SVERIGES GEOLOGISKA UNDERSÖKNING

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ÅRSBOK 47 (1953) N:o 2

PETROLOGY OF THE MÖLNDAL—STYRSÖ—VALLDA REGION IN THE VICINITY OF GOTHENBURG

BY

PER H. LUNDEGÅRDH

WITH ONE PLATE

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Contents.

General Stratigraphic and Tectonic Features.

In a recent paper (P. H. Lundegårdh 1951), I have described the petrology of the Onsala peninsula south of Gothenburg in Western Sweden. I have pointed out that this peninsula is essentially composed of gneisses and gneissic granites. Furthermore, the occurrence of various greenstones, sedimentary rocks, and pegmatites has been reported.

Some twenty years ago and earlier, the bed-rock of South-Western Sweden as a whole was distinguished as the »iron-gneiss» formation on account of a considerable content of magnetite in certain varieties (part of the acid and alkaline gneisses). During its evolution, the »iron-gneiss» formation has been subjected to a number of tectonic and metamorphic actions. It is thus not surprising that highly divergent opinions regarding its genesis have appeared from time to time.

H. E. Johansson (1924 and 1931) was inclined to define the »iron-gneiss» formation as folded and flattened or rumpled products of one single magmatic differentiation. He did not, however, give any reliable interpretation of the mechanism of such a differentiation. Consequently, other opinions regarding the genesis of the »iron-gneiss» formation grew strong. Contrary to Johansson's hypothesis, these opinions also take into consideration the supra-crustal rocks (lavas, tuffs, and clastic sediments) that have been discovered in various parts of the formation.

Nowadays, we presume that a series of exogenic and endogenic processes have given origin to the bed-rock of South-Western Sweden. These processes involve weathering of pre-existent rocks, transport, sedimentation, volcanism, folding, and faulting (including overthrusts of blocks and sheets), as well as infra-crustal alterations owing to heat supply, such as re-crystallizations, migrations of ions, metasomatism, dissolutions, and magmatic activity. A short summary of most of our present petrological knowledge of South-Western Sweden will be found in a modern text-book by N. H. Magnusson (1949). Considerations regarding the orogenic evolution of this part of Sweden have also been offered by H. G. Backlund (1941). W. Larsson has published a detailed scheme of the bed-rock of Northern Dalsland and South-Western Vermland (1947, p. 322).

With certain modifications (see below), the division of the Swedish Archaean as given by Magnusson in his text-book of 1949 and in earlier papers will be used in the following text. According to Magnusson's scheme, most rocks of South-Western Sweden, and among these the main rocks of the Gothenburg-Onsala fold, should be classed as *Gothian* (Table I). Backlund's *Gotho-Karelides* comprise Magnusson's older, Gothian, and younger, Karelian cycles (compare Backlund 1941).

In my description of the petrology of the Onsala peninsula (P. H. Lundegårdh 1951, p. 197), I mentioned that the supra-crustal rocks might be divided into two series. The early series should correspond to the oldest gneiss complex of W. Larsson (1947) and has to be defined as a lower Gothian supra-crustal series. The late series should have developed simultaneously with the Åmål series, which is then an upper Gothian supra-crustal series (Table I). When I mapped the rocks of the Mölndal-Styrsö-Vallda region between Onsala and Gothenburg[1,2], I observed that the distribution of the various supra-crustal rocks (mainly gneisses and amphibolites) spoke in favour of their division into two series. Further supports were provided by the petrographical characters of certain members of the supra-crustal series. I have, however, not yet been able to prove the correctness of such a splitting of the supra-crustal series. In the petrological map (Plate 1), the same colours and signs have therefore been used for volcanics and sediments which have developed and altered similarly, the age problem having been ignored.

Basic intrusive rocks — gabbros, primary diorites, diabases and dolerites — will be found now and then in the Mölndal-Styrsö-Vallda region. Gabbros are the rarest of these, and secondary diorites (re-crystallized volcanics) have proved to be much more common than primary ones. Both groups of rocks are Gothian, whereas the diabase and dolerite cutting the bed-rock as dikes have intruded later. The big dikes running towards W-WNW seem to be Algonkian, whereas the northern to north-eastern dikes belong to the Karelian era.

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[1] In this work, I was now and then assisted by Mr L. Bergström and Mr J. Lundqvist. The petrological and structural maps have been prepared for reproduction by Mrs Elisabeth Björk.

[2] The parish of V. Frölunda W of Mölndal (see Plate 1) belongs to the territory of Gothenburg.

With few exceptions, the granites S of Gothenburg should be classed as late Gothian. Older granites may be included in the veined gneiss E of Mölndal church (see Plate 1). This rock has suffered from strong metamorphism, however. Accordingly, it has as a rule lost its primary characters. Late Karelian

Table 1.

The Rocks of the Mölndal-Styrsö-Onsala region in order from youngest to oldest. The corresponding rocks of Northern Bohuslän and Dalsland[1] *will be found to the right.*

	Mölndal-Styrsö-Onsala region	Era		Northern Bohuslän and Dalsland
	Diabase and dolerite (W—WNW)			
	Late pegmatite Youngest granite Diabase (N—NE)	Karelium		Bohus pegmatite Bohus granite Koster diabase and hyperite
	Middle pegmatite, aplite, secondary microline eyes, veined gneiss	Late Gothium		?
	Askim granite[2]			Kroppefjell granite
	Microcline-granite[3]			
	Frölunda granite[3]			Intermediate granite
	Plagioclase-granite[2]			Åmål granite
	Basic granite[2]			
	Quartz-diorite, secondary			—
	Diorite, secondary			—
	Basic and ultra-basic plutonic rocks			Diorite
Late supra-crustal series[5]	Volcanics (compare below)[4]		Åmål series[5]	Volcanics (compare below)
	Acid alkaline gneiss[6]			Felspar-quartzite
	Conglomerate (rare)			Piemontite-quartzite
	Quartzite, sandstone[7]			Conglomerate
	Acid volcanics			Acid volcanics
	Intermediate volcanics			Intermediate volcanics
	Basic volcanics			Basic volcanics
	Early pegmatite, aplite, veined gneiss	Early Gothium		Pegmatite, veined gneiss
	Gneiss-granites			Gneiss-granites
	Basic and ultra-basic plutonic rocks			Ultra-basic plutonic rocks
Early supra-crustal series[5]	Slate gneiss		Oldest gneiss complex[5]	Clay slate
	Basic, intermediate and acid volcanics			—
	Quartzite			Quartzite
	Basic volcanics			Basic and acid volcanics

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[1] Northern Bohuslän according to A. Gavelin: Yttrande med anledning af H. E. Johanssons föredrag om svenska kvarts- och fältspatförekomster, G. F. F., Bd 36, Stockholm 1914, and B. Asklund: Kosteröarna, ett nyckelområde för västra Sveriges geologi, S. G. U., Ser. C, N:o 517, Stockholm 1950. Northern Dalsland according to W. Larsson: Några resultat av berggrundsgeologiska studier inom Dalformationens norra gränsområde, G. F. F., Bd 69, Stockholm 1947, and Petrological map of the Vårvik region in Northern Dalsland, printed in 1949, S. G. U., Ser. Aa, N:o 187. (The description of the map has not been published yet.)

[2] For the most part secondarily magmatic.

[3] Most frequently secondary rocks *in situ*.

[4] Include porphyrite with phenocrysts of plagioclase.

[5] The mutual age relations of the rocks included are uncertain.

[6] In Gothenburg this rock is sometimes intimately associated with arkose.

[7] Long and thin columns of secondary hornblende have locally developed here.

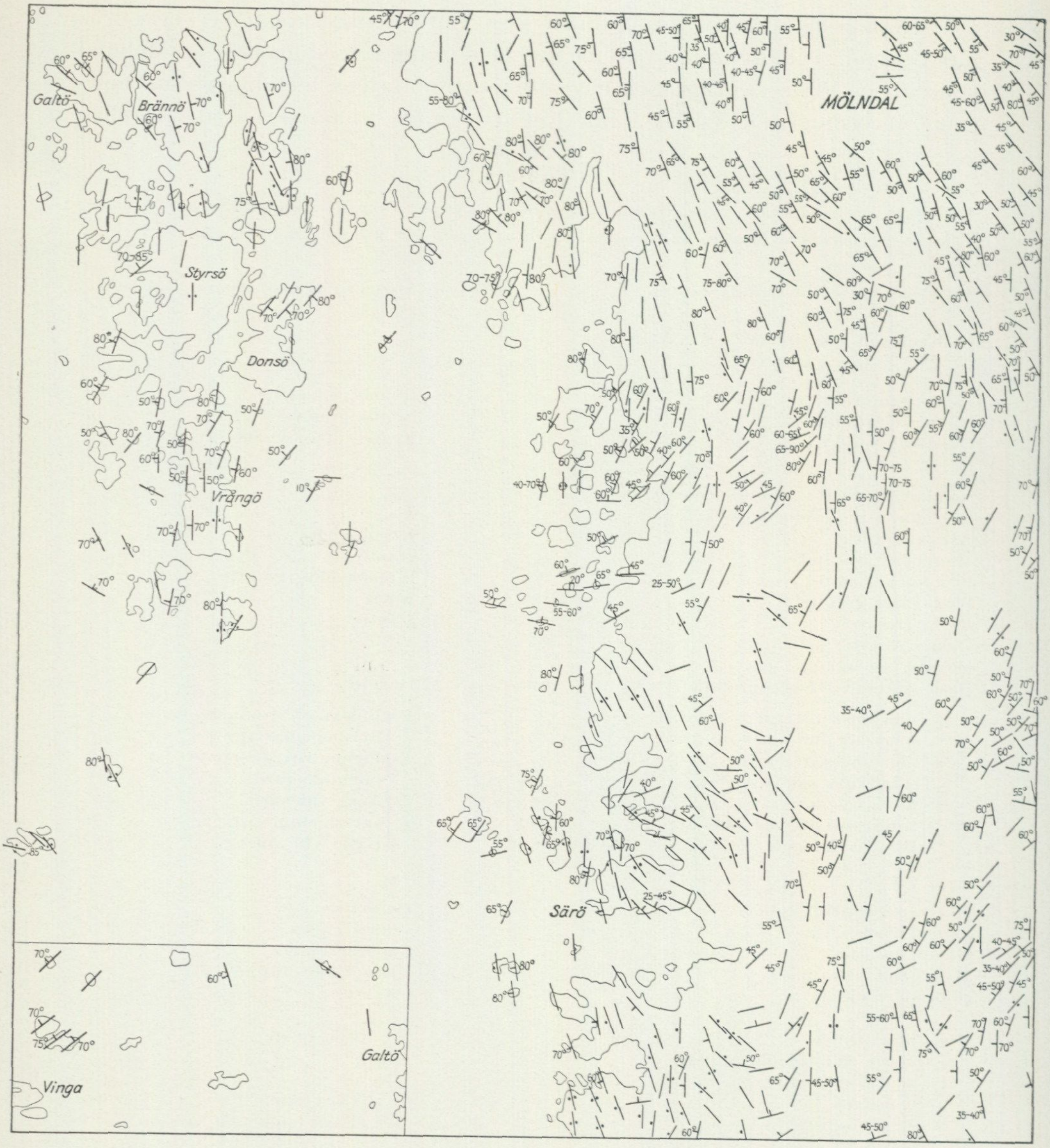

Fig. 1. Stratification and schistosity of the rocks of the Mölndal-Styrsö-Vallda region. Scale 1 : 150 000.

För publicering godkänd i Rikets allmänna kartverk den 21/3 1953.

granite has been recently discovered at Näset in the parish of V. Frölunda (see Plate 1).

It seems likely that we have to distinguish between three generations of pegmatite. The first of these has developed in early Gothian time, the second is older than the Karelian diabase (see above) and should be classed as final

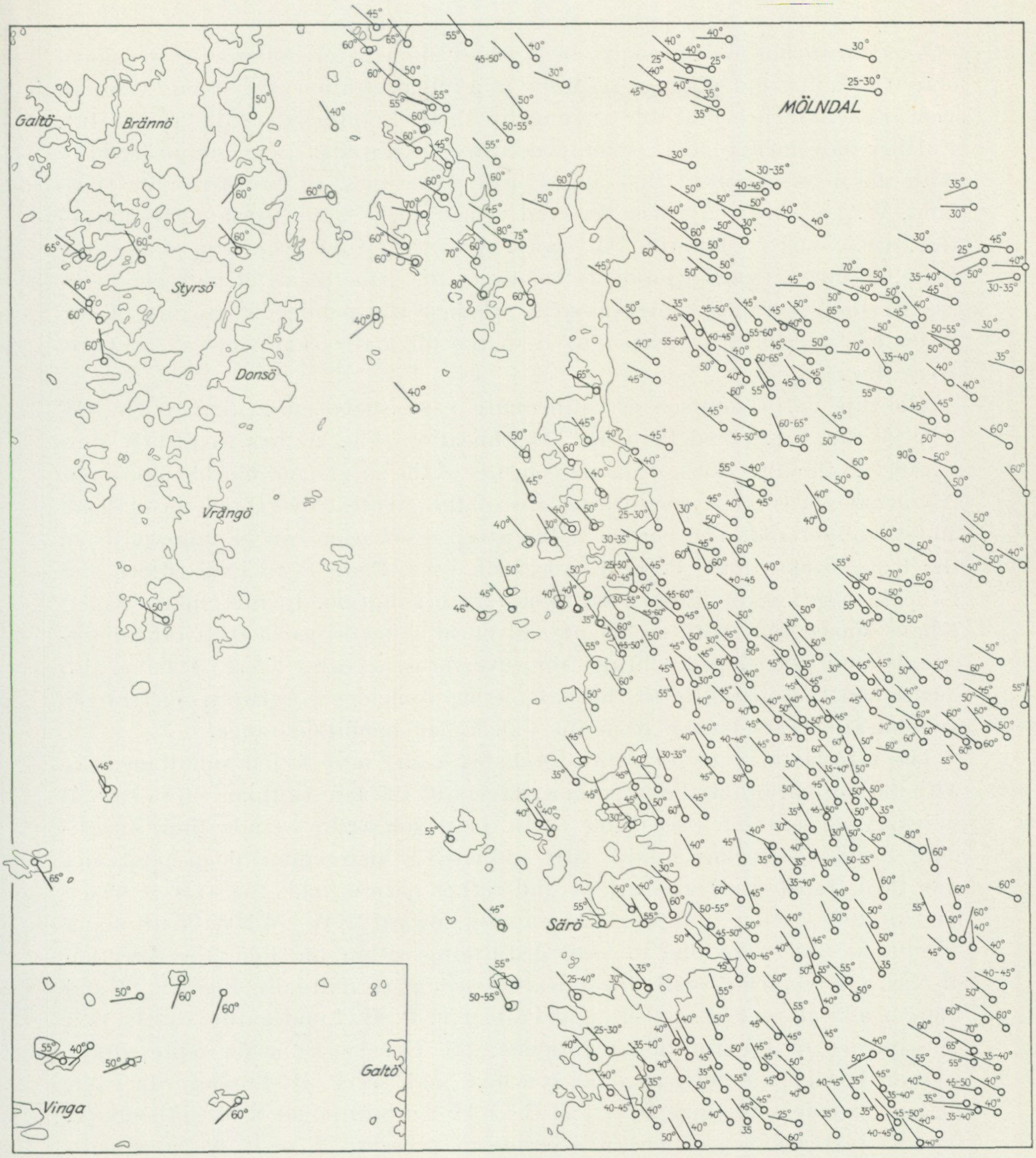

Fig. 2. Lineation of the rocks of the Mölndal-Styrsö-Vallda region. Scale 1 : 150 000.
För publicering godkänd i Rikets allmänna kartverk den 21/3 1953.

Gothian, whereas the third one is late Karelian. The veined gneisses are associated with the first and second generations of pegmatite.

Most frequently the rocks of the Mölndal-Styrsö-Vallda region display schistosities of varying strength, both plane (Fig. 1) and linear (Fig. 2) ones. The former have become intense along the borders of those blocks and sheets of the bed-rock that have moved in relation to each other as a result of the final stress of the late Gothian tectonization (compare Plate 1). This period of overthrusts has most probably been rather immediately followed by tensional activity: faults and glidings resulting in a migmatization (the second Gothian veined-gneiss epoch in Table 1; compare P. H. Lundegårdh 1951, p. 188 ff.). Further movements have certainly occurred in Karelian time, simultaneously with the deformation of the supra-crustal Dal series. In Northernmost Dalsland, W. Larsson (1947) has observed veined gneiss and associated pegmatite that are younger than the Dal series. According to W. Larsson, these late Karelian migmatization products belong to the same phase of rock evolution as the Bohus granite and pegmatite, though the palingenic magma of the latter has developed in deeper parts of the migmatization zone (W. Larsson 1947, Fig. 1).

The dip of the faults S of Gothenburg varies between 25 and 85° WNW—WSW (*cf.* Fig. 1 and Plate 1[1]). The lineation (Fig. 2) thus frequently runs parallel to the directions of the movements of the sheets and blocks. Moreover, it coincides with the general direction of the greatest overthrust in Halland and Vestergötland. The border of this steep dislocation can be followed from the Kungsbacka fjord (P. H. Lundegårdh 1951, Plate 1) to Lake Mjörn and Lake Venern and has thus a north-eastern orientation. In my Onsala paper, I have shown that both the plane and linear schistosities of the Gothenburg-Onsala fold developed during the overthrust epoch. There, I have also mentioned that parallels to this interesting coincidence between overthrusts and lineation, are known from the Caledonian mountain range.

The late Gothian tectonization probably came into action simultaneously with the formation of the uppermost layers of the late Gothian supra-crustal series (Åmål series etc.; see Table 1). In the region where we now find Gothenburg, a sinking syncline of both early and late Gothian sediments and volcanics was then transformed into a long and rather narrow fold, the axis of which has rotated so that it dips rather rapidly towards NW—WNW. With many exceptions, *inter alia* due to local distortions within the fold, the direction of this axis coincides with the lineation (compare mutually Figs. 1—2 and Plate 1 as well as Figs. 17—18 and Plate 1 in P. H. Lundegårdh 1951). As a consequence of the rotation mentioned, the Onsala peninsula represents a section through the bottom of the synclinal fold (see P. H. Lundegårdh 1951, Plate 1), whereas the upper parts of the fold can be studied N of Gothenburg. Its total extension in Bohuslän is unknown, however. E of it, we meet with other folds of Gothian age. In Karelian time, wide parts of South-Western Sweden (Bohuslän and Dalsland especially) were once again subjected to orogenic processes.[2] As mentioned above, both diabase, granite, and pegmatite have then intruded into the Gothenburg-Onsala fold.

The earliest Gothian rocks will be found in the outermost parts of the fold. In the centre, we meet with the bulk of the late Gothian granites, which have developed by transformation of pre-existent rocks (mainly sediments

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[1] Compare also Plate 1 and Figs. 17—18 in P. H. Lundegårdh 1951.

[2] See W. Larsson 1947.

and volcanics) during the folding of the syncline and most of which have become tectonized themselves by the stress of the overthrust epoch.

As early as 1929, N. H. Magnusson pointed out that the various rocks of the synclinal basin of Gillberga in South-Western Vermland received their present structures simultaneously. This means that both early Gothian gneisses, younger supra-crustal rocks belonging to the Åmål series, and late Gothian plutonites (Åmål-Kroppefjell granites and associated basites) have become schistose at the same time.

The Gillberga basin forms the north-easternmost part of a folded stroke of late Gothian rocks, which can be followed southwards as far as to the Onsala peninsula. The Gothenburg-Onsala fold should thus have developed simultaneously with the Gillberga basin. In Karelian time, however, part of the Gothian formation became covered with sediments and volcanics that have also been folded and faulted. Most of these supra-crustal deposits belong to the middle Karelian Dal series, which was in late middle and late Karelian time subjected to foldings, disjointings, and overthrusts. The deformation mentioned has been effected by an eastern—western stress. W. Larsson (1953) has found that in the Vårvik region (Northernmost Dalsland) the Karelian fold axis shows a distinct, slightly dipping, northern—southern orientation (perpendicular to the stress), whereas the fold axis of the Gothian rocks W—SW of the Vårvik region dips slowly westwards. Rather slow, easterly dips are displayed by the fold axes of the rocks E-ESE of the Vårvik region. In Northernmost Dalsland, the stroke of Karelian tectonization has thus to be considered as rather narrow (see W. Larsson 1949).

In the Gillberga basin, the lineation points towards NE or SW, while in the Gothenburg-Onsala fold the direction is most frequently NW. Although both regions are situated in the same northern—southern stroke as the Dal series, they have thus remained rigid during the Karelian orogenesis and their Gothian structures have been preserved.

In 1950, B. Asklund published a summary of his petrological investigations on the Koster and Väder (Weather) isles in Northern Bohuslän. He there distinguishes between the following generations of rocks: 1 — an early supra-crustal, leptitic series, 2 — an early infra-crustal series composed of greenstones, various non-porphyritic gneiss-granites, and a final gneiss-granite with red or grey, coarse microcline eyes, 3 — diaschistic dike rocks of a lamprophyric type, 4 — a late infra-crustal series comprising gabbroic rocks and granite, 5 — Koster diabase and dolerite, 6 — Bohus granite and pegmatite, 7 — younger eastern—western dolerite, and 8 — Permian rhomben porphyry. All the rocks of groups 2 and 3 are supposed to be magmatic and to derive from the same parental magma. A concordant formation of sheets of heterogeneous basites and gneiss-granites compose the older part of the early infra-crustal series. Asklund finds that this conformous band-and-lens architecture speaks in favour of the conception of a magmatic differentiation *in situ* as the origin of these rocks. We have obviously here to deal with a non-actualistic reasoning of the same kind as was formerly applied by H. E. Johansson (see 1931 and p. 3). The data given indicate, indeed, that both amphibolitized basic volcanics and supra-crustal rocks granitized *in situ* have been included in the early infra-crustal series, though of course secondary magmatic activity has largely contributed to the architecture now visible (see for instance Figs. 8—9 in Asklund 1950).

When we compare the early infra-crustal series of the Koster isles with the late Gothian infra-crustal series of the Gothenburg-Onsala fold, we find a striking parallelism, whereas the late infra-crustal series of the Koster and Väder isles displays quite another character. Asklund's reasoning indicates, however, a pre-Gothian, *viz.* Svionian, age of the early Koster series.

Supra-Crustal Rocks.

Quartzite, Slate Gneiss, and Associated Rocks.

In the south-eastern part of the Onsala peninsula, at the harbour of Gottskär and northwards from there (see P. H. Lundegårdh 1951, Plate 1), the dominant rock is a mixed femic gneiss. When the gneiss was deep-folded in late Gothian time, the bulk of it underwent plastical deformation and metasomatism. At the harbour, we can study one of the results of these alterations: minor penetrative masses of secondary diorite and quartz-diorite. Here, we can also see how the most acid and most basic rock components of the mixed gneiss have escaped the alterations mentioned and display alternating thin layers of white *quartzite* and green black, skarny *davainite* (secondary hornblendite). Though they are not very extensive owing to dislocations during the late Gothian orogenesis (Fig. 3), the layers border sharply upon each other and are on the whole remarkably well-preserved. When studying the rocks of Gottskär, we also study the outermost part of the ancient Gothian syncline mentioned in the introduction. The quartzite and davainite layers as well as the surrounding gneiss should thus belong to the early Gothian supra-crustal series.

During my mapping of the isles outside the Styrsö archipelago (Plate 1), I discovered a great number of quartzite remnants in the peculiar plagioclase-porphyrite of Vinga and Koholmen (p. 30). The xenoliths are angular and border sharply upon the surrounding rock, from which they have become separated by thin shells of hornblende (Fig. 16, p. 31). As Vinga and Koholmen are also situated in the outermost part of the Gothenburg-Onsala fold, the quartzite remnants may be supposed to derive from an early Gothian series of supra-crustal rocks.

Far to the north, in the archipelago of Northern Bohuslän, we find a similar rock on the isle of Slängerumpan. B. Asklund (1947, pp. 40—41) reports that the oldest bed-rock of Slängerumpan is an amphibolite dipping 30—50° SW. This bed is covered by a quartzite layer the thickness of which may sometimes amount to 100 m. Asklund presumes that a continuous layer of quartzite has

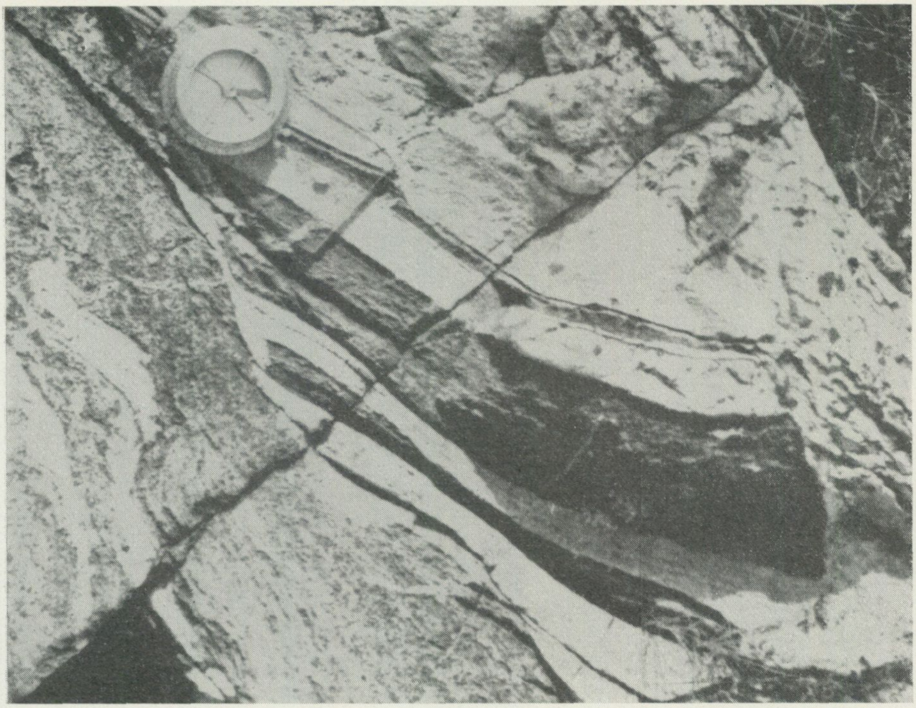

Fig. 3. Part of disjointed and dislocated sheet of interstratified quartzite and davainite in mobilized basic gneiss. At the harbour of Gottskär, the Onsala peninsula. Photo by P. H. Lundegårdh 1951.

once existed near the western border of the Bohus granite. The quartzites of Vinga, Koholmen and Gottskär have probably developed simultaneously with this layer.

Not far E of the quartzites, we find a stroke of *clayish sandy slates*, which I have followed from the Solberga-Marstrand region N of Gothenburg to the Styrsö archipelago. At Tjuvkil and Rörtången, two villages between Marstrand and Solberga, the slate is well-preserved and only weakly folded (Fig. 4). The metamorphism grows stronger and stronger the more closely we approach the Styrsö archipelago, however. (That is to say: the more closely we approach the bottom of the fold considered.)

In the Styrsö archipelago, the acid components of the slates have most frequently been assembled to white or grey-white concordant veins and winding layers. These are as a rule medium-grained, or even coarse, contrary to the rest of the rock, which has remained fine-grained. Numerous veins, glands, lenses, and intrusions of red-grey-white pegmatite probably containing juvenile silicate compounds are also found all over the slate gneiss region outside Gothenburg, as evident from Fig. 5 and Plate 1 (the red winding signs that have been plotted on the yellow colour of the supra-crustal gneiss).

We have seen that the veined slate gneiss is the principal rock of the Styrsö

Fig. 4. Clayish sandy slate. Rörtången, parish of Solberga, N of Gothenburg. Photo by P. H. Lundegårdh 1950.

archipelago. Plate 1 shows that its extension southwards cannot be calculated, as the bed-rock has there been covered by the sea. Veined derivatives of slate gneiss are included in the outer parts of the Onsala peninsula, however (P. H. Lundegårdh 1951, Plate 1), though their areal distribution is here much lower than outside Gothenburg. On the whole, the eastern part of the Gothenburg-Onsala fold is very poor in derivatives of clayish slates, as compared with its western part. In fact, the character of the sedimentation seems to have been different in the western and eastern parts of the ancient syncline.

E of the Styrsö region, though still in the western part of the fold, several remnants of slate gneiss without pegmatite veins have been observed in the Frölunda granite (the principal rock of the Näset-Fiskebäck-Frölunda peninsula; see Plate 1). Moreover, the Frölunda granite itself has developed by alteration *in situ* of strata of clayish sandy slates (see p. 40). From the Onsala peninsula, only few finds of slate gneiss without pegmatite veins have been reported (see P. H. Lundegårdh 1951, pp. 168—69).

The naked fresh bed-rock of the isles SW of Gothenburg with their low hills, smooth shelves and shallow valleys is well apt to petrological investigations. From my pocket-books, I shall now quote a few descriptions of typical veined slate gneisses.

In the central parts of Vrångö, S of Styrsö, the rock in question displays

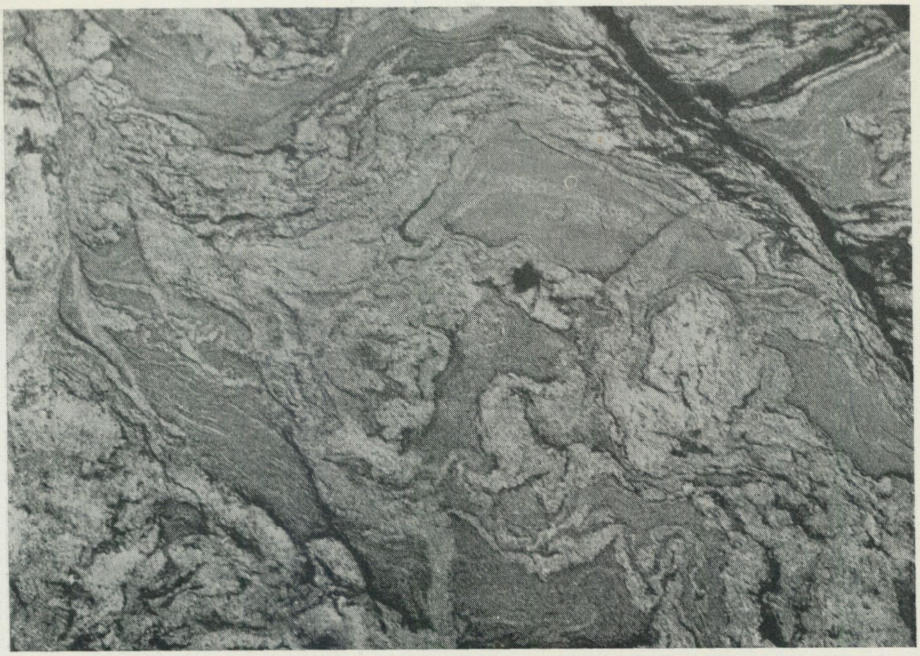

Fig. 5. Veined and folded slate gneiss. Isle of Vrångö, parish of Styrsö. Photo by P. H. Lundegårdh 1950.

folded and frequently distorted layers of variable acidity. Thus, white or grey-white, usually granitic (sometimes aplitic) layers essentially composed of rather coarse individuals of quartz and feldspar, alternate with grey, intermediate, or black-grey, mafic and basic layers, which are as a rule fine-grained. The acid layers are more common than the intermediate and basic ones. During the migmatization, the acid layers have been plastic and in part they have dissolved, whereas the intermediate and basic layers, though flexible, have remained more intact. All over the area considered, the rock is filled with the various kinds of pegmatite injections and segregations described above and displayed in Fig. 5.

The concordant beds of meta-basites now and then observed in the veined gneiss have been rather rigid. Xenoliths of amphibolite derived from disjointed beds[1] are thus as common as preserved layers, and the *boudinage* shown in Fig. 6 may serve as an illustration of the tectonization of these ancient volcanics.

In the southern part of Köpstadsö, NNE of Styrsö, the slate gneiss strata frequently wind to and fro. The rock is dark grey to grey and basic to intermediate or sometimes even acid. The felsic layers have most often been mobilized or at least plastically deformed. When they re-crystallized, they grew coarser and frequently developed an aplitic or granitic character. The mafic layers

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[1] Compare P. H. Lundegårdh 1951, Fig. 14.

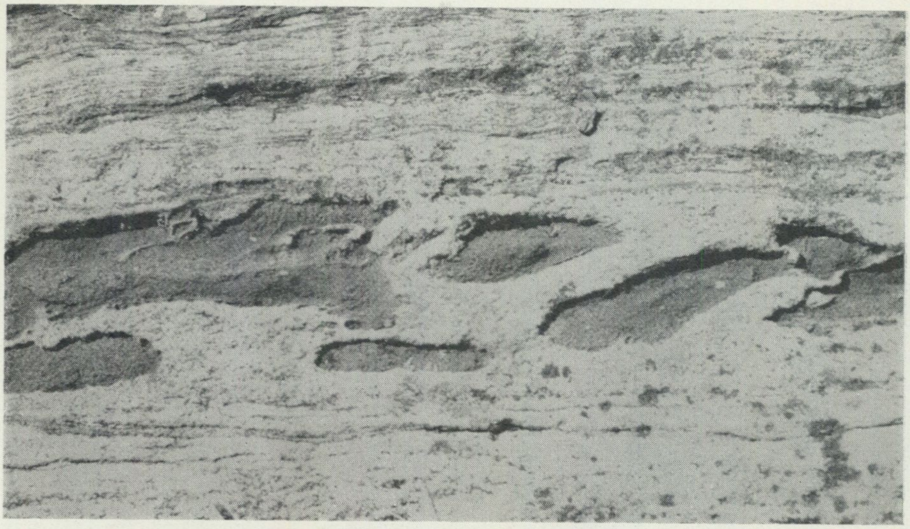

Fig. 6. Disjointed sheet of amphibolite in acid to intermediate gneiss. Isle of Vrångö, parish of Styrsö. Photo by P. H. Lundegårdh 1950.

have remained fine-grained and contain most of the biotite of the gneiss, whereas the muscovite is concentrated in the felsic layers. The slate gneiss is filled with glands, lenses, bands, veins, and real intrusions of red-grey-white pegmatite sometimes accompanied by aplite. In part distorted layers of amphibolite and amphibolitic gneiss have been observed now and then.

Under the microscope, the dark fine-grained layers of the veined slate gneiss display a granoblastic re-crystallization texture including the following minerals: quartz, oligoclase, biotite, smaller amounts of muscovite and accessoric quantities of zircon, apatite, titanite, and magnetite. The pale layers are most frequently medium-grained and are apt to show granitic structure. They are composed of quartz, microcline (frequently perthitic), oligoclase, muscovite, and biotite. The former kind of mica is more common than the latter. Accessoric minerals are titanite and apatite. Sometimes, garnet has also been found, whereas, owing to the sandy character of the mother sediment, no minerals extraordinarily high in aluminium, such as cordierite, sillimanite etc., have developed.

The pegmatite and aplite of the veined gneiss will be described later (p. 47 ff.).

I have already mentioned that *amphibolitic rocks* are rather frequent in the slate gneiss region. Before the Gothian orogenesis, these meta-basites displayed concordant beds of basaltic lava, tuff and tuffite. At present, their mineral composition and textural-structural development do not reflect many of their primary features, however. They are mainly composed of acid plagioclase (most frequently oligoclase) and common hornblende, further of some quartz, biotite, apatite, and, though not always, magnetite (often titani-

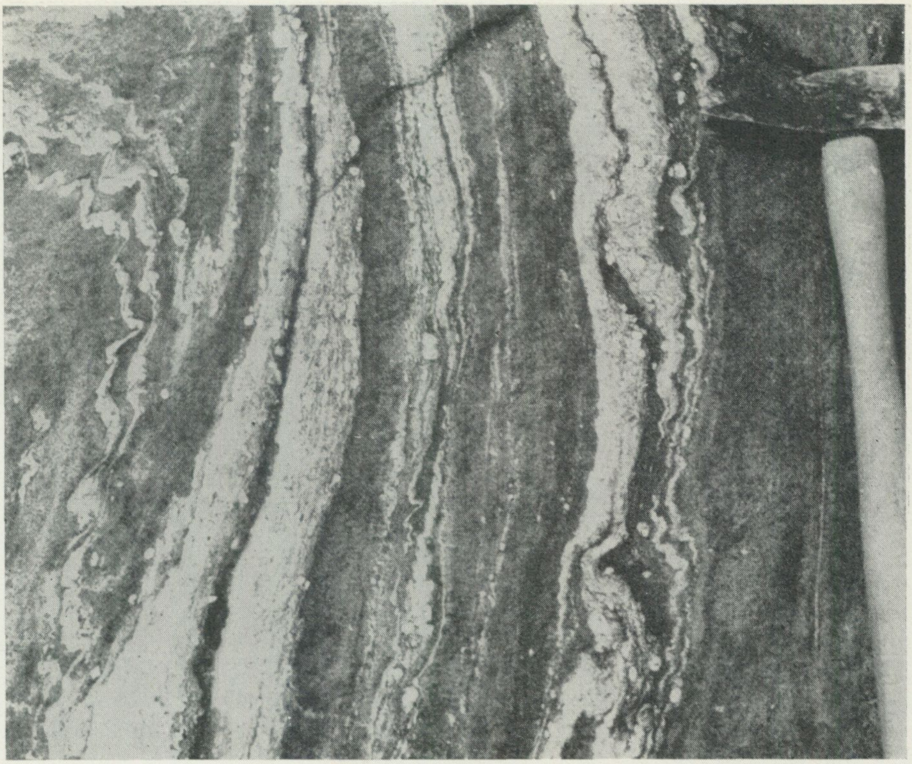

Fig. 7. Banded gneiss: interstratified amphibolitic gneiss and more acid gneiss with porphyroblasts of microcline. NW of Långåker, parish of Kållered. Photo by J. Lundqvist 1951.

ferous), epidote, and titanite. Except for the larger individuals sometimes preserved (the phenocrysts of the ancient lava), the plagioclase has crystallized as granoblastic grains. All the quartz has developed similarly. In a thin section of amphibolitic gneiss from the southernmost part of Donsö (see Plate 1), the hornblende shows the following pleochroic colours: α — colourless or very pale greenish-yellowish, β — olive-green, and γ — blue-green. $2V\gamma$ amounts to about 95° and $c{:}\gamma$ to 14—15°.

Other rocks associated with the veined slate gneiss are sedimentary leptites (fine-grained, granoblastic) and mixed or banded gneisses (Fig. 7). Intermediate to basic gneisses of tuffitic origin are sometimes also found. A dark grey leptitic slate derivative from Stora Rävholmen near SW of Styrsö has been investigated microscopically. Owing to alterations, its primary stratification cannot always be recognized. The main minerals are quartz, oligoclase, and biotite. Garnet is quite common, too, and should be classed as an inferior constituent. Accessoric minerals are magnetite, apatite, muscovite, zircon, and allanite. Of the minerals mentioned, only garnet and biotite to some extent follow the layering and thus make this structure visible.

Small aggregates of quartz, most frequently lens-shaped, have been met

Fig. 8. Sheet of schistose conglomerate in plagioclase-granite. Isle of Rivö, parish of Styrsö. Photo by P. H. Lundegårdh 1951.

with now and then all over the slate gneiss region. It seems likely that this quartz has been once liberated during the successive alteration of the clayish sandy sediments and that it has moved to positions of minimal pressure during the folding.

Strokes and masses of acid, intermediate and basic granitic rocks are quite common in the slate gneiss region, especially on Rivö and Styrsö (see Plate 1). Sometimes, these rocks have developed by granitizations *in situ*, sometimes by intrusions of palingenic (secondary) granitic magma. Both processes seem to have occurred in late Gothian time. The western parts of Stora Känsö and Vargö (see Plate 1) essentially consist of granitized slate gneiss. Numerous *schlieren* (remnants of folded slate layers) very rich in mica here reveal the sedimentary origin of the granite.

On Rivö W of Fiskebäck (see Plate 1), a grey plagioclase-granite has intruded into the slate gneiss. At the strait between Rivö and Asperö, a sheet of schistose *conglomerate* (Fig. 8) has been observed in this granite. The conglomerate displays pebbles of re-crystallized and rather coarse quartzite in a matrix of mafic gneiss. The age of the conglomerate will be discussed on p. 24.

Meta-Basites, Alkaline Gneiss, Common Gneisses, and Associated Rocks.

E and SE of the Styrsö archipelago, the Gothenburg-Onsala fold contains alternating layers of meta-basites and gneisses derived from volcanics and sediments. These have become in part distorted, in part destroyed by tectonizations, granitizations, dissolutions, and magmatic intrusions. Owing to the high degree of metamorphism of the supra-crustal rocks mentioned, their age and

Fig. 9. Amphibolitic gneiss with a layer of intermediate gneiss that has altered to Askim granite. NW of Långåker, parish of Kållered. Photo by J. Lundqvist 1951.

primary character may seem difficult to discern. The positions of the various strokes of rocks in the fold serve to indicate the general stratigraphy of the supra-crustal series, however (compare Table 1). Thus, the innermost rocks are youngest, *viz.* late Gothian. These expose the picture of disjointed steep beds of meta-basites covering a kernel stroke of alkaline gneiss (see Plate 1). Among the former, preserved volcanics have been recently discovered, at first on the Onsala peninsula (P. H. Lundegårdh 1951, pp. 163—65). In rare cases, even the alkaline gneiss is associated with rocks whose primary structures have been preserved (in Gothenburg arkose; on the Onsala peninsula agglomerate, see P. H. Lundegårdh 1951, p. 167).

The remaining gneisses of the mainland part of the Mölndal-Styrsö-Vallda region are most probably in part early, in part late Gothian. As was mentioned in the introduction, the division of the supra-crustal rocks in two series is not definitive, however.

To a considerable extent, the gneisses of the Mölndal-Styrsö-Vallda region have been granitized *in situ*. Thus, the alkaline gneiss has been now and then transformed into microcline-granite, while the intermediate and basic gneisses have given origin to intermediate and basic granites (compare the Frölunda granite mentioned above). On the other hand, the greater part of the intermediate, porphyritic Askim granite, and the plagioclasic, frequently rather basic granites, have developed by crystallization of secondary (palingenic) magmas, *viz.* deep-folded, liquefied and mobilized rocks. The same mode of development holds for part of the intermediate, non-porphyritic granites. On the whole, we can say that both modes of granitization now discussed have frequently intermixed.

As regards granitizations *in situ,* the following general statements have to be considered. H. G. Backlund (1936, 1941, 1943) has repeatedly pointed out that, during the evolution of the crust, there has been no lack of time for large-scale granitizations, further that granitizations can proceed under the condition of constant volume, owing to the migrations in opposite directions and resulting replacements effected by the ions involved in the alteration process. Moreover, I. Th. Rosenqvist (1949, 1952) has stated that alterations of this kind have most probably been mainly effected by intergranular migrations of dissolved ions.

The metamorphic basic volcanics, or meta-basites, of the Mölndal-Styrsö-Vallda region can be divided into three groups, two of which will be described here. These groups are *amphibolite* (meta-basite with more than 50 % hornblende) and *amphibolitic gneiss* (meta-basite with less than 50 % hornblende though still rich in this mineral). The latter may pass into mafic gneiss. It has proved impossible to distinguish between the amphibolite and the amphibolitic gneiss during the map-work (compare Plate 1), as both rocks have the same appearance. The third group, the *secondary quartz-diorite* and *diorite,* is described in the next chapter.

Originally, the beds of basic volcanics to a very great extent alternated with layers of more acid composition, as a rule tuffites and epiclastic sediments (for instance quartzite, see p. 10). This interstratification has been preserved in a number of cases, as is seen from Figs. 7 and 9. Most frequently, it has been distorted, however. During the Gothian orogenesis, the intermediate and acid strata became plastic and movable. In part, they were even dissolved and could then behave like magmas. Typical results of these processes are displayed in Figs. 10—11. Fig. 12 shows an interesting though very local phenomenon: tensional joints filled with mobilized gneiss.

When interstratifications of inhomogeneous supra-crustal rocks have been preserved, we speak of *banded gneisses,* when distortions have occurred, we use the term *mixed gneisses.*

The amphibolitic gneiss and amphibolite are grey-black, black or green-black, fine-grained rocks. Most frequently, they have become influenced by the regional tectonization, though they are usually less schistose than other supra-crustal rocks of the Gothenburg-Onsala fold. As a rule, their present texture has developed secondarily. In certain cases, however, plagioclase phenocrysts have been preserved from the original volcanics.

The main constituents are common hornblende (secondary after pyroxene etc.) and plagioclase (oligoclase or andesine). Variable quantities of quartz, biotite, and epidote are also found. In the amphibolitic gneiss, the former belong to the main minerals. Chlorite is sometimes an important constituent, too. Most of the epidote and chlorite seems to have developed during the final Gothian migmatization (the second veined gneiss epoch in Table 1; *cf.* p. 38), whereas the principal alteration of the basic volcanics is a result of the deep-folding of the Gothenburg-Onsala syncline.

In order to make the mineralogical picture of the meta-basites complete,

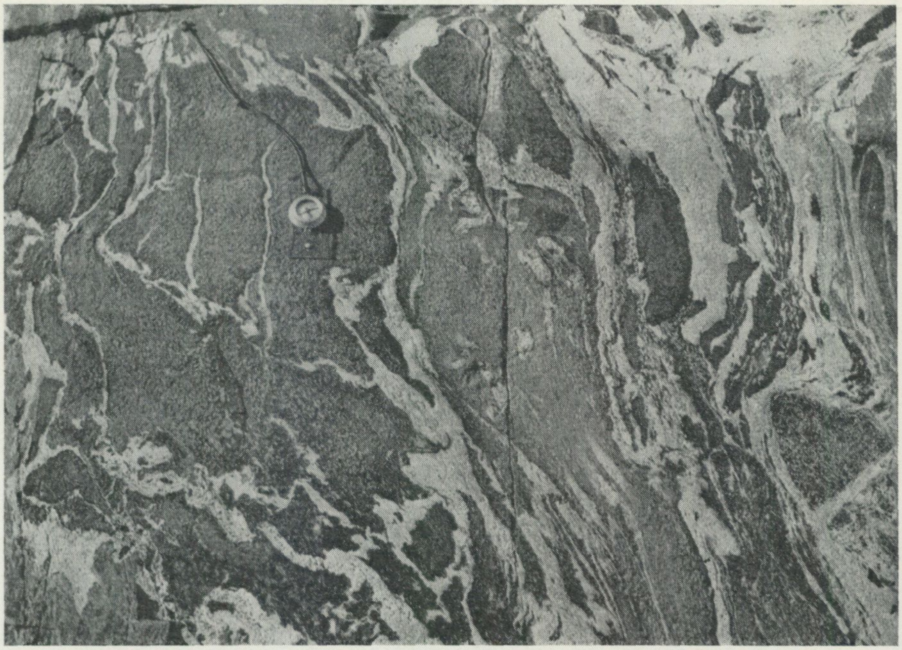

Fig. 10. Basic to amphibolitic gneiss penetrated by mobilized intermediate gneiss. Stensholmen (islet NW of Särö), parish of Släp. Photo by P. H. Lundegårdh 1951.

we have to mention the constant presence of a small amount of apatite. Magnetite (frequently titaniferous) is another minor constituent that ought to be reported. In rare cases, this mineral is lacking, however.

The hornblende has crystallized as columns, prisms, or irregular individuals. The latter are frequently composed of aggregates of small grains. Certain individuals have sometimes grown coarser than the rest of the rock, thus giving it a porphyritic appearance. Repeated development of long and thin hornblende columns (sometimes even needles) is characteristic of strongly lineated areas. Most columns are, of course, then approximately parallel to the lineation.

The plagioclase (except the sparse phenocrysts) and the quartz are as a rule granoblastic.

In the meta-basites, some few strokes and masses of preserved volcanics have been observed (compare P. H. Lundegårdh 1951, pp. 163—65). Immediately E of the highway $1^1/_2$ km NNW of Kållered church (Plate 1), for instance, I have encountered a sill of grey-black to black dolerite[1] composed of labradorite, common green hornblende (secondary), clinopyroxene, biotite (secondary), magnetite, and red garnet (secondary). Furthermore, a minor content of apatite (small rods) should be reported.

The labradorite forms primary laths (ophitic texture) and flocks of granoblastic grains. The margins of the former have become corroded during the

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[1] Spectral analysis in Table III, discussion of the data obtained on p. 54.

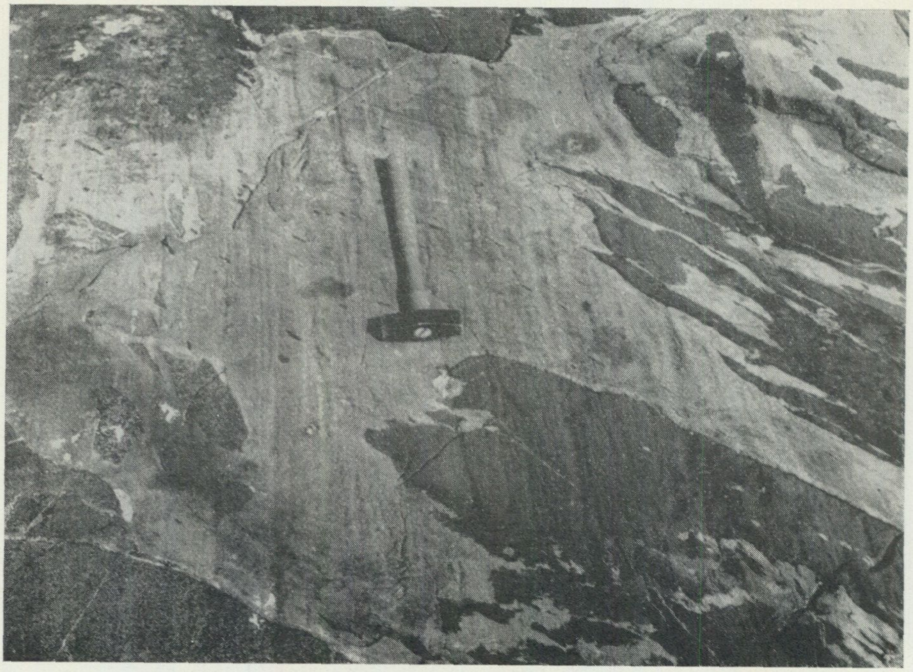

Fig. 11. Intrusions of mobilized acid gneiss in amphibolite. Maleviksholmen (isle NW of Särö), parish of Släp. Photo by P. H. Lundegårdh 1951.

alteration of the rock. A few primary individuals show zonal extinction. The clinopyroxene, probably an augite ($\gamma \wedge c = 40°$), has become strongly impregnated with dispersed magnetite. The secondary hornblende has either developed as separate granoblastic grains or penetrates the pyroxene along margins and fissures. The biotite has most frequently assembled to aggregates of minor individuals. The garnet is penetrative.

In the mountains 2 km ENE of Vallda church (inferior locality) and 2 km NE of V. Frölunda church (superior locality), a fine-grained, grey-green-black, amphibolitic gneiss with oval pebbles of pale grey quartzite and grey-white sandstone has been discovered (Plate 1 and Fig. 13). The sandstone pebbles are mainly composed of quartz and oligoclase. The length of the pebbles is $^1/_2$—$1^1/_2$ cm. The gneiss should be classed as a *conglomerate with tuffitic matrix.*[1] It is associated with a series of folded and in part disjointed beds of late Gothian basic tuff and lava.

The tuffitic matrix[1] of the conglomerate NE of V. Frölunda church is essentially composed of oligoclase and hornblende (first-rate constituents), biotite and quartz (second-rate minerals), epidote and titanite (inferior minerals). The minor constituents are apatite, allanite, magnetite (probably titaniferous), and pyrite. The texture is secondary: xenomorphic and in part granoblastic. The hornblende is a uralite with pale pleochroism in blue-green (γ) and grass-

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[1] In part, the matrix may be altered lava (see p. 32).

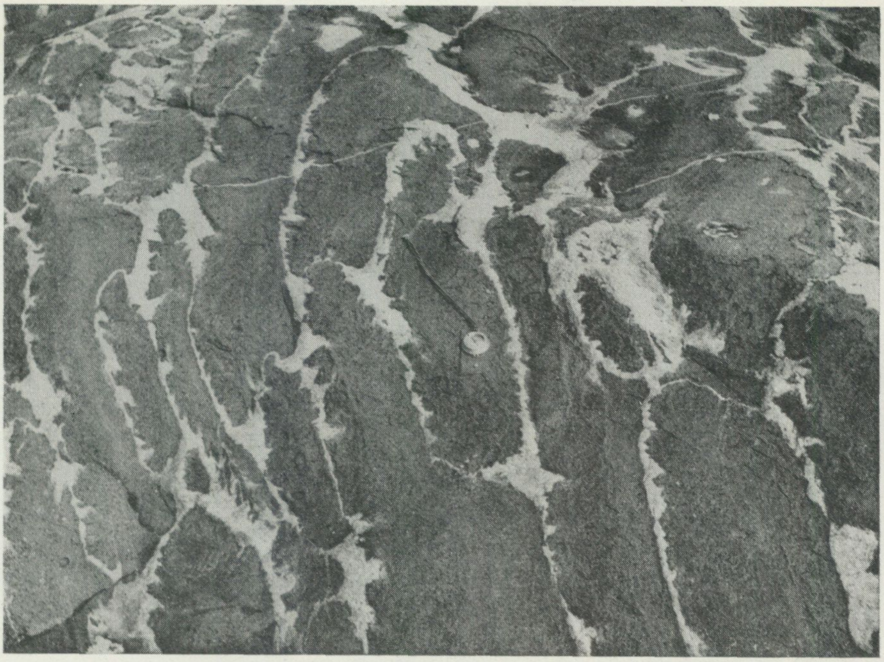

Fig. 12. Amphibolite penetrated by mobilized acid gneiss along tensional joints. North-western Hosholmen (isle SW of Särö), parish of Släp. Photo by P. H. Lundegårdh 1951.

green (β). $2V\gamma$ amounts to 90° or somewhat more. The allanite is, in thin sections, brown-yellow and has become surrounded by homaxial epidote. Owing to alteration, it is most frequently isotropic.

As mentioned above, the pebbles of the conglomerate have become oval. This deformation has been effected by the stress of the late Gothian tectonization. Simultaneously, the tuffite has grown schistose (most frequently parallel to the stratification). As already mentioned, the pebbles consist of either quartz alone or quartz and oligoclase. Minor minerals are epidote, hornblende, allanite (isotropic), titanite, biotite, oxide and sulphide ore. In part, these emanate from the tuffite. In part of the conglomerate, the quartzite pebbles have become enclosed in shells of hornblende. The thickness of the shells is variable, and some pebbles have been completely amphibolitized. The significance of this phenomenon will be discussed on p. 32.

The pebbles seem to derive their origin from a *sedimentary rock composed of alternating layers of quartzite and sandstone*. Such a rock has also been found 1 km SW of Askim church and on the southernmost part of Sillfarsholmen, an isle between Köpstadsö and St. Förö (in the western vicinity of 'St. Förö' in Plate 1). N of the Fiskebäck—V. Frölunda area (outside the northern border of Plate 1), it is rather common (see H. E. Johansson 1931, p. 28). When investigated microscopically, the sedimentary rock of Sillfarsholmen displays a strong epidotization of the quartz-oligoclase (sandstone) layers, whereas the

Fig. 13. Basic tuffite with pebbles of quartzite and sandstone. Natural size. NE of V. Frölunda church, at the northern border of Plate 1. Photo by C. Larsson 1952.

quartzite layers have remained intact. Furthermore, the rock is traversed by long, thin columns of common, secondary hornblende (Fig. 14). These have developed before the epidotization (compare p. 23) and have then become in part altered to penninite. The primary stratification is well-preserved. It has been made visible *inter alia* by the distinct layers of pure, granoblastic quartz, *inter alia* by several grains of magnetite (probably titaniferous and frequently associated with titanite). The epidote of the ancient sandstone layers, too, has been distributed parallel to the stratification. This mineral has crystallized as an immense number of minor individuals, many of which are idiomorphic. The remaining oligoclase, on the other hand, is xenomorphic and even apt to show granoblastic texture.

The quartzite-sandstone rocks SW of Askim church and outside the northern border of Plate 1 have altered similarly. Thus, for instance, they contain the same penetrative columns of secondary hornblende as the Sillfarsholmen sediment (compare H. E. Johansson 1931, p. 28). Both on Sillfarsholmen and SW of Askim church, the formation of hornblende has started from faces that are at the same time planes of stratification and schistosity. The number of hornblende columns is still highest along these faces. Furthermore, on Sillfarsholmen, the formation of hornblende is dependent on the presence of basic volcanics in the close vicinity of the quartzite-sandstone rock. From the vol-

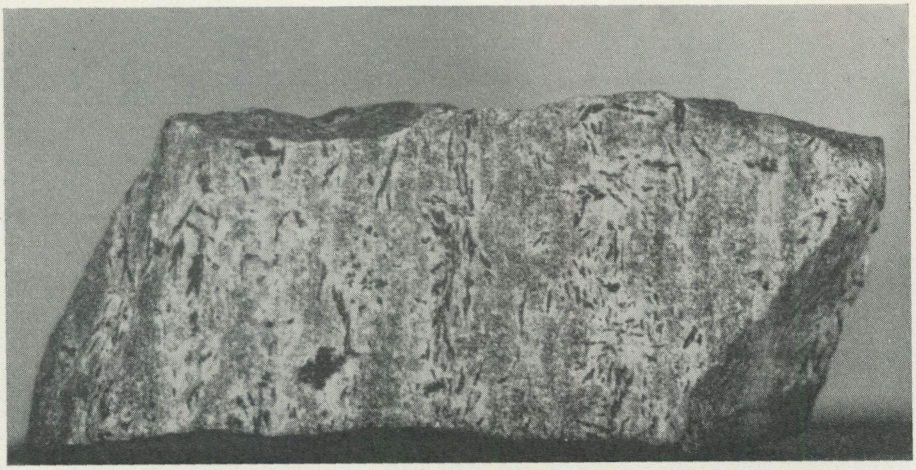

Fig. 14. Quartzite-sandstone rock with porphyroblasts of hornblende. Scale 4 : 5. Sillfarsholmen (islet between Styrsö and Fiskebäck), parish of Styrsö. Photo by C. Larsson 1952.

canics, magnesium and iron have been introduced along the mutual planes of stratification and schistosity. Metasomatic reactions have then taken place. On a small scale, these imply a basification of part of the sediment (the hornblende columns) and an acidification of the nearest volcanics (an increase of the quartz and felspar content).

Structurally, the hornblende-bearing quartzite-sandstone rock is reminiscent of the *Garbenschiefer* of the Caledonian mountain-range. Similar rocks have also been found in the late Gothian supra-crustal rocks of the Gillberga basin in South-Western Vermland (N. H. Magnusson 1929, p. 13). Furthermore, W. Larsson (1949) has observed a few strokes of rocks with thin columns of secondary hornblende SW of the Gillberga basin. Larsson reports that even late Gothian granites, such as the Åmål granite, have there been subjected to secondary formation of columnar hornblende. If we consider the process mentioned to have occurred at the same time all through the Gothian bedrock of South-Western Sweden, we have to place it in the second Gothian period of migmatization (see Table I). During the Karelian orogenesis, the quartzite-sandstone rock does not seem to have been subjected to any more considerable heating. (Compare the problematic and in any case restricted low-temperature metasomatism effected by the late Karelian magmatic activity in the southern vicinity of Gothenburg, for instance at Näset, p. 47.) The penninization of the columnar hornblende and the simultaneous epidotization of part of the quartz-oligoclase layers may, however, have taken place either in late Karelian time or when the influence of the late Gothian migmatizing agents faded (*cf.* p. 38). On the other hand, we have in Northern Dalsland and South-Westernmost Vermland no visible migmatization in latest Gothian time, whereas considerable alterations were caused by the Karelian orogenesis. As touched upon in the introduction, the Dal series of sediments and volcanics grew thick, sank, and became tectonized together with the underlying Gothian bed-rock. According to W. Larsson (1947), the Bohus granite and pegmatite should be classed as the final results of a late Karelian migmatization that has given origin to veined gneiss and earlier pegmatite at higher levels of the crust, for instance in Northernmost Dalsland. W. Larsson (personal communication) is therefore inclined to interpret the hornblende porphyroblasts SW of the Gillberga basin as products of this migmatization. As the Gillberga basin has been far less influenced by the Karelian orogenesis, the porphyroblasts here met with may be older (late Gothian).

The quartzite-sandstone rock seems to belong to the lower group of late Gothian sediments and volcanics. Outside it, we have, in the fold, metamorphic lavas and tuffs most probably corresponding to the basal part of the Åmål series (see Table 1). Before the folding, these have covered the early Gothian Marstrand-Styrsö slate. The general conformity between the late Gothian volcanics mentioned and the early Gothian slate, bear evidence of a rather quiet evolution of the Marstrand-Gothenburg-Onsala region in early and middle Gothian time (compare Fig. 4).

As the conglomerate has derived all its pebbles from the quartzite-sandstone rock, its interformative character can be considered as indisputable. In Table 1, it has thus been placed closely above the rock mentioned. The position of the conglomerate on Rivö (p. 16) is more uncertain, however. This conglomerate also displays a higher frequency of quartzite pebbles than the mainland one, and its position in the fold indicates an early Gothian age.

The quartzite-sandstone rock and the tuffitic conglomerate seem to be the only wholly definable sediments of the inner part of the Gothenburg-Onsala fold. There are to be found, however, much more extensive strokes of rocks, the sedimentary origin of which cannot possibly be doubted when their compositions are studied. These rocks now display layered granoblastic gneisses of variable acidity. The stratification is the single primary structure observed. It has, however, most frequently become intensified during the late Gothian tectonization, especially in and along the faults of the region investigated.

The dominant gneiss is a rather acid, felsic, red-grey to pale red variety — the renowned *alkaline gneiss* of the Gothenburg region. Together with the late Gothian volcanics (basic tuffs, tuffites, and lavas), this rock constitutes the innermost layers of the Gothenburg-Onsala fold and continues in the centre of the fold N of Gothenburg, as evident from H. E. Johansson's petrological map of the Kungelv-Gothenburg region (H. E. Johansson 1931). The Gothenburg stroke of alkaline gneiss has been faulted parallel to the stratification and schistosity so that, N of Mölndal, its eastern part disappears from the present surface of the bed-rock (compare mutually Plate 1 and the petrological map in H. E. Johansson 1931). Parallel strokes have been found E of Gothenburg, as exemplified by H. E. Johansson's map.

S—SSW of the Kållered area (Plate 1), the Gothenburg stroke of alkaline gneiss has lost its continuity owing to distortions effected by the evolution of the late Gothian granites. In part, the alkaline gneiss has there even altered into microcline-granite.

The main minerals of the alkaline gneiss are microcline,[1] quartz, and oligoclase or oligoclase-albite. As a rule, the former are first-rate constituents. NW of Kållered church and from there towards Gothenburg, the leading mineral is always microcline (see the geometric analyses given below).

Though it is far less common than the plagioclase, biotite may also be counted a main mineral. Among minor constituents, I shall at first mention those that are nearly always present, *viz.* magnetite, titanite, zircon, and apatite. Magnetite is at times very common and in certain cases displays coarse individuals. Owing to their frequent content of magnetite, the alkaline and acid gneisses of South-Western Sweden were formerly distinguished as 'iron gneiss'. In this name, all rocks associated with the alkaline and acid gneisses were also incorporated and thus we got the 'iron-gneiss' formation (compare the introduction). Titanite is sometimes common, too (compare the geometric analyses given below). In and NNW of the Kållered area, hornblende rich in iron appears among the minor minerals and may even replace biotite and magnetite (see below). Garnet and fluorite have also been observed here.

WSW—S of Kållered church, epidote enters the alkaline gneiss and gradually replaces the hornblende.

The mafic minerals have most frequently been arranged so as to make the stratification of the rock visible even in detail. A remarkable exception from this rule is given by the hornblende, however. I have already mentioned that the content of hornblende may grow high in the north-easternmost part of the Mölndal-Styrsö-Vallda region. Indeed, I have been able to distinguish in Plate 1 a stroke of *alkaline hornblende gneiss*. Even the amphibole of this rock is alkaline.[2] It displays secondary prisms and short columns that have crystallized as solitary individuals of variable orientations. Simultaneously, the original minerals have re-crystallized and grown larger. The ancient sediment has thus obtained a rather granitic habitus. In thin sections, however, the primary stratification may still be traced, though it has frequently been destroyed during the growth of the secondary crystals.

The typical hornblende gneiss of the stroke distinguished in Plate 1 is a pink or reddish white, medium- to fine-grained rock composed as follows: microcline > quartz > oligoclase-albite > black hornblende ≫ garnet, titanite, and zircon. (The three last-mentioned are minor minerals.) A geometric analysis of the alkaline hornblende gneiss 3 km NW of Kållered church has given the following data (volume-%):

Microcline	46.0
Quartz	29.5
Oligoclase-albite	18.4
Alkaline hornblende	6.0
Garnet, titanite, zircon	0.2
	100.1

Σ felsic minerals = 93.8 % Σ mafic minerals = 6.2 %

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[1] Perthitic interlamination of acid plagioclase is uncommon.

[2] In the Gothenburg region, H. E. Johansson (1931, p. 34) has observed alkaline clinopyroxene, too.

For comparison, a sample of the common alkaline gneiss 2 km W of Mölndal church has also been subjected to geometric analysis (volume-%):

Microcline	44.1
Quartz	29.5
Oligoclase	18.8
Biotite	3.8
Titanite	1.5
Common hornblende	1.0
Magnetite	0.8
Garnet	0.3
Zircon, ilmenite etc.	0.2
	100.0

Σ felsic minerals = 92.4 % Σ mafic minerals = 7.6 %

The relative and absolute contents of the three felsic minerals are thus about the same in both rocks. All the minerals of the rocks are fresh, and no indications of tectonization have been observed. In view of their exposed positions in the Gothenburg-Onsala fold (see Plate 1), it is therefore evident that the rocks considered cannot possibly have obtained their present appearance before the final Gothian migmatization. Indeed, I am inclined to interpret it as a product of this process. The hornblende of the quartzite-sandstone rock earlier described should thus have developed simultaneously with the amphibole of the alkaline gneiss, and both should be products of metasomatism (compare below).

The hornblende of the common alkaline gneiss shows normal pleochroic colours (γ — deep blue-green, β — deep olive-green), whereas the amphibole of the alkaline hornblende gneiss has quite another pleochroism: γ (sometimes α) — deep blue, β — deep blue-violet, α (sometimes γ) — pale green-yellow, or grey-green, or medium green-yellow. The extinction angle is very small. In most individuals, $\gamma/\backslash c$ falls between 0 and 5°. The birefringence is here moderate, *viz.* 0.012 à 0.014. A minority of individuals (with inverse pleochroism as indicated by the parentheses above) show $\alpha/\backslash c = 0—5°$ and very weak birefringence. It is quite obvious that we have here to do with two members of the glaucophane-riebeckite series. Most of the crystals examined have to be classed as *crossite* (intermediate stage between glaucophane and riebeckite), whereas the weakly birefringent individuals show optical properties that are characteristic of *riebeckite*.

The composition of crossite approximately corresponds to the following formula: $OH(OH,\mathrm{Na})\ Na_2\ (\mathrm{Mg},\ Fe^{++})_3\ (\mathrm{Al},\ Fe^{+++})_2 Si_8 O_{22}$

In riebeckite, the iron content has increased:

$$(OH)_2 Na_2 Fe_3^{++} Fe_2^{+++} Si_8 O_{22}$$

Both sorts of amphiboles are thus rich in sodium and iron. The former metal has been supplied by metasomatism, the latter derives from the magnetite that is now lacking. The magnesium of the crossite is likely to have come from pre-existent biotite.

Two chemical analyses of red, granitic, fine-grained alkaline gneiss from Gothenburg have been published by P. J. Holmquist (1906, pp. 268—69):

Fig. 15. Intense selective weathering of alkaline gneiss. $2^1/_2$ km W of Mölndal church. Photo by G. Lundqvist 1951.

	I. S of Johannis' church	II. At Vega street
SiO_2	75.34	75.69
TiO_2	0.15	0.16
Al_2O_3	12.51	11.64
Fe_2O_3	0.62	1.30
FeO	1.52	0.84
MnO	0.23	0.21
MgO	0.20	0.20
CaO	0.40	0.75
Na_2O	2.00	2.42
K_2O	6.55	6.16
P_2O	—	0.04
H_2O	0.36	0.66
	99.88	100.07

In the southern, south-western and western slopes of many hills and mountains, the hornblende-bearing alkaline gneiss of the Gothenburg-Mölndal region has been and is still being subjected to a rather intense mechanical weathering of the same kind that has given origin to the name of the Finnish *Rapakivi*[1] granite (Plate 1 and Fig. 15; see also the Swedish geological map-sheet 'Göteborg'[2]). There seems to exist a positive correlation between alkalinity and disposition of weathering, as already suggested by H. E. Johansson (1931, pp. 34—35).

As is displayed by Fig. 15, the weathering of the alkaline gneiss works

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[1] *Rapa kivi* = rotten stone.

[1] Sveriges geol. undersökn., Ser. Aa, N:o 173, Stockholm 1931.

selectively. Part of the gneiss has thus escaped disintegration and remains as ovoids or sheets in the mass of sliding gravels.

The remaining gneisses of the mainland part of the Mölndal-Styrsö-Vallda region expose to view a spectrum of basic and intermediate and even acid, re-crystallized and often granitic varieties. The general mode of occurrence (interstratifications etc.) and principal kinds of alteration of these *common gneisses* have already been described. The basic gneiss essentially consists of plagioclase, quartz, common hornblende, and biotite, while the intermediate and acid varieties are most frequently characterized by an increasing content of microcline. Simultaneously, the hornblende has been seen to disappear gradually or suddenly. In most cases, the intermediate and acid varieties are also richer in quartz and poorer in plagioclase than the basic ones. A typical exponent of magnetite-bearing acid gneiss will be found in Table II. The plagioclase is an oligoclase or, in the basic varieties, sometimes an oligoclase-andesine. Titanite, magnetite (often titaniferous), and apatite are the minor minerals most frequently met with, though zircon and pseudo-allanite are also characteristic accessories, at least in the intermediate and acid varieties. The occurrence of muscovite seems to be more accidental. (The mainland slate derivatives are then not considered.)

Garnet is quite rare, whereas epidote is the leading secondary mineral of the common gneisses. In certain strokes, it belongs to the main minerals. The same must also be said of the late Gothian granites described in the next chapter. In the above text, we have seen that epidote is a first-rate constituent of the quartzite-sandstone rock, too, and that it is common even in the basic volcanics.

Epidote is a typical low-temperature mineral. My investigation of the Askim granite at Gottskär (P. H. Lundegårdh 1951, p. 181 ff.) has shown that it is secondary and post-tectonic. Most frequently, it appears as aggregates of flocks of idiomorphic grains. At Gottskär, the epidote seems to have developed simultaneously with the microcline porphyroblasts of the granite. As I am inclined to interpret the latter as products of the final Gothian migmatization, I should also like to place most epidotization at the end of the Gothian era, in spite of the finds of Karelian granite and pegmatite S of Gothenburg.

The presence of garnet and, in the alkaline gneisses, hornblende, too (see above), as a rule excludes the occurrence of epidote. As the former are high-temperature minerals, this might indicate a contemporaneous development of all these minerals. Indeed, considering the mainland part of the Mölndal-Styrsö-Vallda region, the north-eastern corner is without doubt characterized by another mineral facies than the rest of the region. Compare, for instance, the garnet-bearing supra-crustal dolerite NNW of Kållered church (p. 19) with its chemical equivalents in the Särö-Vallda region. In the latter, the primary clinopyroxene has a rule been totally altered and instead of garnet we find epidote. Compare also once again the hornblende-garnet-bearing alkaline gneiss NW of Kållered church with the epidote-bearing alkaline gneiss SSW of Kållered. It is significant that in the gneiss at Kållered

Table II.

Chemical analyses of rocks from the Mölndal-Styrsö-Onsala region.

Analyst: A. Aaremäe.

Kind of rock	Gneiss, grey, acid	Basaltic tuff, agglomeratic	Plagioclase-porphyrite	Uralite-porphyrite	Granite, grey, rather basic	Askim granite	Dolerite (dike)
Locality	At the highway 2.5 km SSW of Gottskär[1]	At the highway NW of Meryt[1]	South-eastern part of Vinga	2 km WNW of Meryt[1]	75 m ENE of Släp church	1.5 km E of the railway station of Billdal	4.5 km ESE of the railway station of Billdal
SiO_2	72.34	48.97	59.47	46.56	63.39	66.88	49.10
TiO_2	0.39	1.25	1.77	0.47	0.72	0.58	2.96
Al_2O_3	12.94	15.61	14.11	7.16	16.14	15.35	17.18
Fe_2O_3	0.47	1.67	1.99	3.28	1.77	0.99	1.76
FeO	2.48	8.16	7.20	6.59	3.68	3.02	9.63
MnO	0.06	0.17	0.12	0.14	0.09	0.06	0.12
MgO	0.64	7.52	2.11	16.94	2.05	1.26	4.68
CaO	1.16	9.54	4.70	14.94	4.76	3.54	7.37
BaO	0.07	0.03	0.05	0.03	0.05	0.05	0.04
K_2O	5.74	1.88	3.24	0.47	2.40	3.30	1.37
Na_2O	2.34	2.38	3.02	0.55	3.43	3.26	3.65
P_2O_5	0.11	0.18	0.52	0.08	0.16	0.15	0.48
$H_2O > 110°$	0.97	2.31	1.49	2.81	1.39	1.10	1.27
S	0.05	0.28	0.09	0.08	0.18	0.23	0.11
F	0.19	0.09	0.16	0.01	0.02	0.20	0.03
$H_2O < 110°$	0.08	0.18	0.08	0.11	0.14	0.14	0.15
Sum	100.03	100.22	100.12	100.22	100.37	100.11	99.90
Oxygen replaced by sulphur and fluorine	0.10	0.15	0.10	0.04	0.08	0.17	0.04
Total sum	99.93	100.07	100.02	100.18	100.29	99.94	99.86

both hornblende and epidote belong to the ordinary constituents, whereas garnet is already lacking. Pressure conditions being favourable, garnet and epidote can join, however. The gneiss 2½ km SSW of Gottskär (see Table II), for instance, contains both the low-temperature mineral epidote and the high-pressure mineral garnet, though the latter only occurs as sparse grains in the mafic layers of the rock.

The slate gneiss stroke of the Styrsö archipelago is also free from epidote, whereas garnet is sometimes met with. Furthermore, the slate gneiss seems to have become migmatized in latest Gothian time, *viz.* at the same time as the gneissic rocks of Eastern Mölndal. The slate gneiss stroke and the rocks of the north-eastern corner of the region investigated can therefore be said to have been simultaneously subjected to the same kind and degree of metamorphism.

The rapid variations of metamorphism within the Gothenburg-Onsala fold have already been touched upon in my Onsala paper (P. H. Lundegårdh

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[1] See P. H. Lundegårdh 1951, Plate 1.

1951). I there considered them to be indicative of the existence of two supra-crustal series. According to this opinion, we should have to deal with preserved associations of secondary minerals developed by altering agents of different ages. The above interpretations have, however, shown that, in the Gothenburg-Onsala fold, two mineral facies have been able to develop simultaneously in different parts of the same rock. Furthermore, the mode of occurrence of the acid gneiss rich in alkaline hornblende bears evidence of sudden changes of the degree of one and the same alteration process. Examples of similar rapid intensifications of regional metamorphism are displayed by the charnockites of Central and Southern Halland (P. Quensel 1951). As these also belong to the Gothian evolution of rocks, they may, indeed, have attained their present mineral facies simultaneously with the development of alkaline hornblende in the Gothenburg-Mölndal region (Quensel 1951, pp. 315 and 318).

Porphyrite with Phenocrysts of Plagioclase.

The naked isles of Vinga, Koholmen (immediately S of Vinga), and Fjärskär (2 km ESE of Vinga; see Plate 1) expose a supra-crustal greenstone of peculiar chemical composition (Table II; see also Table III and p. 55). The weathered surface of the rock has a pale reddish-grey hue (on Fjärskär grey-red) that made me expect to meet with a granite when I first landed at Vinga. The yellowish-white felspar eyes immediately reminded me of phenocrysts, however. A great number of well-preserved xenoliths (Fig. 16) soon confirmed the correctness of my primary impression. Indeed, the porphyritic greenstone seems to have wholly escaped secondary alterations, and no signs of tectonization except jointing have been observed.

In fresh specimens, the Vinga greenstone displays a fine-grained greenish black-grey matrix essentially composed of common hornblende with sparse remnants of clinopyroxene and oligoclase (at times tabular) with alteration products, sericite especially (compare the high potassium value in Table II) but sometimes calcite and clinozoisite, too. Further, the matrix, which is xenomorphic, contains much titanomagnetite, quartz, and microcline. Minor minerals are penninite, biotite, and apatite (numerous rods). The felspar phenocrysts are in part tabular and also composed of oligoclase.[1] Fresh phenocrysts have a greyish-greenish-white hue. On the whole, oligoclase is the leading mineral of the rock.

The hornblende of the plagioclase-porphyrite is optically negative (2V large) and pleochroic in various shades of green. It has developed as aggregates of small individuals showing irregular shape and variable orientation. It is associated with titanomagnetite, at times with biotite and penninite, too.

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[1] When my thin sections of rocks from the Mölndal-Styrsö-Vallda region were examined, a basic porphyritic xenolith filled one section completely and therefore happened to be intermixed with the ordinary plagioclase-porphyrite. The plagioclase of the xenolith proved to be andesine to labradorite, and thus the plagioclase-porphyrite was at first presented to Swedish petrologists as porphyrite with phenocrysts of labradorite (Geol. föreningens i Stockholm förhandl., Bd 74, p. 531, Stockholm 1953).

Fig. 16. Plagioclase-porphyrite with xenolith of quartzite enclosed in thin shell of hornblende. Isle of Vinga, parish of Styrsö. Photo by P. H. Lundegårdh 1952.

In the clinopyroxene, a diallage, $\gamma \wedge c$ amounts to about 43°. As mentioned, most clinopyroxene occurs as remnants in the hornblende. Single minute crystals have, however, also been observed in the oligoclase. Obviously, these have been saved from alteration thanks to the surrounding felspar.

The quartz and microcline are the latest primary minerals of the plagioclase-porphyrite. Their mother liquor, a typical residual solution, has moved in the intergranular film, and their replacement of pre-existent minerals has started from there. Among the phenomena developed by this process, I shall mention myrmekitic intergrowths. Simultaneously, the water and potassium of the rest solution have effected strong autometamorphism and autometasomatism. The uralitization of the pyroxene and the sericitization of the plagioclase bear witness of this alteration. In connection with the sericitization, the plagioclase has become impregnated with minute hematite grains. On Vinga and Koholmen, the deuteric sericitization is moderate and the impregnation weak or sometimes even lacking, whereas on Fjärskär, which seems to lie nearer the border of the plagioclase-porphyrite, the oligoclase individuals of the matrix have been completely changed into a sericite mass crowded with hematite grains. Neither the quartz nor the microcline has escaped the hematite impregnation, and most of the rock thus displays a beautifully red colour. Simultaneously, part of the uralite and all of the biotite have been chloritized.

Only the phenocrysts have remained comparatively intact, inasmuch as their kernels are free from hematite and their sericitization is incomplete.

The borders of the plagioclase-porphyrite are covered by the sea. As already touched upon, the rock is, however, very rich in well-preserved angular xenoliths. Pieces of early Gothian quartzite (Fig. 16) are most common, but a great number of the xenoliths display various other rocks such as red felsic gneiss, sandy slate belonging to the Marstrand-Styrsö stroke, meta-basites (compare the foot-note on p. 30), and pegmatite derived from some kind of veined gneiss. Furthermore, single remnants of a red helsinkitic rock have been encountered. On the other hand, xenoliths of late Gothian granites have never been observed, although Frölunda granite (also non-deformed) occurs as near as on In-Vinga, two small islands lying 1 km NNE of Vinga (see Plate 1). I therefore feel like equalizing the plagioclase-porphyrite with the latest Gothian volcanics,[1] in spite of the fact that no indications of secondary metamorphism have been traced. The xenolithic pegmatite should then be at least early Gothian. (Xenoliths of Svionian = Pre-Gothian rocks may of course occur in the plagioclase-porphyrite.)

Most of the quartzite xenoliths and part of the others have been enclosed in thin shells of black hornblende during the solidification of the plagioclase-porphyrite (Fig. 16). We have earlier seen (p. 21), that similar hornblende shells have been found around many of the oval quartzite pebbles of the late Gothian conglomerate. Furthermore, we have observed that some of these pebbles have been completely amphibolized. We do not know, whether this alteration is primary or secondary. If it is primary, we have, however, to interpret the amphibolitic matrix of the conglomerate as a basic lava.

Infra-Crustal Rocks.

Davainite, Gabbro, Diorite.

In magmatic evolutions, ultra-basic rocks as a rule develop first. It is thus quite natural, that even in the Gothenburg-Onsala fold the earliest products of magmatic differentiation are ultra-basites. These are rare rocks, however. In the Mölndal-Styrsö-Vallda region, we only know three small deposits of ultra-basic magmatic differentiation products, while on the Onsala peninsula five minor masses have been discovered (P. H. Lundegårdh 1951, p. 170). A sample from one of latter has been analysed chemically (Table II).

In Table I, I have tried to distinguish between two generations of magmatic ultra-basites. The older of these should correspond to the soapstones of Dalsland (see W. Larsson 1947) and Brattön ENE of Marstrand (near the locality shown in Fig. 4).

The younger ultra-basites have intruded into the late Gothian supra-crustal series, probably at the beginning of the late Gothian folding. Both generations of ultra-basite are frequently associated with normal gabbroic rocks.

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[1] In the Åmål series (Table I), we have also porphyrites.

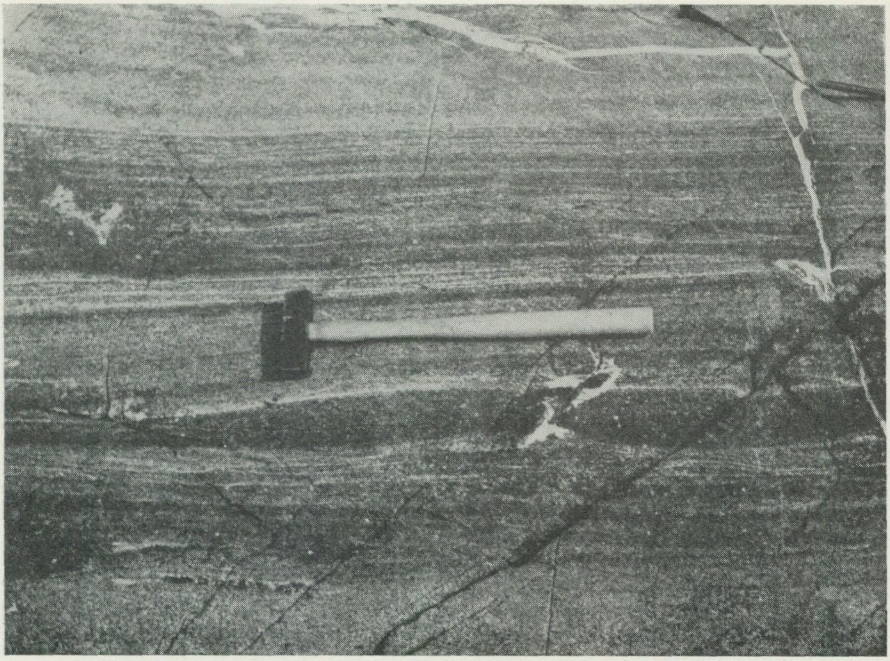

Fig. 17. Amphibolized olivine-gabbro with bands of davainite (meta-peridotite). Stensholmen (islet NW of Särö), parish of Släp. Photo by P. H. Lundegårdh 1951.

The ultra-basic magmatic differentiation products of the Mölndal-Styrsö-Vallda region are situated on Stensholmen 2 km NW of the centre of Särö, further 2 km SSE and 2 km S of Vallda church (Plate 1). The Stensholmen ultra-basite occurs as parallel sheets in a metamorphic olivine-gabbro passing into diorite or dioritic amphibolite. The orientation of the sheets is in general N15°E, 65°ESE. They usually appear as bands in the outcrops examined (Fig 17).

The ultra-basic sheets of Stensholmen display a black green, felt-like matrix of variable grain. During the late Gothian tectonization, they have become rather schistose. They are composed as follows: hornblende $>$ penninite $>$ magnetite $\gg$ biotite $>$ pyrite $\approx$ calcite $\gg$ apatite. They should be classed as *davainitic* (compare below).

The hornblende has developed as larger and smaller, xenomorphic, or sometimes hypidiomorphic (prismatic), individuals which have become intermixed with penninite all through the rock. In this mass, the remaining minerals have been scattered in a rather poikilitic manner, though they are in part idiomorphic (the pyrite especially). Much of the calcite has crystallized along fissures, however. In thin sections, two kinds of hornblende have been observed, *viz.* a common one showing rather strong pleochroism and an actinolitic one that has very pale pleochroic colours. This indicates that the original rock has been a lherzolite (a peridotite very rich in clinopyroxene).

The Stensholmen davainite has been subjected to spectral analysis (Table III). The data obtained are discussed on p. 55.

The davainitic sheets seem to have developed by rhythmic crystallization differentiation of a gabbroic (= basaltic) magma, though the possibility of metamorphic banding cannot be wholly rejected (compare P. H. Lundegårdh 1946, pp. 73—75). The interstratified olivine-gabbro has altered to hornblende-gabbro, and the diorite also consists of plagioclase and secondary hornblende. When grading or changing into amphibolite (= the margin of the basic intrusion), the diorite is never banded. The davainite and amphibolitic-dioritic rocks have in part been brecciated by mobilized gneiss (Fig. 18).

The ultra-basic intrusion 2 km SSE of Vallda church displays a sheet-like, steep, homogeneous mass of black-green, medium-grained to coarse davainite with a marked tendency to porphyritic texture (hypidiomorphic hornblende porphyroblasts). During the late Gothian tectonization, a great number of fissures parallel to the schistosity of the adjacent gneiss and granite have developed. The hornblende grains around the porphyroblasts have then been frequently crushed.

Except hornblende, which is the predominant mineral, the davainite SSE of Vallda consists of moderate quantities of biotite and smaller amounts of titanite, epidote, apatite, magnetite, and pyrite. Furthermore, the occurrence of sparse individuals of primary plagioclase should be reported. These are almost completely altered to saussurite, however. Accidental grains of secondary, rather fresh and acid plagioclase have also been observed.

The hornblende is a common secondary one with pale green pleochroism. $\gamma \wedge c$ amounts to about 12° and $2V\gamma$ to 95—100°.

The ultra-basite 2 km S of Vallda church has developed quite similarly though the intrusive body is here more rounded than SSE of Vallda and the visible marginal zone rather dioritic or amphibolitic. Mobilized acid gneiss has also repeatedly penetrated and brecciated this davainite.

Among the metamorphic basic volcanics of the Mölndal-Vallda region, davainitic rocks have been observed in a few outcrops. The areal distribution of these wholly secondary ultra-basites is very restricted.

Gabbro is as rare a member of the Mölndal-Styrsö-Vallda rock family as davainite. The metamorphic olivine-gabbro on Stensholmen NW of Särö has already been mentioned. In the mainland part of Plate 1, gabbro will only be found in the mountains $3^1/_2$ à 4 km S of Mölndal church and 2 km ENE—NE of V. Frölunda church.

The gabbro S of Mölndal is a strongly metamorphic, greyish or greenish black, fine- to medium-grained rock which passes into quartz-diorite. The only primary constituent of greater importance is a corroded tabular plagioclase, most of which has altered to sericite. The rest of the rock essentially consists of common hornblende that seems to be secondary after clinopyroxene, of granoblastic oligoclase, and of biotite. Granoblastic and in part poikilitic quartz is frequently also a rather important mineral. With increasing content of quartz, the gabbro passes into quartz-diorite. Minor minerals are apatite and

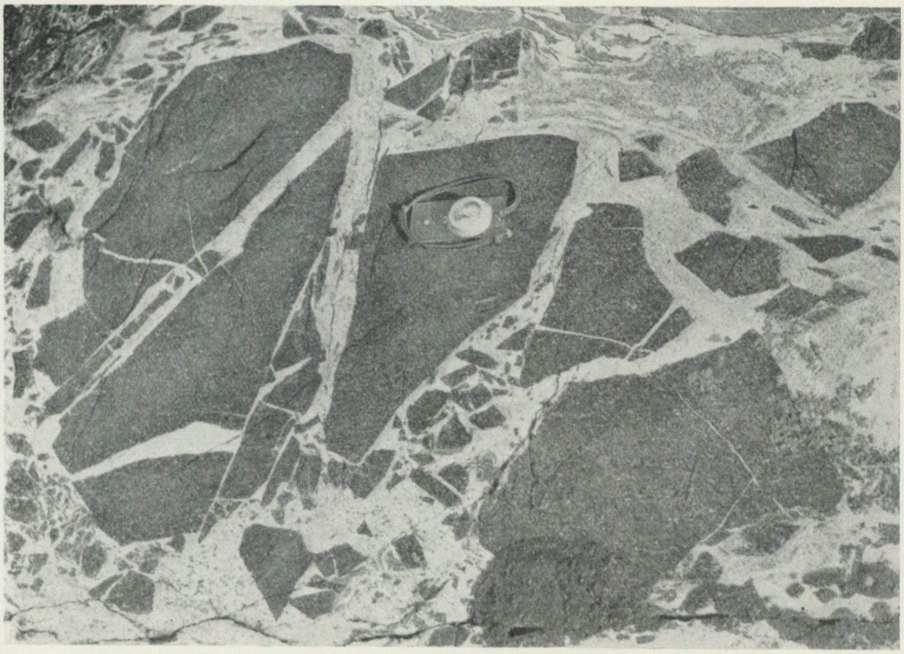

Fig. 18. Amphibolite and davainite brecciated by mobilized intermediate gneiss. Stensholmen, parish of Släp. Photo by P. H. Lundegårdh 1951.

titanite. The latter is especially common in the dioritic varieties. Pyrite is the only accidental constituent met with.

The gabbro 2 km ENE—NE of V. Frölunda church has developed quite otherwise. A single look at this lens of grey(greenish)-black, rather fine-grained *biotite-norite* enclosed in an amphibolitic uralitization shell (Plate 1) will be enough to distinguish it from the greenstones above described. Genetically, the biotite-norite belongs to the Slottskogen[1] stroke of hyperitic dolerite and norite and amphibolitic derivatives described by H. E. Johansson (1931, pp. 32—33). The Slottskogen basite has in part been disjointed during the late Gothian tectonization, as evidenced by the lens 2 km ENE—NE of V. Frölunda.

The mineral composition of the biotite-norite of this lens is as follows: plagioclase $>$ biotite $\approx$ augitic diallage $\gg$ quartz $>$ uralite $>$ magnetite $\approx$ hypersthene $\gg$ apatite (minor mineral). A spectral analysis is given in Table III. The data obtained are discussed on p. 56.

The plagioclase is sometimes tabular but more often xenomorphic. The largest individuals show zonal extinction (margin = 30 % anorthite, kernel = 50 % anorthite). On the whole, the plagioclase is an andesine (35 % anorthite or a little more). Now and then, the plagioclase individuals have in part altered to sericite.

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[1] Municipal park in South-Western Gothenburg.

The biotite forms large primary packs of sheets showing beautiful pleochroism in red-brown. These packs are frequently associated with magnetite. The augitic diallage is well-preserved though in many cases marginally uralitized. $2V\gamma$ amounts to about 65° and $\gamma/\!\!\setminus c$ to about 45°. As a rule, it constitutes fairly small individuals and at times aggregates of rounded grains, whereas the hypersthene has developed as somewhat larger and less xenomorphic individuals. The hypersthene has also remained rather intact.

The quartz is late and penetrative. Myrmekitic intergrowths have been met with in single cases. The uralite is a common hornblende pleochroic in various shades of green.

The Slottskogen stroke of noritic basites obviously continues far southwards, though it has there become disjointed and as a rule completely uralitized, too. At present, it is thus characterized by dioritic and amphibolitic greenstones that most frequently cannot be distinguished from the metamorphic basic volcanics of the region. $3^1/_2$ km SE of Billdal, however (Plate 1), an eastern—western, dioritic and in part meta-noritic, xenolith measuring 800 m in length has been found in intrusive Askim-granite that locally passes into plagioclase-granite. W. Larsson, who has investigated the late Gothian diorite of Northernmost Dalsland (Table 1), has told me that this rock has the same general appearance as the greenstone SE of Billdal. The mode of occurrence of both rocks is also similar (compare mutually Plate 1 and W. Larsson 1949).

Most part of the xenolith $3^1/_2$ km SE of Billdal displays an amphibolitic quartz-bearing diorite, but now and then and especially in the westernmost part of the xenolith, the meta-noritic character is quite obvious. A thin section from here shows a greenstone consisting of plagioclase $\approx$ uralite $>$ magnetite $\gg$ quartz $\approx$ biotite $>$ epidote $\gg$ apatite (minor mineral) $\gg$ pyrite (accidental mineral).

The plagioclase contains about 50 % anorthite (andesine-labradorite) and has in part crystallized as hypidiomorphic, lath-shaped individuals. Frequently, it has undergone partial sericitization. Flocks of minute grains of epidote, in part idiomorphic, are also common. The quartz of the rocks is late, interstitial and penetrative. Some plagioclase individuals grow acid when bordering upon quartz.

The uralite shows $2V\gamma$ about 95° and variable $\gamma/\!\!\setminus c$. Its pleochroism is green and most frequently, especially in larger individuals, marginally strong and centrally weak. Oriented microlites of ilmenite occur now and then. Furthermore, single remnants of augite must be reported. Most of the uralite is evidently secondary after this mineral, though pseudomorphs after hypersthene have been sometimes observed, too.

As already mentioned (p. 18), the leading greenstones of the Mölndal-Styrsö-Vallda region are secondary, amphibolitic and dioritic rocks (see also Plate 1). Most of the latter have been shown to derive their origin from the same kind of basites as the former and have therefore to be classed as mere alteration products of basic volcanics (compare P. H. Lundegårdh 1951, p. 174). These dioritic rocks have developed during the late Gothian folding, simultaneously with the late Gothian granites. Thus, even regarding their age, they do not differ considerably from the majority of those rather few dioritic rocks that can be proved to have an infra-crustal magmatic origin, for instance the rock $3^1/_2$ km SE of Billdal (see above). The only distinction is the slightly higher age of the latter (see Table 1).

These statements evidence that transitions between dioritic and amphibolitic rocks are very common (compare also Plate 1 and P. H. Lundegårdh 1951: Plate 1). They also tell us that no mineralogical differences do as a rule exist between the two groups of basites. The diorite and quartz-diorite thus essentially consist of plagioclase, common hornblende, biotite, and quartz (main mineral only in the latter kind of rock). Furthermore, epidote is an important constituent that at times must be classed as a main mineral. It is frequently accompanied by considerable quantities of chlorite. Minor constituents are apatite, titanite (which is lacking in many samples of diorite[1]), and magnetite (most often titaniferous). Now and then, pyrite has also been observed.

The dioritic basites display grey, grey-green, black-green, or greenish-grey-black, fine- to medium-grained rocks. The plagioclase, an andesine (in the quartz-diorite sometimes oligoclase-andesine), is in part tabular, whereas the remaining minerals (except the epidote) are xenomorphic. In samples of primary diorite, the plagioclase may show zonal extinction. Most frequently, the mineral has in part altered to sericite, and in many cases it has also become filled with minute, idiomorphic or hypidiomorphic crystals of epidote.

The hornblende is pleochroic in various shades of green. $2V\gamma$ as a rule lies between 95 and 100°, $\gamma/\backslash c$ between 15 and 20°. Poikilitic inclusions of quartz have been found in many samples. The hornblende has most frequently developed as aggregates of grains including most part of the other mafic minerals, though single grains and larger, penetrative individuals also occur.

The quartz is late, penetrative, and therefore often poikilitic.

Most of the epidote and chlorite of the dioritic rocks seem to have developed during the final stage of the late Gothian migmatization and, in any case, contemporaneously with the epidote of the late Gothian granites (see p. 38). Partial or total re-crystallization of some of the dioritic (and amphibolitic) rocks are also likely to have occurred during this epoch, though of course somewhat earlier than the crystallization of the low-temperature minerals just mentioned (compare the alteration of the Sillfarsholmen quartzite-sandstone rock, p. 21). Indeed, we have in certain kinds of diorite (for instance on Sillfarsholmen) large schillering intergrowths of hornblende which have developed later than the remaining amphibole and, at least a part of the plagioclase of the rocks in question. The occurrence of such greenstones twice altered seems to be as accidental as the occurrence of hornblende porphyroblasts in the quartzite-sandstone rock and alkaline gneiss (see the foregoing chapter).

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[1] Titanium is as a rule concentrated in late products of differentiations of basic magmas (see P. H. Lundegårdh 1950).

Granites.

The Gothian granites of the Swedish West Coast can be divided into two groups, *viz. early Gothian* and *late Gothian granites*. The former seem to be rare in the Mölndal-Styrsö-Vallda region. Indeed, they have only been traced in the veined gneiss stroke E of the Gothenburg-Mölndal-Kungsbacka fault. It is, however, difficult to distinguish them there from supra-crustal gneisses, and they have thus not been marked on Plate 1.

In the region considered, the late Gothian granites constitute the dominant group of acid infra-crustal rocks. They have been painted brown in Plate 1. They have to be classified as follows:

1. Black-grey to dark grey, basic granite most frequently rich in hornblende. This granite frequently passes into quartz-diorite.
2. Red-grey to grey, intermediate granite (Frölunda granite and plagioclase-granite).
3. Red-grey to red, rather acid granite (microcline-granite).
4. Grey-red to dark red-grey granite with coarse eyes of microcline (Askim granite).

The late Gothian granites are most frequently rather gneissic. This structure is generally due to tectonization and appears as plane and linear schistosities (Figs. 1—2). The resultant rock is thus a typical *gneiss-granite*, or schistose granite. As I mentioned in the introduction, the strength of the tectonization has been highly variable. In Plate 1, strokes of granite (and other rocks) showing marked schistosity have been striated.

Sometimes, the parallel structure of the late Gothian granites has another origin. In those cases when the granites have developed *in situ* by alteration of pre-existent rocks (granitization *in situ*), gneissose remnants of the altered rocks are common. A granitized mica schist, for instance, can thus be recognized as parallel bands, *schlieren* etc. in the secondary granite, which has then to be classed as *granite-gneiss*, or gneissose granite. The granite-gneisses can of course also have been subjected to tectonization. Rocks that are at the same time gneissose and schistose can therefore sometimes be encountered. The schistosity may even cut the gneissosity. Moreover, examples are known where dikes of gneiss, mobilized along disjointing planes of schistosity during the final Gothian migmatization, cut *schlieren* and sheets of remnant gneiss and meta-basite in secondary granites (especially in various parts of the coast region between Fiskebäck and Kullavik; see Fig. 23).

The *basic granite* is concentrated in the south-eastern part of the Mölndal-Styrsö-Vallda region (Plate 1). It displays a black-grey to dark grey, fine- to medium-grained, locally non-deformed but far more often gneissic rock (quartz-dioritic gneiss-granite). Main minerals are plagioclase, quartz, biotite, common hornblende, and, in most samples investigated, epidote, too. As has been mentioned earlier, the epidote has developed secondarily, in most part of the region probably during the final Gothian migmatization (see p. 28). Around the late Karelian rocks in the north, epidotization also seems to have occurred in late Karelian time, however (p. 47). Now and then, this mineral has replaced all the hornblende, for instance at Släp church (the basic granite analysed in Table II). It has crystallized as small individuals which frequently expose well-defined faces and are then rod-shaped. It does not only form interstitial individuals but has also crystallized onto the biotite. Further, it appears as flocks of minute idiomorphic and hypidiomorphic grains in the plagioclase (which has simultaneously lost part of its lime). The latter should be defined as an oligoclase-andesine or basic oligoclase, that has frequently re-crystallized to acid oligoclase, or in rare cases even to oligoclase-albite, during the epidotization. Partial sericitization is another common kind of alteration. The larger plagioclase individuals are often roughly tabular (primary hypidiomorphic development). Plagioclase is most frequently the leading mineral of the basic granite, which also repeatedly passes into intermediate plagioclase-granite.

The xenomorphic or hypidiomorphic hornblende shows normal pleochroism in various shades of green. $2V\gamma$ as a rule falls between 90 and 100°, $\gamma/\backslash c$ between 18 and 20°.

The minor minerals are the normal ones of basic granites, *viz.* titanite, titaniferous magnetite (in part probably titanomagnetite), and apatite. In the plagioclase, zoisite is sometimes met with, and the biotite may locally have altered to penninite. Late microcline appears now and then, frequently as porphyroblasts. Single grains of zircon, allanite (in part pseudo-allanite), and pyrite have also been observed in many samples of basic granites.

As touched upon above, a sample of rather basic granite from Släp church has been analysed chemically. Epidote belongs to the main minerals of this rock and has there replaced all the hornblende. Furthermore, it has aquired part of its lime from the plagioclase. The rock is now composed as follows: oligoclase $>$ quartz $>$ biotite $>$ epidote $\gg$ titanite $\gg$ apatite $>$ pyrite. Apatite and pyrite are minor minerals, whereas titanite has occupied a somewhat stronger position.

Most of the basic granite seems to have developed on crystallization of a secondary magma (see the plagioclase-granite below).

The *intermediate granite* comprises two different varieties, *viz.* the Frölunda granite, which is rich in microcline, and the plagioclase granite, which is as a rule poor in, or free from, microcline. Furthermore, muscovite is rather frequent in the former.

The *Frölunda granite* is concentrated in and N of the Fiskebäck-Näset-V. Frölunda area, where it is the dominant rock. It displays a grey, or at times red-grey, medium- or fine medium- to fine-grained rock, which has most frequently escaped tectonization. The Frölunda granite consists of quartz, oligoclase (often showing weak sericitization), microcline (sometimes perthitic), and biotite (second-rate main mineral). Muscovite and secondary epidote (see the basic granite) are rather important constituents, too. Titanite, apatite, and sometimes also magnetite should be classified as minor minerals.

The Frölunda granite is in most cases quite homogeneous. Now and then, however, it displays alternating, parallel, straight or slightly winding sheets of variable composition. All gradations exist between hardly recognizable inhomogeneity and distinct banding, as can be seen both on and near the coast between Fiskebäck and Näset (Plate 1). Among banded varieties there encountered, I shall mention a rock composed of alternating layers of dark grey, rather basic granite and red grey, rather acid granite.

Moreover, the Frölunda granite frequently contains concordant *schlieren*, bands, and dike-like sheets of rocks with preserved supra-crustal characters. This even holds for homogeneous varieties. I have already mentioned the granite on St. Känsö and Vargö with its *schlieren* of mica inherited from pre-existent slate gneiss (p. 16). I will also call attention to the In-Vinga isles N of Vinga. Fig. 24 displays a detail of the bed-rock on In-Vinga. The narrow greyish white bands and *schlieren* are Frölunda granite, whereas the thick grey layers are re-crystallized, more or less granitic supra-crustal gneiss. The Frölunda granite is here intermediate to acid, the gneiss basic to intermediate. On part of In-Vinga, the gneiss vanishes, however, and the Frölunda granite forms rather homogeneous masses.

The petrological data now reported show that most of the Frölunda granite has developed by granitization *in situ*. Furthermore, the considerable content of muscovite and the petrographical character of the supra-crustal remnants indicate that the pre-existent rock has been early Gothian slate gneiss with intercalated layers of basic volcanics.

Of course it is the most resistant layers of the pre-existent slate gneiss stroke and especially then the intercalated beds of meta-basites (amphibolitic and femic gneisses) that have been preserved as sheets in the secondary granite. Owing to tectonization during the granitization, these sheets have often been disjointed and now appear as rounded or angular pieces. Fig. 21 shows such an irregular inclusion.

However, real eruptive dikes that are older than the post-Gothian diabase and dolerite also occur in the late Gothian granites, as has been already touched upon in my description of the geological map-sheet 'Onsala' (P. H. Lundegårdh 1952, Fig. 10[1], p. 29). At Västra Hagen, an important petrological locality situated 1¼ km NE of the centre of Onsala Sandö (see P. H. Lundegårdh 1951, Plate 1), such dikes have been shown to derive from gneisses that have become plastically deformed and in part mobilized during the final Gothian migmatization. In the Mölndal-Styrsö-Vallda region, sparse though straight and sometimes rather extensive dikes of mobilized gneiss have also been observed (Fig. 23). These dikes are as a rule grey, fine-grained, and acid to intermediate.

Further, the existence of dikes of late Gothian palingenic granites should be reported. Both basic granite, plagioclase-granite, and Askim granite are represented among these dikes. As a rule, they penetrate gneisses and basites bordering upon masses of granite (Figs. 19—20), but they may at times occur

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[1] With the exception of this figure, the paper in Swedish now cited does not differ from P. H. Lundegårdh 1951.

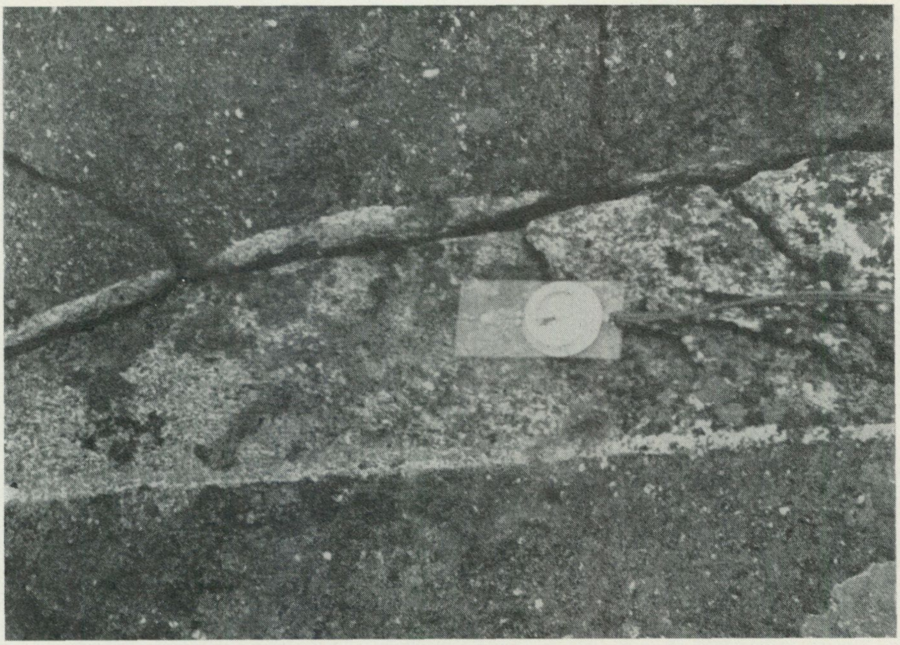

Fig. 19. Dike of grey plagioclase-granite in quartz-dioritic amphibolitic gneiss. Stora Småholmen (islet SW of Billdal), parish of Askim. Photo by P. H. Lundegårdh 1951.

even in granitized rocks, such as the Frölunda granite. In the left part of Fig. 21, we observe a dike of grey, rather basic plagioclase-granite in Frölunda granite. As is also shown in Fig. 21, this dike has been cut and dislocated by late Karelian granite.

The *plagioclase-granite* is grey, fine medium- to medium-grained, and as a rule slightly schistose. Main minerals are oligoclase (sometimes oligoclase-albite due to secondary development of epidote), quartz, biotite, and in many samples epidote, too (compare the basic granite). The larger plagioclase individuals are often tabular. Partial sericitization and impregnation with flocks of small epidote crystals are common phenomena. Plagioclase is the leading mineral of this rock, whereas hornblende, on the other hand, has inferior importance or is, in normal cases, even lacking. Titanite, muscovite, and apatite have to be classified as minor constituents. Pyrite, zircon, and allanite (incl. pseudomorphs) are more accidental. Microcline sometimes attains a strong position. When this mineral begins to form coarse eyes, the rock passes into Askim granite (see below).

In hand specimens, the two kinds of intermediate granite do not often differ greatly from each other, though the Frölunda granite is on the whole more fine-grained than the plagioclase-granite. They have also been given the same symbol in Plate 1. Genetically, the difference between the two rocks is great, however, though they pass into each other in the Askim area. We have seen that most of the Frölunda granite has developed by granitization *in situ.* We have also read about dikes of plagioclase-granite, and basic granite, too, in Frölunda granite, in supra-crustal gneisses, and in basites. Pictures of such dikes have also been shown (Figs. 19 and 21). Moreover, the plagioclase-granite and basic granite are usually free from remnants of older rocks that can be interpreted as indicative of *granitizations in situ,* whereas, on the other hand, genuine eruptive breccias are sometimes met with (see P. H. Lundegårdh 1951, Fig. 6). Most of the plagioclase-granite and basic granite therefore seem to be magmatic rocks, though their magma was certainly secondary, *viz.* composed of liquefied rocks from the deepest part of the Gothenburg-Onsala fold (see the summary, p. 56). In certain areas, for instance Särö and Vallda Sandö S of Särö, the general character of the supra-crustal remnants observed is the same as in the Frölunda granite, however, and thus bears strong evidence of a granitization *in situ.*

Transitions between plagioclase-granite (even basic varieties) and Askim granite are found all over the mainland part of the Mölndal-Styrsö-Vallda region (see Plate 1). As soon as the former grows rich in coarse microcline eyes, it should be classed as Askim granite. Since many of the microcline eyes are secondary, *viz.* porphyroblasts, the high frequency of transitions is by no means remarkable (see the Askim granite described below).

The red-grey to red, fine- to medium-grained *microcline-granite* is a granitization product of the same kind as the Frölunda granite, though the parental rock is, in this case, acid and alkaline gneiss. The intimate relationship between the latter and the microcline-granite is indicated already by their distribution as shown in Plate 1, and the mode of development of the microcline-granite is elucidated in several outcrops, for instance SSE—S of Särö.

The microcline-granite also consists of the same minerals as the acid and alkaline gneiss, *viz.* microcline, quartz, and oligoclase-albite to oligoclase, further biotite and magnetite. Regarding the latter, which are second-rate minerals, it ought to be mentioned that they are usually not simultaneously frequent. Considerable amounts of biotite thus depress the content of magnetite, or even exclude this mineral, and *vice versa.* Minor constituents are epidote, muscovite, zircon, titanite, and apatite. The epidote, which is also here secondary (see the basic granite), may sometimes attain a strong position.

Remnants of microcline-granite in intermediate and Askim granite have been observed in a few outcrops, for example in the mountains 5 km SE of Billdal.

The leading late Gothian granite is the porphyritic *Askim granite.* The matrix of this rock as a rule corresponds to one or other of the granites described above and is consequently quite variable. Most frequently, however, the matrix has the same intermediate composition as a microcline-bearing plagioclase-granite. The microcline of the Askim granite is thus concentrated to the eyes. There are, indeed, varieties to be found, the matrix of which is free or almost free from potassic felspar.

The matrix of the Askim granite is grey-red to grey or dark grey and fine- to medium-grained (occasionally in part coarse), whereas the oval or rectangular microcline eyes are pink or red owing to impregnation with minute hematite

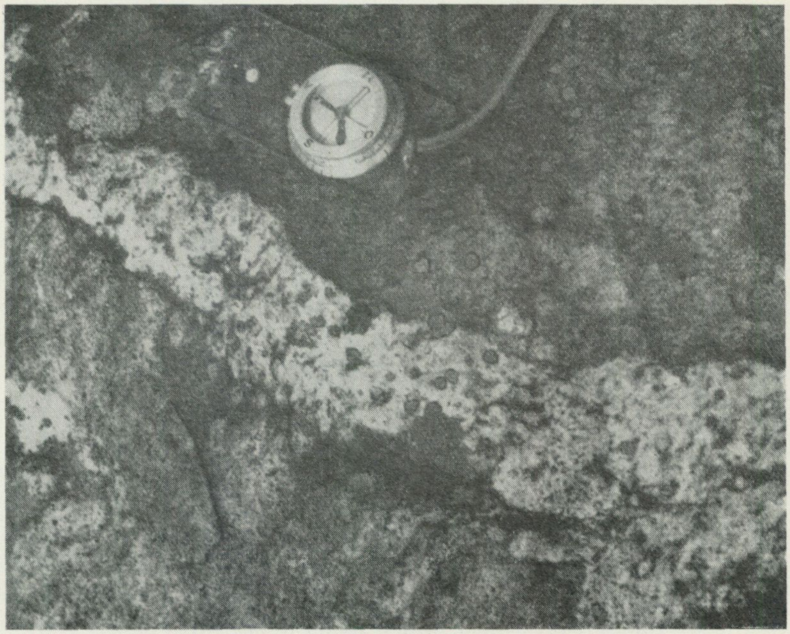

Fig. 20. Dike of Askim granite in basic gneiss. 2 km NE of V. Frölunda church. Photo by P. H. Lundegårdh 1952.

grains. They usually measure $^1/_2$—5 cm in length. Perthitic interlamination of acid plagioclase is common. Apart from microcline, the main minerals are quartz, oligoclase, biotite, and, in strongly altered varieties, epidote (compare the basic granite). Another important mineral is titanite. The following minor constituents have been observed: apatite, titaniferous magnetite, and often muscovite, too. Zircon and pseudo-allanite (sometimes allanite) should be classified as accidental minerals.

The tectonization of the Askim granite is highly variable. In the Billdal-Kullavik area, for instance (Plate 1), the rock is often non-deformed (chemical analysis in Table II), but in most cases it has become more or less schistose. The crushed minerals — oligoclase and quartz preferentially, have re-crystallized as granoblastic aggregates.

In dislocation zones (striated in Plate 1), the schistosity grows very strong. A detailed description of Askim granite thus tectonized will be found in my Onsala paper (P. H. Lundegårdh 1951, pp. 180—83). The genesis of the microcline eyes is also discussed there. On the east coast of the Onsala peninsula, most of these existed when the final Gothian tectonization and migmatization started. Only a minority of eyes have proved to be younger than the tectonization mentioned. The older eyes have often been cracked. The layers or sheets of minerals composing the zones of schistosity also pass around these eyes without interruptions, whereas they have been in part replaced by the penetrative microcline forming the post-tectonic porphyroblasts. The latter are frequently also idiomorphic = rectangular. The petrological significance of the post-tectonic eyes is great, because they have obviously developed at low temperature. Indeed, any more considerable post-tectonic heating of the schistose Askim granite would have brought about complete re-crystallization. All cracked and smashed minerals would have then disappeared.

500 m SE of Släp church, an instructive outcrop has been found. The predominant rock is here a plagioclase-granite which eastwards passes into Askim granite. In the border zone, the microcline eyes are concentrated along planes of schistosity that have allowed potassium-bearing solutions to invade the plagioclase-granite. Furthermore, the porphyroblasts are associated with sparse and small, non-deformed dikes of red aplite. Similar dikes have been observed at a few other localities, and it may even happen that these late dikes contain microcline eyes.

In view of the data now referred to, I am inclined to interpret most of the late microcline eyes of the Gothenburg-Onsala fold as final Gothian, though, in the vicinity of Gothenburg, such porphyroblasts may also have developed in late Karelian time.[1] We have there intrusive rocks produced by the late Karelian migmatization, *viz.* granite and pegmatite. Furthermore, we have, round the Karelian granite of Näset, areas rich in late microcline porphyroblasts, the development of which has caused the Frölunda granite there occurring to pass into secondary Askim granite (compare Plate 1).

2 km NE of V. Frölunda church, just outside the northern border of Plate 1 and close to an intrusion of late Karelian pegmatite,[2] even arkose and conglomerate have been in part transformed into Askim granite by the mere activity of granitizing solutions. The conglomerate belongs to the stroke described on p. 20 and has the same general character, though its matrix is in part less basic, which has thus rendered granitization possible. Accordingly, the conglomerate with amphibolitic matrix has remained intact, whereas the conglomerate with matrix corresponding to femic gneiss has been granitized. In this case, however, the alteration observed is most probably late Gothian. Indeed, the great distance between the minor late Karelian intrusions S of Gothenburg and the ancient zone of late Karelian migmatization has certainly prevented the Gothian bed-rock of the Mölndal-Styrsö-Vallda region from any more considerable alteration in Karelian time. Epidotization and chloritization may have occurred (see for instance p. 21), and even microcline low-temperature porphyroblasts may have developed (see above), but complete granitizations of supra-crustal rocks cannot possibly have been effected.

The selective granitization just mentioned, implying the preservation of the basic part of a supra-crustal rock, is a normal phenomenon in the Gothenburg-Onsala fold. Fig. 10 shows a banded gneiss, the acid layers of which have been transformed into Askim granite while the amphibolitic layers only contain sparse microcline porphyroblasts.

Investigations on the schistose Askim granite of the Onsala peninsula (see

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[1] Compare the secondary epidotization earlier discussed (p. 38).

[2] The Högsbo pegmatite, see p. 49.

above) and other parts of the Gothenburg-Onsala fold have shown that most of the microcline eyes of this rock are older than the final Gothian tectonization. The field work has revealed the absence of remnants indicating granitizations *in situ* in most areas of Askim granite. Developments of secondary Askim granite similar to those just mentioned (granitized matrix and secondary eyes) are thus inferior phenomena. On the contrary, the central and southern mainland parts of the Mölndal-Styrsö-Vallda region display huge eruptive breccias of supra-crustal rocks in late Gothian granites, among these Askim granite (the Billdal-Kullavik area especially, see Plate 1). Small breccias are also rather frequent (see P. H. Lundegårdh 1951, Fig. 7). Furthermore eruptive dikes of Askim granite in older rocks are sometimes met with (Fig. 20). The magmatic character of most of the Askim granite is thus quite obvious, though this magma was certainly secondary (see the summary, p. 56).

As regards the genesis of the early eyes, I shall mention that small and large inclusions of non-porphyritic acid gneiss (in rare cases even microcline-granite) have sometimes been met with in the magmatic Askim granite, for instance at the sea about 2 km SSW of Billdal (acid gneiss, see Plate 1). If wholly secondary potassic solutions had been at work here, the acid gneiss, too, would have contained numerous microcline porphyroblasts. Further, I shall mention the existence of sparse eruptive dikes of Askim granite not only in rather resistant basites but also in more acid rocks (femic gneiss especially, see Fig. 20), and even close to the contacts the latter are free from microcline eyes.

These data evidence that the early eyes derive from the same magma as the granitic matrix enclosing them. They are penetrative, and in part they even seem to be less influenced by the syn-orogenic stress than the matrix. Accordingly, the latter should be interpreted as the principal product of the crystallizing magma, whereas the eyes should have taken at least most of its potassium from the residual magmatic solutions. The remaining components of the eyes should derive from the original mineral individuals that have been replaced by the growing microcline. We can thus define the early microcline eyes as products of deuteric potassic metasomatism. Several remnants of plagioclase in the early eyes evidence the correctness of this statement.

Plate 1 shows that the borders between Askim granite and non-porphyritic late Gothian granites are sometimes distinct, sometimes diffuse. The frequency of diffuse borders, *viz.* transitional granites, obviously to a high degree depends on the frequency of late eyes (compare the outcrop SE of Släp above described). It certainly also depends, however, on the mode of the magmatic evolution of granites in various parts of the Gothenburg-Onsala fold. Early crystallization of a basic granitic magma portion low in potassium, followed by late crystallization of an intermediate granitic magma portion rather high in potassium within the same part of the fold, thus inclines to create distinct contacts between the resultant non-porphyritic (basic) and porphyritic (intermediate) granites. On the other hand, variable frequency of residual solutions rich in potassium within one crystallizing mass of intermediate granite inclines to develop plagioclase-granite, transitional granites, and Askim granite. Such a frequency

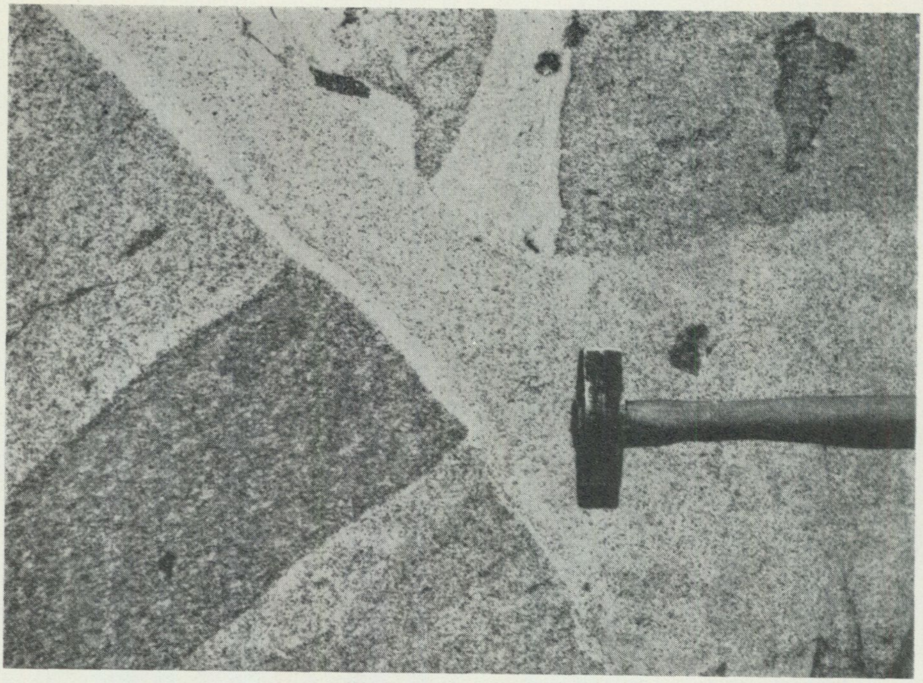

Fig. 21. Intrusion of late fine-grained granite in Frölunda granite with dike of basic granite (to the left) and remnant of amphibolitic gneiss (upper right corner). S of Näset, parish of V. Frölunda. Photo by P. H. Lundegårdh 1952.

variation seems to be due to a co-operation of crystallization differentiation and squeeze developed by the syn-orogenic stress.

A sample of typical non-deformed Askim granite from the Billdal-Kullavik area has been subjected to chemical analysis (Table II). As is reflected by the contents of sodium and potassium respectively, the matrix is rather sodic, *viz.* poor in microcline. On the whole, the rock might thus be characterized as a plagioclase-granite with microcline eyes. The latter are penetrative and frequently enclose remnants of plagioclase. The mineral composition is as follows: plagioclase (with sericite) $\geq$ microcline $\approx$ quartz $>$ biotite $\gg$ epidote (with clinozoisite) $>$ titanite $\gg$ apatite $>$ magnetite (titaniferous) and/or titanomagnetite $\gg$ zircon $\approx$ penninite $\approx$ muscovite $>$ pseudo-allanite.

The *late Karelian granite* S of Näset has already been mentioned now and then. This rock has intruded into Frölunda granite (Plate 1). Its borders are always distinct and discordant (Fig. 21). If often contains small xenoliths of meta-basites, and dikes of final Karelian pegmatite (Fig. 22 and p. 49) are sometimes found. The general behaviour of the Näset rock is quite similar to that of the Bohus granite. Regional studies and comparisons have also shown that the granite S of Näset as well as the pegmatite cutting it belong to the distal products of the late Karelian migmatization.

The granite S of Näset is grey, fine-grained and non-deformed. It has the following mineral composition: quartz $\geq$ microcline $>$ oligoclase $>$ biotite $\gg$ muscovite $\approx$ epidote $\gg$ titanite $\gg$ apatite $\gg$ pseudo-allanite. Titanite and apatite are minor minerals, pseudo-allanite is an accidental constituent. The microcline is penetrative. The largest mineral individuals of the rock are composed of either microcline (sometimes perthitic) or quartz, though small grains of both are also frequent. The oligoclase has in part been sericitized. It often contains deuteric muscovite and epidote. The titanite has sometimes altered to a dense mass of minute grains.

The considerable epidote content of the late Karelian granite indicates strong alteration effected by residual solutions. These have probably also penetrated the surrounding Frölunda granite and may have there developed not only epidote (compare p. 39) but even eyes of microcline (see p. 44).

Pegmatite, Aplite, Veined Gneisses.

In the Mölndal-Styrsö-Vallda region, the coarse *pegmatite* and its inferior sugar-grained companion *aplite* as a rule appear as irregular masses, minor dikes, glands, veins, and *schlieren*. In the northern part of the region, however, their mother solutions have sometimes been able to produce larger dikes.

The colour of the pegmatite passes from grey-white to various shades of red. Red-grey-white tints are most common. The aplite is generally pink or pale red-grey. The principal minerals of both rocks are grey quartz, grey-white, pink or red microcline, and white sodic plagioclase. In the pegmatite, some mica is also frequently present. Most microcline individuals examined are perthitic.

In the region considered, two groups of pegmatite have been distinguished, *viz.* an older one of Gothian age and a younger one of late Karelian age. The Gothian pegmatite dominates. It forms both intrusions in and part of the *veined gneisses* (Plate 1, p. 11 ff. and Fig. 5), whereas the Karelian pegmatite always appears as distinct dikes (Fig. 22). The Gothian pegmatite is concentrated in the eastern part of the Kållered-Mölndal area and in the Styrsö archipelago, while the Karelian pegmatite has only been observed in the V. Frölunda-Askim area and in the western part of the Mölndal area.

As I have earlier touched upon (p. 6 and Table I), the Gothian pegmatite has been divided into two generations. The older of these seems to be represented among the xenoliths of the plagioclase-porphyrite (p. 32) and should have developed during an early Gothian migmatization of the lowest (= outermost) strata of the ancient Gothenburg-Onsala syncline. Owing to the extensive alterations effected by the final Gothian migmatization (see below), the areal distribution of the early pegmatite is unknown, however.

The younger, and most important, generation of Gothian pegmatite is characterized by a frequent content of magnetite, which may at times grow considerable and which has most probably been inherited from dissolved acid gneiss (compare p. 25). Garnet, too, has been observed. This secondary peg-

Fig. 22. Dike of latest pegmatite in late fine-grained granite. S of Näset, parish of V. Frölunda. Photo by P. H. Lundegårdh 1952.

matite is the principal product of the final Gothian migmatization, which has been described in my Onsala paper (P. H. Lundegårdh 1951, pp. 188—191). I have interpreted this process as due to an eastern—western strain that caused glidings of blocks (the Mölndal-Kungsbacka fault, for instance) and opened the concordant sheets of the outer and older supra-crustal rocks of the Gothenburg-Onsala fold. These became thus migmatizable, *viz.* permeable to rising solutions of acid silicates (see p. 11 ff. and Fig. 5). On the other hand, the massive granitic kernel of the fold with its huge but soldered xenoliths and strokes of younger supra-crustal rocks has been less susceptible to altering actions. Accordingly, we have there only dikes of late Gothian pegmatite, no real veined gneisses.

During the migmatization, part of the outer strata of the Gothenburg-Onsala fold became plastical. Glidings frequently disjointed more rigid rocks (Fig. 6; see also P. H. Lundegårdh 1951, Figs. 11, 12, and 14). Furthermore, the acid strata were in part dissolved and mobilized. They have originated the intrusive granite dikes exemplified by Fig. 23 and described on p. 40.

In the gneisses of the inner parts of the Gothenburg-Onsala fold, minor pegmatitic and aplitic *schlieren* and veins are sometimes met with. These have developed contemporaneously with the late Gothian granites. Their composi-

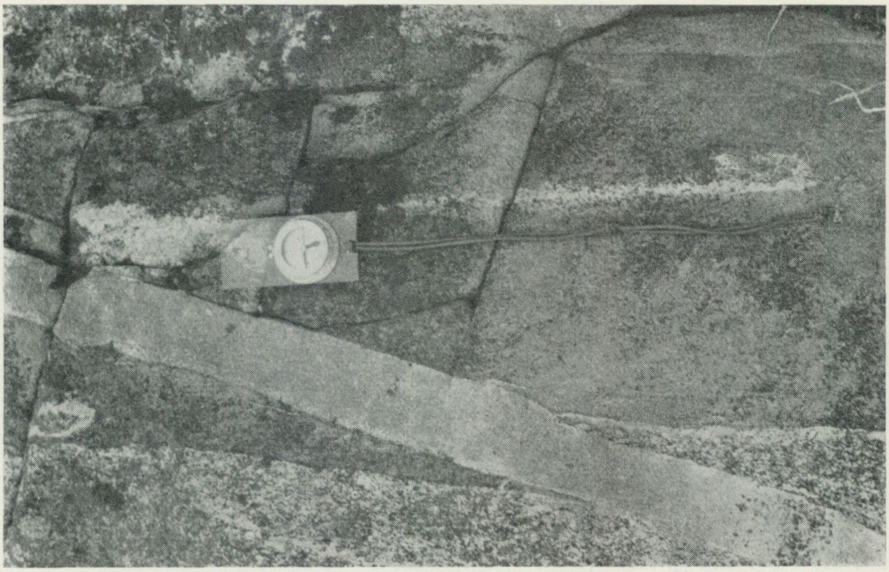

Fig. 23. Discordant granitic dike of dissolved and mobilized acid gneiss in grey plagioclase-granite with sheet of amphibolite (around the compass). Tjurholmen (islet WNW of Kullavik), parish of Släp. Photo by P. H. Lundegårdh 1951.

tion depends upon the character of the mother rocks. Conditions being favourable, they can thus even contain hornblende.

The late Karelian pegmatite is intimately related to the granite S of Näset (see above), which it has been seen to cut (Fig. 22). It often contains green microcline (amazonstone) and fluorite (green and violet). The content of certain rare minerals — beryl, columbite, and monazite, is sometimes considerable. The most important locality is the Högsbo intrusion — a pair of dikes situated 2 km NE of V. Frölunda church, just outside the northern border of Plate 1.

The Högsbo pegmatite has been investigated by N. Sundius (1950, p. 473). He reports that the rock has intruded as two parallel dikes (width = 6 and 12—15 m respectively), the strike and dip of which are N70°W, 60°SSW. (It should be noted that part of the dolerite dikes described in the next chapter show the same orientation.) The plagioclase and mica (muscovite preferentially) is concentrated in the marginal zones of the dikes, whereas the inner parts are essentially composed of quartz and pale red, perthitic microcline. Crystals of the latter mineral measuring as much as 2 m in length have been observed. Veins of white albite especially, and quartz, sometimes occur in the perthitic microcline.

In the kernel of the larger dike, violet and green fluorite seems to have been concentrated. Furthermore, beryl, columbite, and monazite have crystallized in the inner part of this dike. The specific gravity of the Högsbo columbite and monazite amounts to 5.39 and 4.8 respectively.

In his Högsbo paper, Sundius also mentions that columbite has only been found in Sweden at Timmerhult on Orust, Central Bohuslän, and Varuträsk in Vesterbotten, Northern Sweden. Monazite is known from L. Holma in Lur, Northern Bohuslän, and Kårarvet at Falun, Dalecarlia. Of these four occurrences, the two in Bohuslän are intrusions of late Karelian pegmatite. Even with respect to its content of rare minerals, the Högsbo pegmatite should thus be classed as late Karelian. Moreover, the absence of magnetite and the presence of the rare minerals mentioned, evidence the distal, or rather, epi-orogenic character of the Högsbo pegmatite.

Basic Dike Rocks.

Early Diabase.

Between Näset and Fiskebäck, on In-Vinga N of Vinga, and in the northern part of the Styrsö archipelago, especially on Rivö and Galtö (Plate 1), swarms of dikes of green-black to black, fine-grained diabase cut the veined gneisses and late Gothian granite (Fig. 24). The dikes are quite narrow (Fig. 24). As a rule, their width varies from 2 cm to 3 m. The primary ophitic texture of the diabase has been preserved. The marginal zones of some dikes are, however, schistose and amphibolitic. The strike of most dikes is N—NE. The dip falls steeply towards W—NW.

The diabase considered is essentially composed of corroded primary laths of andesine and of various deuteric mafic minerals, green uralitic hornblende and biotite preferentially, further epidote and chlorite. Titanite is often a rather important constituent, whereas titaniferous magnetite, titanomagnetite, apatite, and pyrite should be classified as minor minerals.

A sample of early diabase from one of the dikes between Fiskebäck and Näset has been subjected to spectral analysis (Table III). The data obtained will be discussed on p. 56.

In the centre of Rivö, the kernel zone of one diabase dike contains small xenoliths of quartzite and altered slate gneiss belonging to the early Gothian supra-crustal series. Most xenoliths display a mass of fine-grained granoblastic, or coarse to medium-grained quartz with blebs of plagioclase and crystals of epidote. In some xenoliths, accidental microcline has been observed.

H. E. Johansson (1931, p. 45) considers the dikes now described to be equivalent to the Koster diabase and dolerite. On the Koster isles in Northern Bohuslän, this group of rocks forms several hundreds of dikes, the strike of which curves from NNE (in S) to N and NNW (in N). B. Asklund, who has mapped and investigated the Koster rocks, mentions that part of the minor dikes and the margins of part of the major dikes have become schistose and amphibolized. The undisturbed and wider dikes display a dolerite composed of labradorite and augite preferentially, further some hypersthene, and at times also olivine (Asklund 1950, p. 53). Asklund parallels the Koster diabase and dolerite with the hyperite of Central Southern Sweden. As the Koster dikes

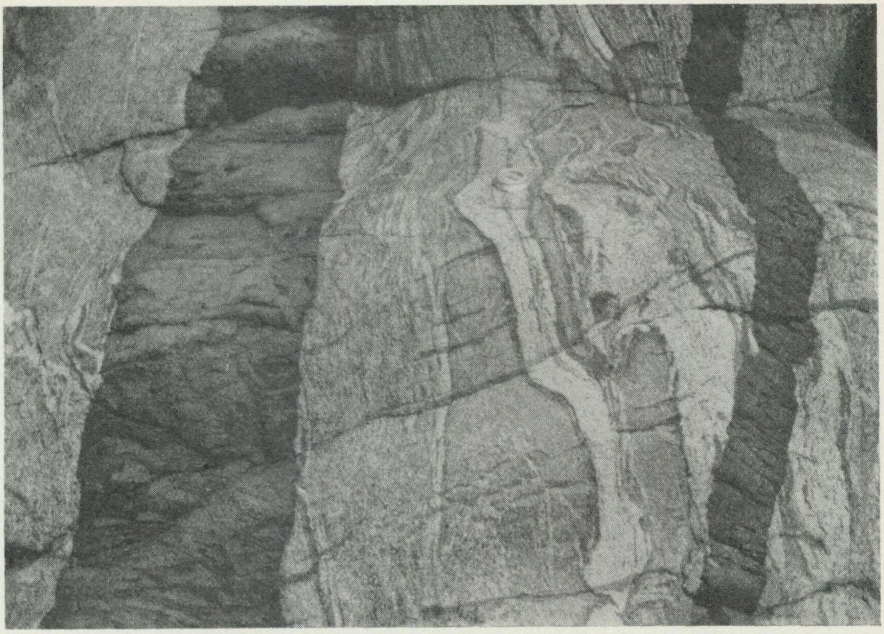

Fig. 24. Dikes of early diabase in mixed gneiss in part transformed into Frölunda granite. Northern In-Vinga, N of Vinga, parish of Styrsö. Photo by P. H. Lundegårdh 1952.

have been cut by the Bohus pegmatite (A. Gavelin 1914; B. Asklund 1950, pp. 53—54) and the Rivö-Galtö dikes are younger than the final Gothian migmatization, the resultant generation of basites should have developed in Karelian time.

Late Diabase and Dolerite.

The youngest magma that intruded into the Mölndal-Styrsö-Vallda region has occupied the space offered by an opening system of steep western to west-north-western and northern-southern joints. The resultant diabase and dolerite dikes have been observed in the southern part of the Styrsö archipelago and in the central and southern parts of the mainland (Plate 1). North of the mapped region, a number of dikes cut the Gothenburg district and the parish of Torsby (see H. E. Johansson 1931, Plate 1). The western to west-north-western joints existed and even in part opened in latest Karelian time, as exemplified by the Högsbo pegmatite dikes (see above). The northern-southern joints developed during the late Gothian tectonization.

The width of the diabase and dolerite dikes accessible for determinations varies from 2 dm to 25 m. The largest dikes in the region investigated pass $1^1/_2$ km S of Billdal (the *Heden dike*) and through Kullavik (the *Kyvik dike*). The maximum width of the former amounts to 25 m at the locality shown in Fig. 25, while the maximum width of the latter is 10 m. Though rather short, the perpendicular dike $5^1/_2$ km E of Billdal has a considerable width, too.

The morphological appearance of the late diabase and dolerite dikes is characteristic. In certain places the rock has been quite resistant to weathering and stands up as hills or walls (Fig. 25), in others it has weathered to beds of gravels or valleys covered with moraine etc. and thus cannot be detected at all.

As is seen from Plate 1, both the Heden and Kyvik dikes have been cut and dislocated by tectonic movements along a northern-southern zone of parallel joints. This zone was developed in late Gothian time, contemporaneously with the great Kungsbacka-Mölndal zone, with which it also runs parallel. Movements have here certainly occurred in late Karelian time and probably in Permian time, too (compare the extensive Permian magmatic activity in the Oslo field NNW of the Gothenburg-Onsala fold).

The kernel zones of the wider dikes display a fresh, black or grey-black dolerite, and the same holds for some of the narrow dikes. The northern-southern dike SW of Vallda church is thus composed of a well-preserved dolerite which is even rather medium-grained, though the dike is quite narrow (2 m). In normal cases, however, the thinner dikes are wholly fine-grained, whereas the wider dikes show fine-grained margins and fine- to medium-grained kernels.

The dolerite, and the diabase, too, shows a beautiful ophitic development with laths of plagioclase which are as a rule marginally corroded in the latter rock. Weak partial sericitization is met with now and then. Zonal extinction has been observed in many crystals. The composition of the plagioclase as a rule varies from 40 to 60 % anorthite, though varieties with more acid plagioclase also exist.

The main mafic minerals of the dolerite are pyroxene (often ophitic), further titaniferous magnetite and frequently olivine, too. The dolerite of the widest part of the Heden dike (Fig. 25) thus shows the following mineral composition: andesine (about 40 % anorthite[1]) > olivine (with serpentine) ≥ clinopyroxene > titaniferous magnetite. Biotite (deuteric; see below) should be classed as an inferior constituent. Quartz (late) > calcite (deuteric) ≥ apatite are minor minerals. This rock has been subjected to chemical and spectral analysis (Tables II—III and p. 56). Its olivine shows $2V\gamma = 90°$, or somewhat more, its clinopyroxene (pigeonite) $\gamma \wedge c$ 28—33° and $2V\gamma < 60°$. Birefringence and indices of refraction increase on increasing values of $\gamma \wedge c$.

A sample from the Kyvik dike about 2 km E of Kullavik is composed of andesine-labradorite (50 % anorthite) ≥ clinopyroxene with deuteric alteration products > titaniferous magnetite. Apatite and quartz (late) are minor minerals. The clinopyroxene, mainly an augite ($\gamma \wedge c = 41—45°$), has to a large extent altered to a dense mass of biotite, uralite, chlorite etc.

The perpendicular dike SW of Vallda (see above) displays labradorite (55—60 % anorthite) > chlorite + serpentine > clinopyroxene > olivine ≫ magnetite. Biotite has here to be classified as a minor mineral, whereas apatite is rare. This is an early and unusually basic modification with no quartz, very little apatite, a rather considerable content of nickel (see Table III and

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[1] When bordering upon quartz, the plagioclase frequently grows more acid.

Fig. 25. Resistant dike of late dolerite. At Hällesås $4^1/_2$ km ESE of Billdal, parish of Lindome. Photo by P. H. Lundegårdh 1951.

p. 56), and an olivine ($2V\gamma = 85°$) richer in magnesium than that of the Heden dolerite ($2V\gamma = 90°$, or somewhat more).

On the isle of Stora Ryggholmen $2^1/_2$ km NW of Kullavik, the dolerite contains both clino- and orthopyroxene (hypersthene).

The main mafic minerals of the late diabase are uralite, chlorite (with serpentine), and biotite. These have all developed by autometamorphism (in part autometasomatism, too). The uralite as a rule shows pale pleochroism in various shades of green. During the alteration of the original mafic minerals, the margins of the plagioclase laths have as a rule become corroded. In certain samples of diabase, small quantities of epidote, pyrite, and calcite have been observed.

In my Onsala paper (P. H. Lundegårdh 1951, p. 194), I suggested that the late diabase and dolerite dikes of the Gothenburg-Onsala fold might be either pre-Hercynian or Lower Permian. The former proposal is supported by the presence of wide beds of early post-Silurian plateau-dolerite in Vestergötland. B. Asklund (1950, p. 56) reports sparse finds of eastern-western to east-northeastern dolerite dikes in the Koster archipelago. These dikes are similar to those met with S of Gothenburg and thus even in part olivine-bearing. Asklund is inclined to parallel his eastern-western dikes with the Vestgöta plateau-dolerite, too. In Scania, several dolerite dikes running towards WNW have, however, been interpreted as Lower Permian by S. Hjelmqvist (1939). This investigator is inclined to consider the opening joints thus filled with rising basic magma as developed by the Hercynian orogenesis.

In his tectonic and morphological monograph on the Swedish Skagerack coast (Bohuslän especially), E. Ljungner (1927, pp. 111—115) gives a survey of the west-north-western diabase and dolerite dikes of South-Western Sweden. Ljungner here interprets them as Algonkian, and among petrological parallels he mentions the Jotnian Åsby dolerite of Central Sweden and the Billingsfors dike in Dalsland. Later in his monograph, Ljungner (1927, p. 249) seems inclined to consider the WNW-dikes to be older than the Bohus granite, which they have never been seen to cut. In a recent paper (Ljungner 1953, p. 112), he stresses this circumstance once again. He has, however, as well as Asklund (1950), suggested an Algonkian age of the Bohus granite, too (Ljungner 1927, p. 249).

Now it has to be pointed out, that the WNW-dikes appear as swarms. The Scanian dikes form such a swarm, the Gothenburgian ones another swarm, and those of the Koster isles a third swarm. The Billingsfors dike in Dalsland belongs to a fourth swarm (compare W. Larsson 1949). Between Scania and the Gothenburg-Onsala fold, no WNW-dikes have been yet observed, in spite of W. Larsson's detailed and careful mapping of the southern part of this region (unpublished maps kindly placed at my disposal). And the rocks of Southern Halland are early Gothian, if not in part still older. Ljungner's objections against a Palaeozoic age of the WNW-dikes thus do not seem to be decisive, though, on considering the petrology and mode of occurrence of the WNW-dikes of Gothenburg, Koster, and Dalsland, I do not feel inclined to parallel them with the Vestgöta dolerite. They are certainly younger than the Bohus granite, but I join Ljungner in classing them as Algonkian.

The dislocations of the Heden and Kyvik dikes seem to have occurred in Permian time, simultaneously with the magmatic activity in the Oslo field.

Geochemical Evidences.

Typical representatives of the basic rocks of the Gothenburg-Onsala fold have been analysed spectrographically by means of the continuous arc method. The elements determined are chromium, cobalt, and nickel. The accuracy of determinations of this kind has been estimated in P. H. Lundegårdh 1946, on pp. 22—23.

As originally stated by V. M. Goldschmidt (see 1945, pp. 3—4), chromium especially, and nickel have been enriched in magmatic first-differentiates. The validity of this rule has been evidenced by numerous geochemical investigations (see P. H. Lundegårdh 1949). On studying the petrological consequences of this rule, I have found (*op. cit.*, p. 6) that cobalt is normally uniformly distributed in the various stages of basic magmatic differentiation (except the final products, where even this metal vanishes together with magnesium).

According to the data given in Table III, the Gothian effusive simatic derivatives (basic volcanics) are rather rich in chromium — the agglomeratic basaltic tuff near Meryt contains as much as 400 p. p. m. (parts per million), whereas the infra-crustal simatic rocks contain far less chromium — a homo-

Table III.

Distribution of chromium, cobalt, and nickel in the basic rocks of the Mölndal-Styrsö-Onsala region, in order from youngest to oldest.

Analysts: J. Raudsepp (J. R.), V. Muld (V. M.), and P. H. Lundegårdh (P. H. L.).

Kind of rock	Locality	Parts per million of		
		Cr	Co	Ni
Olivine-dolerite (E—W-dike) J. R.	4.5 km ESE of the railway station, Billdal	50	30	80
Olivine-dolerite (N—S-dike) J. R.	1 km SW of Vallda church	40	30	150
Diabase J. R.	Dike between Fiskebäck and Näset	65	70	260
Biotite-norite J. R.	2 km NE of V. Frölunda church	65	70	70
Uralite-gabbro P. H. L.	1 to 1.5 km E—ENE of Onsala Sandö[1]	50	60	100
Uralite-porphyrite P. H. L.	2 km WNW of Meryt[1]	150	65	110
Plagioclase-porphyrite J. R.	Vinga WNW of Styrsö	35	25	35
Amphibolitic gneiss[2] V. M.	1.5 km WSW of Gottskär[1]	10	40	50
Dolerite (sill) J. R.	1.5 km NNW of Kållered church	140	40	70
Amphibolitic diorite V. M.	2 km SSW of Lerkil[1]	200	30	50
Basaltic tuff, agglomeratic V. M.	At the highway NW of Meryt[1]	400	30	90
Davainite (meta-peridotite) J. R.	Stensholmen 2 km NW of the centre of Särö	50	90	270

[1] See P. H. Lundegårdh 1951, Plate 1.
[2] May be older than the Stensholmen davainite (see below).

geneous ultra-basic member of the series (uralite-porphyrite WNW of Meryt) shows only 150 p. p. m. Moreover, the basaltic tuff seems to be quite an undifferentiated simatic derivative,[1] whereas the uralite-porphyrite is an early product of basic magmatic differentiation and would thus be expected to contain more chromium than the former. Indeed, the parental simatic magma of the infra-crustal basites seems to have differentiated to some extent before the development of the bodies now visible, in the same manner as the magma of the early generation of ultra-basic gabbro in Central Roslagen NE of Stockholm (P. H. Lundegårdh 1949, p. 20).

On comparing the davainitic bands of the Stensholmen gabbro NW of Särö with the uralite-porphyrite WNW of Meryt, we find that the former are products of rhythmic crystallization differentiation of a magma. They have been originally composed essentially of olivine enriched in nickel. In contrast to chromium, this metal easily enters the olivine lattice.

The plagioclase-porphyrite of Vinga mineralogically displays a late-magmatic character (p. 30), as is also evidenced by the chemical and spectrographical data — Mg:Fe = 0.18, low contents of chromium and nickel. As I have stated

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[1] S. Landergren's (1951, Table 1) geochemical investigations on Gothian supra-crustal metabasites from the vicinity of Varberg in Central Halland have given quite similar results: Cr = 200—300, Co = 30—40, Ni = 90—110 p.p.m. (Two samples of amphibolite.)

earlier (P. H. Lundegårdh 1950, pp. 51—52), the quotient Mg:Fe is > 1 in early products of basic magmatic differentiation, 0.5—1 in middle products, and < 0.5 in late products.

The biotite-norite NE of V. Frölunda, should also be classified as a late basic differentiation product (compare p. 35). Here we find the relation Co = Ni > Cr. According to Goldschmidt's rules, the relation Co > Ni > Cr should hold for late products of differentiating basic magmas (P. H. Lundegårdh 1949, p. 21). The chromium content (65 p. p. m.) is rather high, however, as compared with other Swedish late basic rocks of magmatic origin (see P. H. Lundegårdh 1949).

The early diabase that cuts the bed-rock between Fiskebäck and Näset differs from the Koster diabase in having much more chromium (65 p. p. m.) and nickel (260 p. p. m.). Two general samples of the latter show Cr = 5—10, Co = 45—50, and Ni = 85—90 p. p. m. (P. H. Lundegårdh 1949, Table 9, p. 46.)

Two samples of olivine-bearing late dolerite have also been analysed. These show the same trend as the nearest Palaeozoic plateau-dolerite of Vestergötland, *viz.* that of Hunneberg (Mount Hunne). Two representative samples of central and marginal Hunne dolerite contain 40—60 p. p. m. of Cr, 40—50 p. p. m. of Co, and 70 p. p. m. of Ni (analyst: J. Raudsepp). This is, however, the normal trend of olivine-bearing basites that are not first-differentiates (see P. H. Lundegårdh 1949). Besides, an analysis of a general sample of the more distant Kinne dolerite displays quite different values: Cr = 6, Co = 400, and Ni = 200 p. p. m. (general sample; P. H. Lundegårdh 1949, Table 9, p. 46). The trend encountered in the late dolerite S of Gothenburg cannot thus be considered as indicative of a Palaeozoic age of this rock.

Summary of Genetical Conceptions.

During the late Gothian (Table I) deep-folding and heating of the synclinal Gothenburg-Onsala volcanics and sediments, pressure and space conditions were quite unfavourable to the intrusion of large juvenile magma portions (compare H. G. Backlund 1936). The rather sparse finds of plutonic gabbroic-dioritic rocks evidence the correctness of this statement.

The mineralizers given off by the crystallizing mother magma of these basic rocks and the underlying sima were dissolved in the water of the sediments and immediately attacked the supra-crustal complex. The deeper the complex was folded, the greater became the heat supply, and thus not only granitizations *in situ* were effected (Frölunda granite, microcline-granite) but even dissolutions and mobilizations of supra-crustal rocks (secondary magmas later congealing as basic, plagioclasic, and Askim granites). The mineral components of the ancient supra-crustal rocks enclosing the disjointed beds of meta-basites within, for example, the Kullavik-Billdal area are thus at present components of secondary granites.

In the outer parts of the Gothenburg-Onsala fold, the supra-crustal layers remained concordant and mostly escaped granitization. During the final Gothian migmatization, these schistose concordant layers opened, however, owing to lateral strain, and thus mineralizers could rise once again and start their destructive work. Veined gneisses and intrusions of secondary pegmatite are the visible results. Part of the secondary mother solution of the pegmatite has developed on dissolution of alkaline gneiss rich in magnetite. Accordingly, the pegmatite bears magnetite.

In late Karelian time, wide parts of the bed-rock of South-Western Sweden were subjected to a new orogenesis. Stress and strain worked. Folding, faulting, and migmatizations occurred. The palingenic rocks intruding during the final phase of this orogenesis seem to have an origin both distant and different from that of the late Gothian migmatization products, however, since the resulting pegmatite contains minerals that are lacking in the late Gothian pegmatite. This is also in agreement with W. Larsson's (1947, Fig. 1) conception of a late Karelian zone of palingenesis that has been deep-seated even in relation to the present surface of the crust.

Both in Karelian and post-Karelian time, systems of joints opened and allowed basic magma to rise and congeal. In the Gothenburg-Onsala fold, the visible results are two generations of diabase and dolerite, the younger of which is supposed to be Algonkian.

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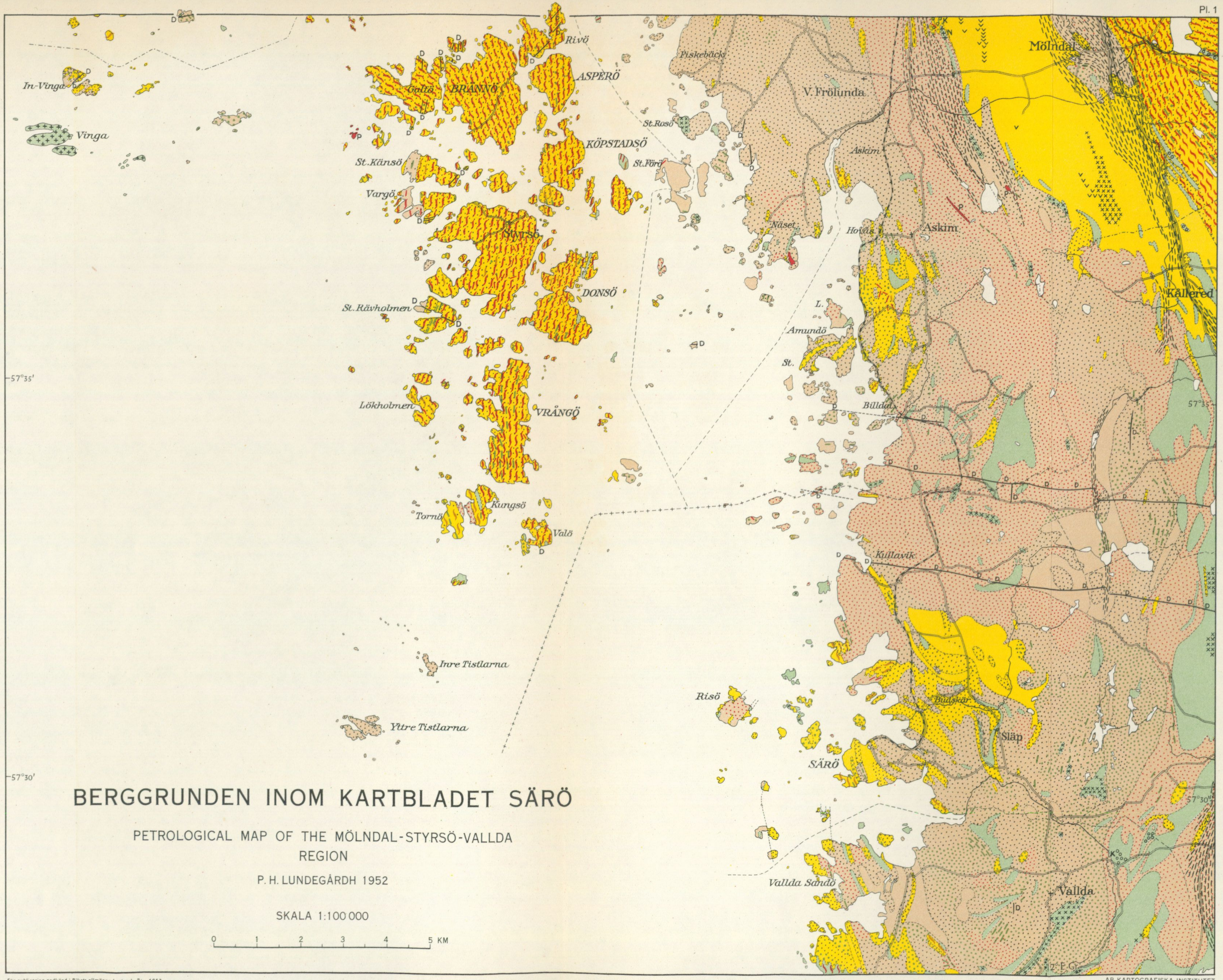
Pl. 1



BERGGRUNDEN INOM KARTBLADET SÄRÖ

PETROLOGICAL MAP OF THE MÖLNDAL-STYRSÖ-VALLDA REGION

P. H. LUNDEGÅRDH 1952

SKALA 1:100 000

/D	Diabasgång (blottning betecknad med D)	*Dike of diabase or dolerite (outcrop marked with D)*
▤	Kraftig förskiffring	*Strong schistosity*
🟥	Granit, ung, finkornig. Pegmatit med aplit (P)	*Granite, young, fine-grained. Pegmatite with aplite (P)*
▨	Pegmatit med aplit som anhopningar av oregelbundna gångar	*Pegmatite with aplite, swarms of irregular dikes*
▨	D:o som tätt återkommande, längs gnejsigheten orienterade sliror, ådror och körtlar i äldre bergarter (ådergnejs)	*Do, concordant veins and lenses in gneissic rocks (veined gneisses)*
▨	Granit, gråröd — mörkt grå, ibland porfyrisk, ofta gnejsig (gnejsgranit), som intrusioner i äldre bergarter	*Granite, grey red to dark grey, sometimes porphyritic, frequently gneissic (gneiss-granite), intrusions in older rocks*
▨	Granit, lik ovanstående, som mer eller mindre diffust avgränsade partier i äldre bergarter	*Granite, similar to the above one, small masses frequently grading into the surrounding older rocks*
▨	Granit, gråröd — mörkt rödgrå, grovporfyrisk, oftast gnejsig (Askimgranit)	*Granite with coarse microcline eyes, grey red to dark red grey, most frequently schistose (Askim granite)*
▨	Granit, rödgrå — röd, övervägande sur, oftast gnejsig (mikroklinrik gnejsgranit)	*Granite, red grey to red, rather acid, most frequently gneissic (gneiss-granite rich in microcline)*
▨	Granit, rödgrå — grå, intermediär, övervägande gnejsig (Frölundagranit och plagioklasrik gnejsgranit)	*Granite, red grey to grey, intermediate, in most cases gneissic (Frölunda granite and gneiss-granite rich in plagioclase)*
▨	Granit, svartgrå — mörkt grå, basisk, vanligen hornbländerik och lätt gnejsig (kvartsdioritisk gnejsgranit)	*Granite, black grey to dark grey, basic, most frequently rich in hornblende and rather gneissic (quartz-dioritic gneiss-granite)*
▨	Kvartsdiorit och diorit, ofta övergående i amfibolit	*Quartz-diorite and diorite, frequently grading into amphibolite*
▨	Plagioklasporfyrit. Biotitnorit, delvis uralitiserad (N)	*Porphyrite with phenocrysts of plagioclase. Biotite-norite, in part uralitized (N)*
▨	Uralitgabbro, hornbländesten	*Uralite-gabbro, hornblendite (davainite)*
🟨	Gnejs, rödgrå — röd, övervägande sur, alkalirik, icke sällan granitisk	*Gneiss, red grey to red, rather acid, alkaline, now and then granitic*
▨	D:o, kraftigt grusvittrande	*Do, strongly weathering*
▨	D:o, rik på alkalihornblände	*Do, rich in alkaline hornblende*
▨	Gnejs, rödgrå — grå, intermediär, ibland granitisk, ibland leptitisk	*Gneiss, red grey to grey, intermediate, sometimes granitic, now and then leptitic*
▨	Gnejs, svartgrå — mörkt grå, basisk, ofta hornbländerik	*Gneiss, black grey to dark grey, basic, frequently rich in hornblende*
▨	Basisk tuffit med bollar av kvartsit och kvarts-oligoklasbergart (K). Basalttuff. Diabas (lager)	*Basic tuffite with pebbles of quartzite etc. (K). Basaltic tuff. Diabase (layers)*
🟩	Amfibolit och amfibolitisk gnejs, ofta kvartsdioritisk, dioritisk eller porfyritisk	*Amphibolite and amphibolitic gneiss, frequently quartz-dioritic, dioritic, or porphyritic*
▨	D:o som smärre skivor och lager i andra bergarter	*Do, minor sheets and layers in other rocks*

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