic measurements in the S part of the map-sheet, displays a dip maximum of about 70° toward SW. These faults are responsible for the topography of much of the province of Södermanland, and together with the E—W fissures they determine the shape of most outcrops in the S and SW parts of the Eskilstuna region. Zones of dislocation striking in more or less N—S directions are occasionally accompanied by quartz-healed breccias and form persistent valleys traversing the whole of the Eskilstuna region. Movements along these fissures

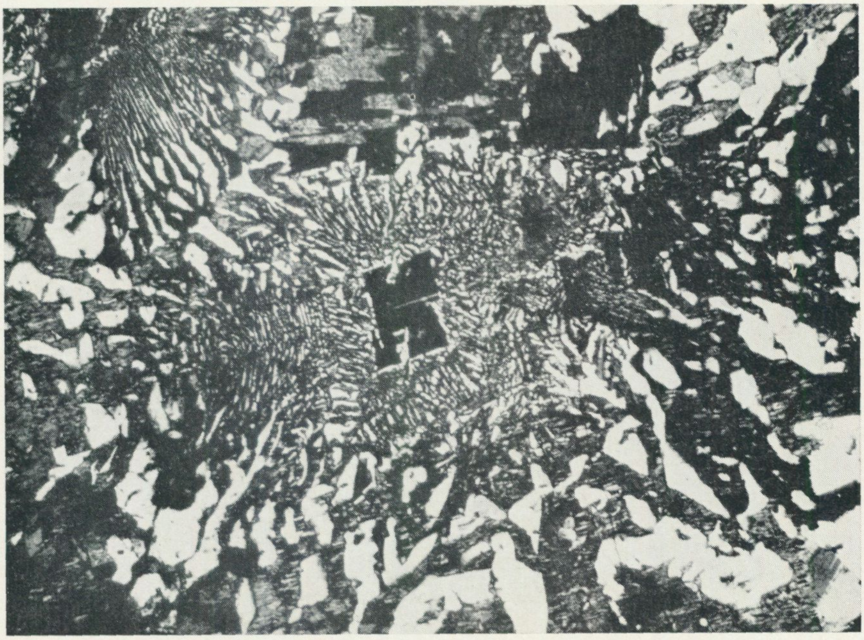

Fig. 22. Fine-grained granophyre. The Kvarnviken dike, 1.5 km W of Näshulta sawmill. + nic., 35 ×. Photo R. Gorbatschev

have taken place in post-dolerite times, but fail, as far as the Eskilstuna region is concerned, to cause any larger dolerite dike dislocations. When meeting this set of faults some of the dolerites are transformed into clinozoisite-sericite-quartz-chlorite-fels with patches of serpentine and talc. A good example is found 300 m N of Bälgviken station.

The hypabyssals are further aligned with the NW—WNW system of fissures, a lot of dolerite apophyses to large dikes following this direction. Examples are found *e.g.* at Näshulta sawmill, where the Kvarnviken dike sends apophyses into the zone of dislocation stretching from Lake Hjälmaren to the lake NW of Näshulta church.[1] In addition, in the SE parts of the investigated region and still more off the S boundary of the map Fig. 1, there is a marked tendency for many dolerite dikes to follow the NW—WNW rather than the E—W system of fractures. Again, in post-dolerite times there has been considerable dislocation along the Näshulta sawmill fault and other parallel faults. These activities have caused the formation of quartz-healed breccias and mylonites in the Kvarnviken dike. The Eskilstuna region further provides numerous other instances of dolerite dikes dislocated by faults belonging to the NW system, which also applies to the large Hällefors and Breven dikes (Krokström 1936a, p. 255). Considerable post-Jotnian movement along these fis-

[1] S of the Kvarnviken dike there is a system of satellite dolerites following WNW and ENE fissures opened by normal stress during the forcing apart of the Kvarnviken dike fissure (cf. the map Fig. 1). In part these fissures coincide with preexisting WNW zones of mechanical failure.

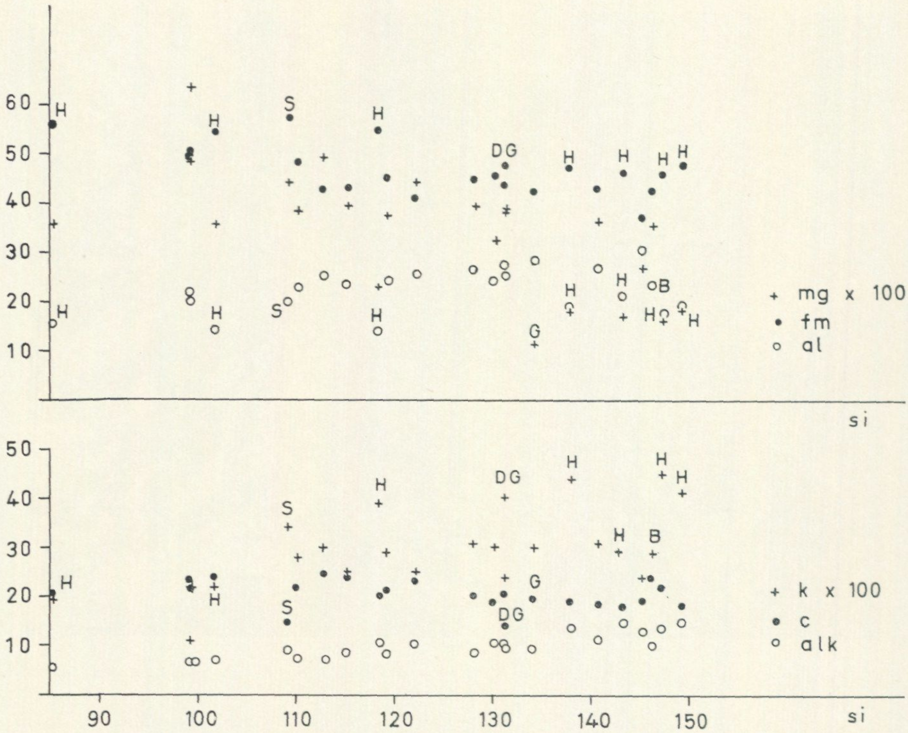

Fig. 23. Niggli diagram of Södermanland, Breven, and Gävle dolerites. H = rocks of the Hällefors central series, DG = glassy dolerite of Djupvik, S = Sandvik-, G = Gävle-, B = Breven central dolerite.

sures is furthermore demonstrated by the tectonics of the Jotnian Mälar sandstone outcropping just W of Stockholm (Gorbatschev and Kint, 1961). The present investigation thus confirms Asklund's (1923) opinion, according to which the original formation of the NW fissures is older than the east-westerly dolerites of Södermanland, but, as can be inferred from the relative amounts of dislocation in the dolerites and the contiguous rocks, the greatest amount of movement has frequently been of post-dolerite time.

Since dislocation along both the E—W and the NW—SE striking fault groups has occurred during pre- as well as post-dolerite periods, and because the origin of the E—W zones of mechanical failure can be demonstrated to be a very early one, no solution of the age of the Eskilstuna dolerites can be negotiated on the base of relative dike-fault age. In his paper on the fault tectonics of the country S of the Lake Mälaren basin Asklund (1923) has undertaken to show, that the NW-striking so called "bronzite"-dolerites are of sub-Jotnian age and older than the oliviniferous E—W dolerites of Södermanland, thus being closely related to the sub-Jotnian basic hypabyssals of, *inter alia,* Southern Finland ("ossipites", cf. Sederholm 1934). Accepting Asklund's principal divisions, later confirmed by numerous other investigators, it should be noted, however, that several of the mineralogical and petrographical features then considered to distinguish the sub-Jotnian dolerites are also the property of Jotnian and post-Jotnian rocks. Thus the mere presence of porphyrites, late acid differentiates, and autometasomatic alterations cannot, at least as far as the Södermanland dolerites are concerned, be attributed any diagnostic value at all, even if the acid rocks here in part are due to the remelting of wallrock. This is claimed by Krokström (1936a) for the Breven granophyre — a decision which was severely criticized by von Eckermann (1937). A consistent mineralogical difference between the Eskilstuna and the "bronzite"-dolerites is the absence of pyroxene-porphyritic varieties of the former. To use the term of Tomkeieff (1940) the sub-Jotnian rocks thus probably have a higher pyroxene ratio. The sub-Jotnian rocks often carry pigeonite with small axial angles (Wahl 1906) as contrasted to the augitic pyroxenes of the Jotnian Åsby and related dolerite types. The space relations of the ortho- and clinopyroxenes in the Eskilstuna dolerites, however, suggest the original presence of pigeonite (cf. p. 7), and thus this mineral, even if probably never attaining a dominant position, might well be expected to enter varieties formed at different depth levels under different crystallization conditions.

Very few data are available on the chemical characteristics of the sub-Jotnian rocks of Southern Central Sweden and particularly the areas here concerned with. While there are detailed investigations on some dolerites or differentiated basic hypabyssals and although chemical data have been utilized as a basis of correlation, no comprehensive work on the chemical composition and especially on the amount and significance of deviation within and between the different groups, has so far been attempted on a quantitative basis.

It is probable that the customary division of the dolerites into oliviniferous Jotnian plus post-Jotnian and tholeiitic sub-Jotnian groups is not strictly valid; according to some authors (Savolahti 1956, v. Eckermann 1936, 1937) there are olivine dolerites older than the sub-Jotnian rapakivi granites and acid porphyritic eruptives, v. Eckermann (1936) even reporting the existence of several early generations of olivine dolerite. The chemically rather uniform olivine dolerites must thus seriously be reckoned to range in age from the sub-Jotnian to the Paleozoic.

The analyzed Eskilstuna pyroxene dolerite (Table 2, p. 18) has pronounced chemical similarities with its nearest neighbour N of Eskilstuna, the dolerite at Löt of the Västerås map-sheet. The latter rock is genetically associated with the Granholmen dolerite situated in Jotnian sandstones and traversed by sandstone-filled cracks, its age thus being Jotnian (Lundegårdh and Lundqvist 1954). The mineralogical and textural difference between the Västerås and Eskilstuna rocks is easily explained by different levels of crystallization, the blocks S of Lake Mälaren being elevated in comparison with the Granholmen area. The olivine dolerite of Eskilstuna (analysis in Table 2, page 18) is, as far as chemical evidence is considered significant, related to the other Södermanland olivine dolerites. As was stressed above there is a continuous gradation of type between the different dolerites of the Eskilstuna region.

Fig. 23 is a plot of the Niggli parametres of the chemically analyzed dolerites of Södermanland, Breven and Gävle. The Södermanland dolerites of this review include the Eskilstuna, Västerås (Lundegårdh and Lundqvist 1954), Hällefors (Krokström 1936a, Kugelberg 1864), Äs (Sidenbladh 1864), Sandvik (v. Eckermann 1934), Djupvik (Åhman 1956), and Karta and Askholmen (Palmgren 1874) rocks. As is seen from the compilation most of the dolerites chemically form a continuous variation series joining the trend of the "deviating rocks" of Krokström's Hällefors-Breven array (1936a, Figs. 28, 29, and 30). The central Hällefors series in comparison shows consistently lower al and mg and higher k and fm values, and thus constitutes a defined group of its own, in some respects joined by the Sandvik and glassy Djupvik dolerites. The Gävle dolerite (v. Eckermann 1925), embedded in Jotnian sandstone, fits well with the main series except for the very low mg value unparalleled in other Swedish dolerites of comparable acidity.

As was shown by Krokström (1936a) the Hällefors central series is somewhat younger than the marginal rocks, which conform chemically with the rest of the analyzed Södermanland dolerites. Whether these deviating characteristics of the central Hällefors dolerite have more than local importance and what possible significance this difference may have for age parallelization, is difficult to estimate pending a more thorough investigation of the chemical variations within other groups of Fennoscandian basic hypabyssals.

Conclusions

There is ample evidence that the dolerites of the Eskilstuna region form a continuous series ranging from olivine dolerites to quartziferous rocks. The field relations and composition of the different types suggest a gradational evolution, the degree of silica saturation generally rising with decreasing age. While many of the petrographic and tectonic characteristics are similar to those of the large Breven and Hällefors dikes, the agreement of detail is not complete. Petrographical data once more indicate, that the variability is due to the differentiation of several compositionally closely related surges of a magma giving rise to early silica-undersaturated differentiates. The appearance of porphyritic, glassy, and amygdaloidal types is a result of interaction between intrusion and crystallization conditions and is not considered to signify greatly differing ages of formation. Proof of this is the Gåstorp dike, where fragments of devitrified glassy porphyrite are found in medium-grained pyroxene dolerite.

Alongside the general trend of evolution of the magma, local crystallization differentiation may give rise to anorthositic types and presumably also other variations on the same evolutionary theme. Thus phosphorus generally has a regional tendency to concentrate in the comparatively acid types of dolerite. Within some dikes, however, there occurs an independent distribution pattern of that element, which may be accounted for either by accumulation in the late local differentiates drifting off from the crystallizing magma, or by retention in the rocks of the quickly chilled aphanitic contact facies, which thus probably approaches the bulk composition of the intruding melt. The amount of apatite is thus, on this limited scale, not necessarily a simple function of the olivine/quartz, Fe/Mg etc proportions, but must be interpreted considering the general as well as the local evolution and crystallization histories of the rock. The same presumably also applies to other elements and minerals.

A consideration of the evolution of the magma from which the dolerites of the Eskilstuna region crystallized, raises the question of whether the composition of the different varieties warrants the assumption of a common parent liquid and what the composition of the source might be. Meeting similar problems in his work on the Hällefors dike, T. Krokström holds that the original magma was undersaturated, as contrasted to the tholeiitic source of the sub-Jotnian dolerites. To account for the chemical differences between the earlier marginal oliviniferous mottled dolerite and the later Hällefors dolerite, which occupies the central parts of the dike, he suggested a mechanism of evolution by gravitative removal of early crystallizing titaniferous iron ore and apatite from a parent magma with a composition similar to that of the oliviniferous marginal rock. He was prevented from considering the oliviniferous rock proper to represent the parental magma by the textural relations of that rock. Citing Krokström: "I have previously emphasized that in these rocks the iron ore is of very late crystallization . . . (and thus) there must have been a third magma, which has been the common parent of the marginal and the central magmas" (Krokström 1936a, p. 237, cf. also Burri and Niggli 1945, pp. 340—357). Now it should be noted, that in elaborating this hypothesis Krokström compares the composition of the marginal dolerite not to the unaltered Hällefors dolerite but to the composition of the albitized rock no 205 (Krokström's analysis no 7). "The objection may be raised that the rock 205 is not quite a typical Hällefors dolerite . . . It has been pointed out, however, that it does not quite agree with the prevalent albitic rocks, and from the chemical analysis the conclusion was arrived at that it owed its special character to internal processes caused by decreasing temperature only . . . Consequently its present composition is not likely to differ very much from the primary one, and as it happens to be the most basic rock of those analysed it is most likely to give the best approximation to the original central magma" (Krokström 1936a, pp. 236—237). However, the specimen here referred to comes from a locality in the immediate vicinity of the large Svalbo Inlet fault zone, and might thus be suspected not to be completely unaffected by tectonic action and attendant redistribution of the most easily moved elements. The Svalbo rock, *e.g.*, has a content of 39.54 % SiO_2 as contrasted to 47.30 % in what Krokström states to be a typical Hällefors dolerite (Krokström's analysis no 3). However this may be in the Hällefors dike, turning to the dolerites of the Eskilstuna region, neither textural nor mineralogical evidence calls for an evolution along the lines suggested by Krokström. As was mentioned above, phosphorus is concentrated in the late differentiates, whereas titanium predominantly habitates the ores of medium age rocks (pyroxene dolerites) and enters sphene in the late acid differentiates (cf. Table 1). This agrees well with data from other intrusions of differentiated basic magma. The process of differentiation made most probable by the observed rock variation and by the textural relations and compositional evolution of the different minerals is a normal one of early crystallizing olivine and plagioclase attended by gravitative removal of the first-named and accumulation of the latter mineral in the high portions of the magma chambers. The compositional correspondence between the olivine dolerites of the Eskilstuna region and the widespread Åsby type as well as mineralogical features, for instance the considerable content of plagioclase in the oliviniferous rocks, suggests a composition for the mother melt approaching that of the olivine dolerites. This notion is given additional support by the early position of the olivine rocks as well as by the recurrent appearance of slightly oliviniferous rocks in the different dike systems. The amount of wallrock absorption and its influence on the composition of the intruding melts is difficult to estimate on the basis of the chemical data available to the author; at the present erosion level this action is rather limited affecting to a notable extent only the Kvarnviken and a few other dikes, but it seems reasonable to expect the process to be of more importance at greater depths, there collaborating in the formation of monzonitic dolerites and granophyric late differentiates.

There is quite a pronounced tendency for the different types of dolerite to form E—W trending belts of dikes: The Ökna—Gustavsberg—Forskilen—Olovslund line is distinguished by olivine dolerites, the Gåstorp—Fiskartorp—Nytorp—Rymmaren zone by porphyrites and the N parts of the investigated area by pyroxene dolerites. Though this division is not without exceptions since practically all the main types of dolerite are represented in each of the dike systems, the arrangement, nevertheless, suggests a successive opening of east-westerly zones of fractures admitting surges of melt from a magma substratum with an evolving composition of the erupting parts. A comparison between the Eskilstuna dolerites and other E—W dolerites of Central Sweden shows great similarities but also marked individual characteristics presumably depending on the slightly different evolution histories and differing times of eruption of these magmas.

While the parent melt of the Eskilstuna dolerites thus for several reasons is assumed to be an undersaturated one, the bulk composition of the Eskilstuna rocks at the present erosion level, and that of a majority of the individual dikes, is not olivine doleritic. This testifies to the considerable effect of differentiation and absorption processes in modifying the original magma of the investigated rocks. The variability and orientation pattern of these closely related dikes stresses the general necessity of caution when attributing dolerites to either of the large groups of late- and post-Archaean basic hypabyssals of Fennoscandia. Problems belonging here hardly admit a solution by the investigation of the chemical, vectorial, or fault-tectonic features of a few dikes only, but call for a consideration in its regional context of the position of the rocks investigated.

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GFF = Geologiska Föreningens i Stockholm Förhandlingar
SGU = Sveriges Geologiska Undersökning, Stockholm (Geological Survey of Sweden)

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