

SVERIGES GEOLOGISKA UNDERSÖKNING

SER. C

Avhandlingar och uppsatser

N:o 544

ÅRSBOK 49 (1955) N:o 4

PETROLOGY OF THE UPPSALA REGION  
EASTERN SWEDEN

BY

PER H. LUNDEGÅRDH

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WITH ONE PLATE

*Pris 6:— kronor*

STOCKHOLM 1956

KUNGL. BOKTRYCKERIET. P. A. NORSTEDT & SÖNER

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### Abstract.

Nowadays Swedish Archean (Archeozoic) is most frequently divided into three eras — Svecofennian, or Svionian, or Early Archean ( $\geq 1700$  millions of years), Gothian (Gothic), or Middle Archean (about 1200—1700 millions of years), and Karelian, or Late Archean (900—about 1200 millions of years). Svecofennian is a term introduced by W. Ramsay, who in 1909 applied it to the orogenic belt stretching from Vermland to South-Eastern Finland. The term Svionian derives its origin from J. J. Sederholm, who employed it for part of the oldest Archean rocks of Finland. In Sweden, N. H. Magnusson has since 1936 used it as a synonym for Svecofennian.

Southern Finland, as well as the equivalent bed-rock of Central Sweden, was originally interpreted as the roots of a mountain range. However, our present knowledge indicates a much more complicated structure. We have, indeed, large bodies of Svecofennian rocks which seem to have never been deep-seated. We have also been able to widen the boundaries of the Svecofennian bed-rock so as to include part of Northern Sweden. Certainly, Svecofennian rocks are to be found in other Archean provinces, too.

The rocks of the Uppsala region are exclusively Svecofennian. As is seen from Plate 1, granites dominate though supracrustal rocks are also frequent. The latter include surprisingly well-preserved volcanics, for example acid hälleflinta, volcanic conglomerates, and fine-grained plagioclase-porphyrite. Hälleflinta is an old Swedish term applied to dense though frequently porphyritic, 'flint-like' volcanics. In the Uppsala region, the acid hälleflinta corresponds to quartz-porphyrity and the fine-grained plagioclase-porphyrity to quartz-andesite. The latter is intimately associated with coarser, hypabyssal plagioclase-porphyrity.

The petrological evolution of the Uppsala region will be evident from Table 1, p. 8.

The oldest rocks of Table 1, p. 8, are concentrated to the north-eastern corner of the region (the environments of Storvreta). They display a winding, interrupted slice with almost vertical dip. The bulk of the oldest supracrustal rocks are re-crystallized volcanics, i. e. leptites. Liparitic lavas and tuffs dominate. Volcanic conglomerate (Fig. 8, p. 26), limestone (Fig. 2, p. 17), and quartzite have also developed. Part of the limestone has altered to epidote.

The next generation of supracrustal rocks is mainly composed of differentiated lavas, which have most frequently been very well preserved. (Compare above. See also Figs. 4, 9, and 10, pp. 20, 28, and 29.) They occur in and around the northern parts of Uppsala. West and north-west of the town, several layers of volcanic conglomerate have been observed (Fig. 6, p. 23). The conglomerate contains numerous angular fragments of various kinds of volcanics and of quartzite. Furthermore, most of it is rich in pebbles of epidotized limestone (Fig. 7, p. 25). Fragments of some kind of pelitic sediment have also been seen. The conglomerate has got associated with a very fine-grained tuff, which is in most cases filled with crystal fragments (Fig. 5, p. 22).

The rocks now considered form an elongated body. They have been overlaid with a third supracrustal series, which appears immediately south-east of Uppsala and north-east of Börje church. In the latter area, it rests upon granitized acid

Uppsala volcanics with very slow dip. The third supracrustal series, the Mälars series approximately corresponding to Bothnian in Finland,<sup>1</sup> is essentially composed of sediments which have altered to gneiss. Boudinaged beds of basic tuff are common (the black rock in Figs. 13—14, pp. 37—38). Intrusions of allied uralite-porphyrite occur north-west and north-east of Uppsala.

During the epoch in Finland known as Bothnian, the crust was subjected to strong tectonic activity including the development of geosynclines. Climatological and morphological conditions were favourable to rapid weathering, transportation, and sedimentation. Predominant rocks are quartzites, clay-slates and, in geosynclinal *milieu*, graywackes etc., though basic volcanics are frequent, too. The latter have attained a very strong position in the northern and eastern parts of the Fennoscandian Svecofennides, especially Västerbotten in Sweden and the Tampere region in Finland. The volcanics comprise both tuffs and hypabyssal rocks (uralite-porphyrites especially).

A syncline filled with rocks belonging to the Mälars series can be followed from the region between Örebro and Falun, north-east of Lake Vänern, to the north-east coast of Uppland. Uppsala lies on the northern border of this syncline. The steep dips of the slices of supracrustal rocks are due to the position between the mentioned syncline and an anticline to the north of Uppsala. The folding thus displayed seems to have taken place after the development of the Mälars rocks. In the Uppsala region, thrust faults have probably occurred along the steep-dipping sheets of supracrustal rocks.

During a later stage of the Svecofennian orogeny, the schistosity planes of the supracrustal sheets opened owing to dilatation, and primorogenic secondary magma could rise. Hence we obtained the Oldest Archean basic granite, which is in Central Uppland generally known as Uppsala granite. This rock is grey and coarse to medium-grained. It consists of andesine, blue quartz, biotite, hornblende, and microcline. If we take andesine and quartz together, they amount to 70 à 80 % of total rock. The former mineral frequently shows zonal growth, indicating a rather superficial crystallization.

The Uppsala granite has numerous inclusions of metamorphic supracrustal rocks (Figs. 18—19, pp. 50 and 52). Most of these are angular. Basic xenoliths (quartz-diorite, amphibolite) dominate, but fragments of acid rocks are also found (leptite, sedimentary gneiss). Furthermore, the Uppsala granite contains a few masses of basic plutonic rocks, which seem to have been transported from deeper parts of the crust by the granite magma (lherzolite and gabbro in the southern vicinity of Uppsala; cf. Figs. 15—17, pp. 44, 45, and 47).

Heat, volatile compounds, and rest solutions emitted from the magma of the Uppsala granite caused recrystallization, metasomatism, dissolutions and mobilizations in the supracrustal rocks. Most part of these have been transformed to red, or sometimes grey, coarse to medium-grained, intermediate and acid granites, which are composed of quartz, microcline, oligoclase (or, sometimes, oligoclase-andesine), and biotite. In the western part of the Uppsala region, the following sequence of rocks displaying increasing alteration can be studied: (acid hälleflinta—) leptite—coarse leptite, or leptite-granite,—granite. This granite is known as Vänge granite. Other kinds of metamorphic supracrustal rocks encountered in the Uppsala region are quartz-diorites, amphibolites, and gneisses.

The intrusion of the Uppsala granite magma and the granitization (including partial mobilizations of supracrustal rocks) rendered possible the transformation of the geosynclinal wall into the winding and dislocated slices of hälleflintas, leptites and gneiss displayed in Plate 1. The final granitizing solutions originated the microcline porphyroblasts of the porphyritic granite.

<sup>1</sup> Compare A. Simonen, 1953.

The evolution of the Oldest Archean granites was followed by a long period of very moderate tectonic and magmatic activity. In Uppland ultra-basic gabbro magma intruded, in the easternmost part of the county especially. In the Uppsala region, a few small intrusions of this kind of gabbro occur near the western boundary. Later, magma rose along opening fissures and solidified as hypabyssal basites (Fig. 21, p. 61), which have undergone strong or total autometamorphism (the metabasite dikes in Plate 1). Main minerals are plagioclase and hornblende, sometimes biotite and quartz, too. A few dikes are diaschistic and in part consist of acid porphyry. One dike containing only porphyry has also been found.

The final Svecofennian rocks of the Uppsala region are pegmatite and granite-aplite frequently grading into fine-grained granite. These are distal crystallization products of solutions developed by regional migmatitization.

In post-Archean time, single faultings took place. In Plate 1 these have been marked with lines of short dashes. Simultaneously, fault breccias developed. Shear zones showing brecciation are also known.

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## Introduction.

In Central Uppland, Eastern Sweden, the Archean (Archeozoic) bed-rock displays a great mass of very old granites (Swedish *urgraniter*) with numerous inclusions of supracrustal rocks, many of which have great areal extension and most of which form lenticular bodies or winding slices. Central Uppland belongs to an old orogenic belt with east-north-eastern strike. This belt stretches from Eastern Vermland in Western Sweden to South-Eastern Finland.

In 1909, W. Ramsay defined the belt mentioned as the *Svecofennian* folding. All rocks involved in and produced by the *Svecofennian* folding have been assigned to the *Svecofennian* cycle, or the *Svecofennides*. (Compare W. Wahl, 1936, and H. G. Backlund, 1937.) In the terminology used by N. H. Magnusson (1936) and successors, *Svecofennian* has been exchanged for *Svionian*. This term was introduced by the late J. J. Sederholm in a more restricted sense, however, viz. to indicate part of the rocks at present included in the older phase of the *Svecofennian* cycle and, regarding Sweden, in addition part of the rocks nowadays classed as *Gothian*<sup>1</sup> (Sederholm, 1920, 1932).

Nowadays, Finnish petrologists agree in defining *Svionian* as the oldest *Svecofennian* supracrustal complex, which in Finland mainly consists of metamorphic volcanics and 'schists' associated with limestone. (Compare A. Simonen, 1953, and H. Väyrynen, 1954.) In Sweden, the whole supracrustal evolution in the early *Svecofennian* has been defined as the *Leptite* period, and the resultant system of rocks as the *Leptite* system (or the *Porphyry-leptite* complex). Magnusson (1949) has divided the *Leptite* system thus: (Oldest Archean granites and plutonic greenstones.)

3. Larsbo and Mälar series.
2. Grythytte slate series.
1. *Leptite-hällefliint* series.  
(Substratum unknown.)

The *leptite-hällefliint* series consists mainly of volcanics (most frequently acid and intermediate ones), though limestones, iron ores, and, locally, quartzites, are also met with. Two groups have been distinguished in many areas occupied by *leptite-hällefliint* rocks, viz. a lower, sodic group and an upper, potassic group. Part of the volcanics of the Uppsala region belong to the latter group, viz. the *leptites* at and to the east of Storvreta stn, in the north-eastern corner of Plate 1. These contain thin layers of limestone.

<sup>1</sup> In accordance with Wahl (1936), the Fennoscandian Archean should be divided into three eras, viz. *Svecofennian* (Early Archean), *Gothian* (Middle Archean), and *Karelian* (Late Archean).

**Table 1. Petrological evolution of the Svecofennian, or Old Archean, rocks of the Uppsala region.**

Late Svecofennian	Distant migmatitization	Granite-aplite, pegmatite
	Development of joints	Dikes of metabasites and acid porphyry Peridotite, ultra-basic gabbro
Middle Svecofennian	Decreasing orogeny	Acid, intermediate, and porphyritic granite <sup>1</sup>
	Strong tectonic activity, strong volcanism	Basic granite Quartz-diorite <sup>2</sup> , diorite, metabasite <sup>2</sup> Gabbro Lherzolite, ultra-basic gabbro
Mälars series		Sedimentary gneiss, basic tuff, intrusions of uranite-porphyrite
Oldest Svecofennian (leptite-hällefliint-series)	Increasing tectonic activity, intense volcanism	Plagioclase-porphyrites, basic leptite (in part porphyritic) <sup>3</sup> Fragment-bearing rocks (mainly volcanic conglomerates) Acid and intermediate hälleflinta, porphyritic, and leptite, in part coarse <sup>3</sup>
		Intense volcanism

<sup>1</sup> In part supracrustal rocks granitized *in situ*.

<sup>2</sup> Mainly metamorphic supracrustal rocks.

<sup>3</sup> Developed by strong recrystallization.

Most of the volcanics of the Uppsala region are still younger, however. The central yellow district in Plate 1, viz. the volcanic district at Uppsala, occupies a stratigraphic position between the upper, potassic group of the leptite-hällefliint series and the Mälars series. The latter is composed essentially of sedimentary rocks admixed with intermediate and basic volcanics. It appears in the southern vicinity of Uppsala, and a small area also occurs to the west of the town (orange fields in Plate 1). (Compare below.)

As early as in 1880, A. E. Törnebohm — the famous investigator of the ore-bearing region of Central Sweden, stated that the uppermost part of the 'granulite' (old synonym of leptite and hälleflinta) series is very poor in ores (1880 b, p. 24—25). The central volcanic district at Uppsala does not contain any ores at all. Moreover, no limestone layers worth attention have been met with.

In P. Geijer's and N. H. Magnusson's iron ore monograph (1944), Magnusson has interpreted the volcanics at Uppsala as younger than the ore-bearing leptite-hällefliint series. On one of the maps contained in the monograph (1944, Plate 2), the volcanics at Uppsala have thus been included in the great complex of rocks belonging to the Larsbo and Mälars series. I am not inclined to go so far, however, especially as there is a marked petrographical difference between these volcanics and most volcanics encountered in the Larsbo-Mälars complex. In agreement with Törnebohm's considerations, I assign the volcanics at Upp-

sala to the uppermost group in his 'granulite' series, which will be here called Oldest Svecofennian. (Compare Table 1.) The volcanics at Uppsala will thus be described in the same chapter as the older volcanics in the Streveta area.

To the west of Uppsala, N.E. of Börje church, recrystallized and granitized Uppsala volcanics are covered with recrystallized and in part mobilized rocks belonging to the Mälars series. This series is in the Uppsala region concentrated to the Uppsala—Bergsbrunna area. It comprises mica gneiss, basic tuff, and uralite-porphyrityte.

In Finnish petrological nomenclature, part, or all, of the supracrustal rocks belonging to, or corresponding to, the Grythytté, Larsbo, and Mälars series have been known as Bothnian, another term originally introduced by Sederholm (1893). Sederholm thought that the oldest Archean granites of Finland should have intruded in the interval between Svionian (see above) and Bothnian, whereas several younger investigators assert that no granites older than Bothnian exist at all. (Compare Simonen, 1953.) Väyrynen (1954) has introduced a third term, Fennoian, for the kinzigite series met with between the Bothnian Tampere (Tammerfors) schist belt and the Svionian rocks in the Southern Finnish coast region. Simonen (1953) states that the kinzigite is a mere high-metamorphic facies of the Tampere schists and thus belongs to Bothnian, too.

In Sweden, it would seem convenient to adopt Bothnian in the sense of Simonen for the Svecofennian sedimentary rocks admixed with intermediate and basic volcanics, because these have always been shown to be younger than the leptite-hällefliint series. The variable interpretations of the meaning of Bothnian from time to time have caused some confusion, however, and therefore the neutral 'Mälars series' will be used in this paper despite of its linguistic resemblance to Mälars sandstone series (Algonkian).

The terminological discussion being finished, a brief summary of the geological events in Svecofennian will be given.

As already touched upon, Oldest Svecofennian was characterized by intense volcanic activity. The limestones and iron ores associated with the volcanics have to be interpreted as chemical sediments. Clastic sediments are also known, however. Most of these show the petrographical features of metamorphic feldspar-quartzites and arkoses though pure quartzites and calcareous schists have also been observed.

The following period was signified by increasing tectonic activity. Elevated parts of the crust supplied depressed parts with eroded matter, and the climatological conditions seem to have favoured rapid degradation. The deepest basins displayed geosynclinal character. They became nearly exclusively filled with slates and graywackes as well as psammities showing graded bedding and being intercalated with intermediate to basic volcanics. Most of these volcanics are pyroclasts. (Compare the Tampere schist belt in Finland, described by Sederholm, 1897, Simonen, 1953, and other petrologists). Intra-

**Table 2. Chemical analyses of**  
(N = new analyses; W = analyses quoted from E. Wiman, 1930;

Component	Porphyritic hällflinta, 3.7 km S.W. of Gila Uppsala church. Analyst: M. STOLPE (S)	Lepite, 6.5 km E.S.E.—E. of Storvreta stn. Analyst: M. STOLPE (S)	Very fine-grained pyro- clastic rock, 3.5 & 4 km E.S.E. of Börje church. Analyst: N. SAHLBOM (W)	Fine-grained plagioclase- porphyrite, older, 4 km E.S.E. of Börje church. Analyst: M. STOLPE (S)	Do., younger, penetra- ting, 4 km S.W. of Gila Uppsala church. Analyst: A. AAREMÅE (N)	Coarser plagioclase- porphyrite, c. 1 km S.W. of Vaksala church. Analyst: M. STOLPE (S)
SiO <sub>2</sub>	74.72	74.22	65.85	61.17	61.46	65.09
TiO <sub>2</sub>	—	—	1.20	—	0.90	—
Al <sub>2</sub> O <sub>3</sub>	11.93	14.31	14.25	19.45	16.26	13.30
Fe <sub>2</sub> O <sub>3</sub>	—	0.34	1.43	3.02	1.70	4.27
FeO	1.74	2.24	4.98	3.18	5.00	3.72
MnO	0.20	—	0.04	—	0.11	0.48
MgO	0.46	1.75	2.00	1.25	2.58	2.62
CaO	1.31	2.16	3.32	2.95	5.15	5.50
BaO	—	—	—	—	0.04	—
Na <sub>2</sub> O	0.65	0.94	2.77	4.11	2.43	1.27
K <sub>2</sub> O	8.12	2.58	2.76	2.30	1.95	1.81
P <sub>2</sub> O <sub>5</sub>	—	—	0.30	—	0.08	—
H <sub>2</sub> O > 110°	1.09 <sup>1</sup>	2.17 <sup>1</sup>	0.69 <sup>2</sup>	2.03 <sup>1</sup>	2.03	1.38 <sup>1</sup>
S	—	—	0.23	—	0.05	—
F	—	—	—	—	0.06	—
H <sub>2</sub> O < 110°	—	—	(0.15 <sup>2, 5</sup> )	—	0.11	—
Σ	—	—	99.89	—	99.91	—
Oxygen re- placed by S and F	—	—	0.09	—	0.04	—
Total sum	100.22	100.71	99.65	99.46	99.87	99.44

<sup>1</sup> Only 'H<sub>2</sub>O' reported in the original analysis.

<sup>2</sup> > and < 105° respectively.

<sup>3</sup> Includes Fe<sup>2+</sup> calculated as Fe<sub>2</sub>O<sub>3</sub>.

<sup>4</sup> In the western vicinity of the Uppsala region.

<sup>5</sup> This figure is not included in the total sum.

## rocks from the Uppsala region.

S = analyses taken from older publications of the Geological Survey.)

Uralite-porphyrite, c. 1 km W. of Vaksala church. Analyst: M. STOLPE (S)	Gabro, 4.5 km W. of Bergsbrunna stn. Analyst: A. AAREMÄE (N)	Primorogenic basic granite (Uppsala granite), 3.5 km E.N.E. of Läby church. Analyst: M. STOLPE (S)	Do., 3.5 km E. of Läby church. Analyst: R. MAUZELIUS (S)	Primorogenic acid granite (Vänge granite), N. of Lake Tena, parish of Vittinge <sup>4</sup> . Analyst: R. MAUZELIUS (S)	Metabasite (dike), 5 km W. of Börje church. Analyst: Geochem. inst., Geol. Survey of Sweden (N)	Porphyry (from diaschis- tic dike), 3 à 3.5 km N.E. of Läby church. Analyst: N. SAHLBOM (W)
59.11	44.08	67.67	69.95	76.45	48.5	70.82
—	0.70	—	0.42	0.12	0.73	0.50
12.14	20.21	14.76	12.30	11.64	14.9	14.25
6.40	2.20	2.06	2.09	0.98	13.0 <sup>3</sup>	1.22
5.17	7.60	2.65	2.72	1.03	—	2.17
trace	0.14	0.74	0.13	0.06	0.23	0.05
4.44	7.16	1.59	2.03	0.38	7.8	0.55
7.34	14.68	3.95	4.26	1.30	9.7	2.36
—	0.02	—	0.06	0.07	—	—
1.80	0.72	4.14	1.99	2.40	2.4	3.99
1.20	0.46	4.27	3.13	4.85	1.0	3.17
—	0.10	—	0.12	0.07	—	trace
1.96 <sup>1</sup>	1.95	1.02 <sup>1</sup>	0.91 <sup>1</sup>	0.56	1.3 <sup>1</sup>	1.07 <sup>2</sup>
—	0.21	—	—	—	—	—
—	0.02	—	—	—	—	—
—	0.12	—	—	—	—	(0.14 <sup>3, 5</sup>
—	100.37	—	—	—	—	—
—	0.09	—	—	—	—	—
99.56	100.28	102.85	100.11	99.91	99.6	100.15

formational conglomerates are common, indicating highly variable water depths. The original thickness of the geosynclinal strata has been very great (in the Tampere region most probably at least 8 kilometres, according to Simonen, 1953).

In basins that have been more stable during the whole period of geosynclinal evolution, differentiated arenaceous and argillaceous sediments predominate. We there meet with conglomerates, arkoses, quartzites, and clay slates which are sometimes marly (Grythytte series, part of the Mälar series). In Södermanland, limestone, too, seems to have formed during this period. The slates have as a rule altered to mica schists, mica gneisses, garnetiferous gneisses (often kinzigitic, with sillimanite and cordierite) etc. The gneisses most frequently contain pegmatite veins developed during the late Svecofennian migmatitization. (Compare below.) Intercalations of intermediate and basic volcanics, in part spilitic, are common.

Complex series are also known, indicating highly variable conditions during their development. In the parish of Hamrånge, to the north of Gävle (Gefle) in Eastern Sweden, we have thus a syncline filled with acid, intermediate, and basic, tuffitic-argillitic rocks, spilite, porphyrites, sericite-bearing quartzite, and volcanic conglomerates. Locally, arkoses, too, have been found. (See P. H. Lundegårdh, 1956.) The bottom of the syncline consists of rocks belonging to the leptite-hälleflint series.

In the easternmost part of Central Sweden, and in Southern Finland especially, intrusions of uraltite and plagioclase porphyrites are quite frequent. It seems probable that these rocks have the same origin as the spilites mentioned above.

In the deepest parts of the orogenic zones, basic magma intruded and masses of gabbroic rocks crystallized (peridotite, lherzolite, gabbros, diorite). The rocks surrounding these intrusions underwent strong heating and were affected by magmatic exudates causing metasomatism, homogeneization, and partial mobilizations. Anticlinal folds and thrust faults enabled the homogeneized mobilized rocks to rise to higher levels of the crust, there crystallizing as primorogenic, or synkinematic, granites.

In the Uppsala region, the grey basic Uppsala granite (brown with green dots in Plate 1) displays a typical primorogenic intrusion of mobilized older rocks mixed with juvenile matter, whereas most part of the red acid Vänge granite (brown with black dots in Plate 1) seems to have developed by metasomatic homogeneization *in situ*.

After the consolidation of the primorogenic granites, the orogenic activity faded. During this period, sets of joints developed. Part of the joints opened and became filled with eruptive rocks, most of which have altered to amphibolites (the metabasite dikes in Plate 1).

The final Svecofennian orogenic activity resulting in regional migmatitizations and the development of acid granites accompanied by pegmatite, has not affected the Uppsala region to any greater extent, though small intrusions (mainly dikes) of granite-aplite and pegmatite are quite frequent. (See Plate 1.) According to recent investigations by A. Parwel and F. E. Wickman (1954),

**Table 3. Spectrographic determinations of chromium, cobalt, nickel, and zinc in rocks from the Uppsala region.**

Analyst: P. H. LUNDEGÅRDH.

Age	Kind of rock	Locality	Parts per million of				
			Cr	Co	Ni	Zn	
Svecofennian	Late	Uralite-porphyrite	3.5 km W. of Börje church	50	40	150	60
		Uralite-diabase	5 km W. of Börje church	100	70	100	150
		Peridotite	4 km W.S.W. of Junkil church	≤ 1	35	150	150
	Middle	Primorogenic acid granite	The neighbourhood of Vänge church	< 5	< 1	< 1	80
		Primorogenic basic granite	South-western part of Uppsala (Ekeby)	25	45	20	200
		Gabbro	4.5 km W. of Bergsbrunna stn (Vipången massif)	5	35	25	70
		Lherzolite	4.5 km W.S.W. of Bergsbrunna stn	100	100	120	150
	Old	Sedimentary gneiss	2.5 km N.W. of Bergsbrunna stn	70	< 10	60	200
		Uralite-porphyrite	1 km W. of Vaksala church	10	15	20	60
		Penetrating plagioclase-porphyrite	4 km S.W. of G:la Uppsala church	10	< 2	2	70

the age of the late Svecofennian pegmatites amounts to 1,700 à 1,800 millions of years. (Uraninite separated from pegmatite at Digelskär, in the skerries of North-Easternmost Uppland, has yielded  $1,700 \pm 200$ , fergusonite separated from pegmatite at Ytterby, N.E. of Stockholm,  $1,790 \pm 200$ , and hjelmite separated from pegmatite at Nya Kårarvet, in the vicinity of Falun, Dalecarlia,  $1,810 \pm 200$  millions of years.)

Post-Svecofennian rocks are not known in the Uppsala region, neither Algonkian dolerite nor alkaline rocks related to the Permian ones (umptequite etc.) at Almunge, to the east of Uppsala.

The smooth land-level of Uppland is, however, a product of the Algonkian degradation. This land-level belongs to a great sub-Cambrian peneplain, much of which was spoilt by tectonization during the Paleozoic (Caledonian folding) and Tertiary. Most of the peneplain was once covered with Cambro-Silurian strata. In Uppland, later periods of degradation effected nearly complete dissection of these rocks. Only sparse fissures filled with sandstone and/or calcite have been preserved. The dissected sedimentary rocks were removed by the huge Quaternary glaciers and became admixed with crystalline decay such as disintegrated granites. The whole mixture finally got redeposited as glacial drift (moraine, gravel, sand, silt, clay).

It would seem reasonable that the environments of Uppsala — the oldest university town of Sweden, should have been subjected to exhaustive petrological

investigations quite long ago. This is, however, true only to a limited extent, as will be evident from the following recapitulation.

In 1876, E. Svedmark published a careful examination of a swarm of short uralite-porphyrite dikes in the early Svecofennian volcanics to the west of Vaksala church, and in 1888 he returned to this subject. The Middle Svecofennian granites of Uppland have been described by no less than three prominent Swedish petrologists, viz. in 1881—1882 by Törnebohm, in 1893 by A. G. Högbom, and in 1906 by P. J. Holmquist.

A little more than a quarter of a century ago, E. Wiman (1927) published an incomplete petrographical sketch-map and description of the environments of Uppsala. The map was reprinted in 1930, as a complement of a detailed description of most rocks encountered at Uppsala. In the same paper, Wiman (1930) gives an account of his investigations in the Widbo area south-east of Uppsala — a slice of Mälar series surrounded by primorogenic Svecofennian granites.

The first geological map of part of the Uppsala region was produced by Axel Erdmann, founder of the Geological Survey of Sweden (*Geologisk karta öfver Fyrisåns dalbäcken*, scale 1:50,000, printed in Stockholm 1857). In 1869, the geological map-sheet Aa 31 of the Geological Survey appeared (Scale 1:50,000). This is the first complete geological map of the Uppsala region. It was produced by M. Stolpe.

Both Erdmann's and Stolpe's maps show the rock content of each outcrop observed as well as the character of the surrounding Quaternary deposits. The geological map-sheet Aa 199, published in 1956 by P. H. Lundegårdh and G. Lundqvist, displays a wholly independent successor of Stolpe's map Aa 31. Contemporaneously with the new map-sheet, a complete petrological large-scale map of the Uppsala region was produced. (See Plate 1.)

In Table 1, a scheme of the various rocks of the Uppsala region is given, and in Table 2, the reader will find a series of chemical analyses of these rocks. A number of determinations of some minor elements can be studied in Table 3.

### Oldest Svecofennian.

The oldest Svecofennian rocks of the Uppsala region have supracrustal character. Volcanics predominate. Clastic and chemical sediments are only occasionally met with.

As regards the volcanics, lava rocks (in part agglomeratic) show the highest frequency though pyroclasts are also abundant. Among the latter, volcanic conglomerates have to be mentioned first. Furthermore, crystal tuffs, tuff breccias, and ordinary tuffs have been observed.

The leading lava rock is a black, black red, dark red, or red brown quartz-porphyrity known under the name of porphyritic hälleflinta. (Hälleflinta is an old Swedish term indicating a dense, 'flint-like' Archean volcanic rock with

average grain size<sup>1</sup>  $\geq 0.02$  mm.) The hällflinta of the Uppsala region is in most cases acid though intermediate varieties have also been encountered.

In the central part of the Uppsala region, fine-grained, andesitic plagioclase-porphyrite is quite abundant, too. This rock is intimately related to a hypabyssal plagioclase-porphyrite with coarser phenocrysts. In Table 1 and Plate 1, the two varieties have been united.

During the Svecofennian orogeny, the Uppsala volcanics became deep-seated owing to folding combined with faulting. They were heated and frequently underwent complete recrystallization. The porphyritic hällflinta thus altered to acid and intermediate leptite while the plagioclase-porphyrites changed to quartz-diorite or basic, in part porphyritic leptite. In many cases, these secondary rocks have lost all primary features except for their chemical bulk compositions.

In the neighbourhood of Uppsala, metamorphic rocks of the kind now described are met with only near the contacts between volcanics and primorogenic granites, whereas they dominate the remaining occurrences of oldest Svecofennian rocks in the Uppsala region. Complete transitions between metamorphic volcanics and primorogenic granites are also frequent. As will be seen later, even part of the primorogenic granites themselves derive their origin from volcanics which have undergone recrystallization to some extent combined with metasomatism.

The oldest Svecofennian rocks of the Uppsala region display a number of slender inclusions in the primorogenic granites. The dips of these inclusions are most frequently steep and directed southwards. The earliest strata are found to the east of Storvreta stn, in the north-eastern corner of Plate 1. W.N.W. and S.E. of Uppsala, Oldest Svecofennian is overlaid with rocks belonging to the Mälars series. Contacts between granitized Oldest Svecofennian and Mälars series are visible W.N.W. of Uppsala, N.E. of Börje church.

#### Quartzite. Limestone.

In the volcanic conglomerates between Börje church and Uppsala (p. 21), numerous small fragments of grey white quartzite have been observed. Similar fragments also occur in part of the leptite 7 km to the east of Storvreta stn (p. 26). The quartzite of the fragments is mostly clastic and quite pure (irrespective of sparse grains of feldspar), contrary to the quartzite of the two larger, sheet-like inclusions in the primorogenic granite S.S.W. of Jumkil (in the north-western part of Plate 1).

The quartzite S.S.W. of Jumkil church is a greenish or yellowish grey to dark grey, fine medium- to fine-grained rock. Its contacts with the surrounding granite are distinct, and no transitions into other sorts of supracrustal rocks have been observed. Its stratigraphic position is thus unclear.

The south-western inclusion shows an almost non-deformed quartzite consisting of both rounded and, most frequently, irregular quartz grains in a felty

<sup>1</sup> exclusive of phenocrysts.

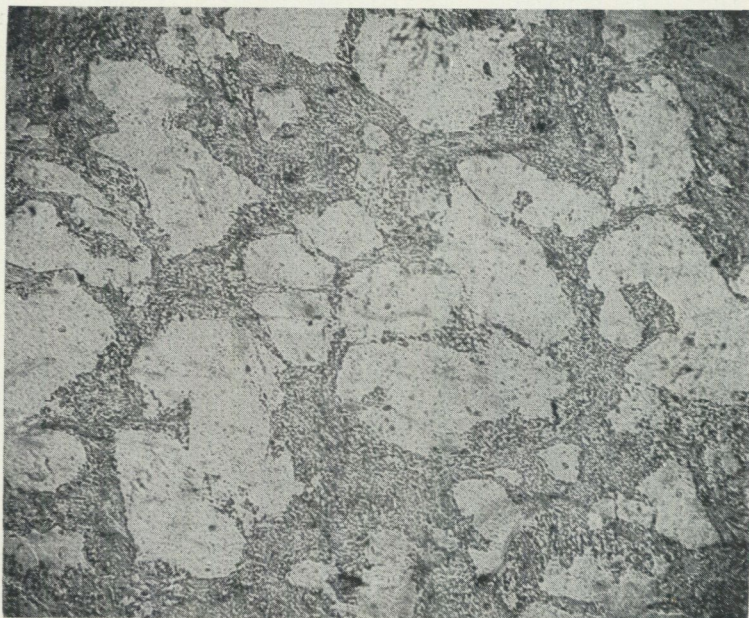


Fig. 1. Quartzite. Thin section magnified  $25\times$ . 2 km S.S.W. of Jumkil church.  
Photo C. Larsson and P. H. Lundegårdh.

alteration matrix of sericite, muscovite, and very fine-grained quartz. The muscovite is in most cases impregnated with minute ore grains. Small quantities of hydrozircon also occur in the quartzite.

The north-eastern inclusion is slightly schistose and composed of irregular quartz grains in a dense matrix of quartz, biotite, and muscovite (Fig. 1). Sparse grains of rounded garnet and angular hydrozircon have been observed.

Similar quartzitic rocks accompany the hälleflintas at Dannemora, 40 kilometers N.N.E. of Uppsala. They have to be interpreted as pyroclasts (personal communication by Prof. Per Geijer).

1,700 m S.E. of Börje church, the porphyritic hälleflinta locally grades into a white, quartzitic rock consisting of small quartz grains (0.5—1 mm in length) in a matrix of quartz and felspar (potassic felspar essentially). E. Wiman, who first examined this quartzite (1930, p. 18), interpreted it as a metasomatic alteration product of the ordinary hälleflinta. He points out the marginal position of the quartzite now described and refers to other marginal occurrences of similar quartzite within the Uppsala volcanics. Even in the centre of the volcanic area, 2 à 2½ km S.W. of G:la Uppsala church, I have observed irregular inclusions of quartzite which are evidently metasomatic.

The leptite in the north-easternmost part of Plate 1 contains a few boudinaged, steep, thin layers of recrystallized granularly limestone, which outcrops 6 km to the east of Storvreta stn (Fig. 2). The margins of this limestone have

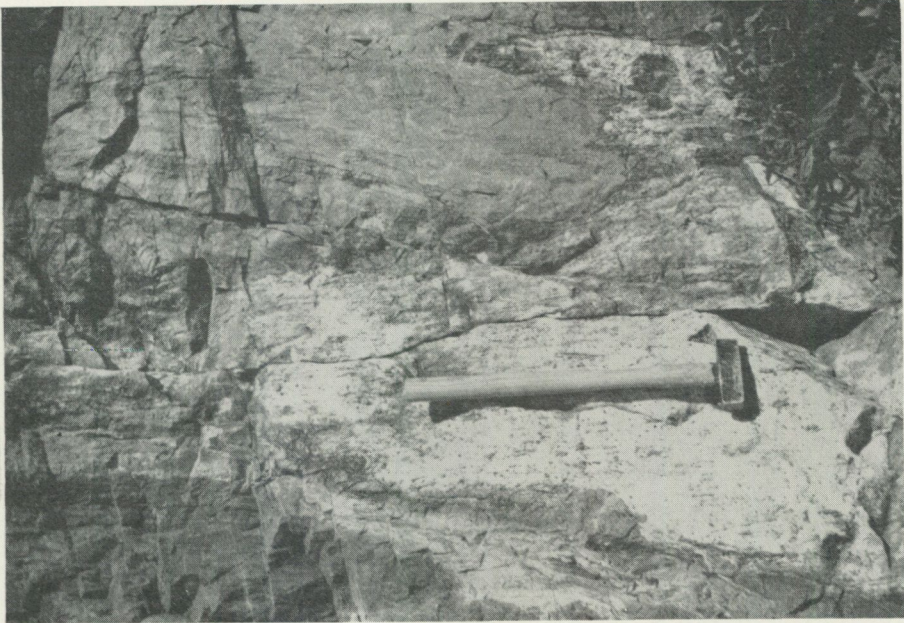


Fig. 2. Layer of limestone (white) in leptyte. Quarry 6 à 6.5 km E.S.E.—E. of Storvreta stn.  
Photo P. H. Lundegårdh.

frequently altered to epidote, and small fragments of it in the primorogenic granite about  $1\frac{1}{2}$  km E.S.E. of the outcrop have become entirely epidotized.

In the neighbourhood of Uppsala, no layers of limestone have been encountered. The volcanic conglomerates between Uppsala and Börje church are, however, very rich in pebbles of epidote. In single cases, this epidote is associated with a little calcite.

The multitude of epidote pebbles in the conglomerates at Uppsala, as well as the high frequency of joints filled with epidote in the same volcanic complex, indicate that considerable amounts of limestone have been present at lower stratigraphic levels. Furthermore, a few thin layers of epidote within one of the conglomerate beds suggest that small quantities of calciferous sediments have been able to develop even there.

### Porphyritic Hälleflinta.

Porphyritic hälleflinta is the leading volcanic rock in the neighbourhood of Uppsala. Moreover, porphyritic hälleflinta occurs in the slice-shaped leptyte inclusion to the east of Storvreta stn.

In and around Uppsala, the porphyritic hälleflinta displays a dense, 'flint-like' rock, the colour of which is in ordinary varieties red brown, dark red, black red, or black. Grey and black grey varieties have also been observed. The chemical character is in most outcrops acid though transitions into inter-

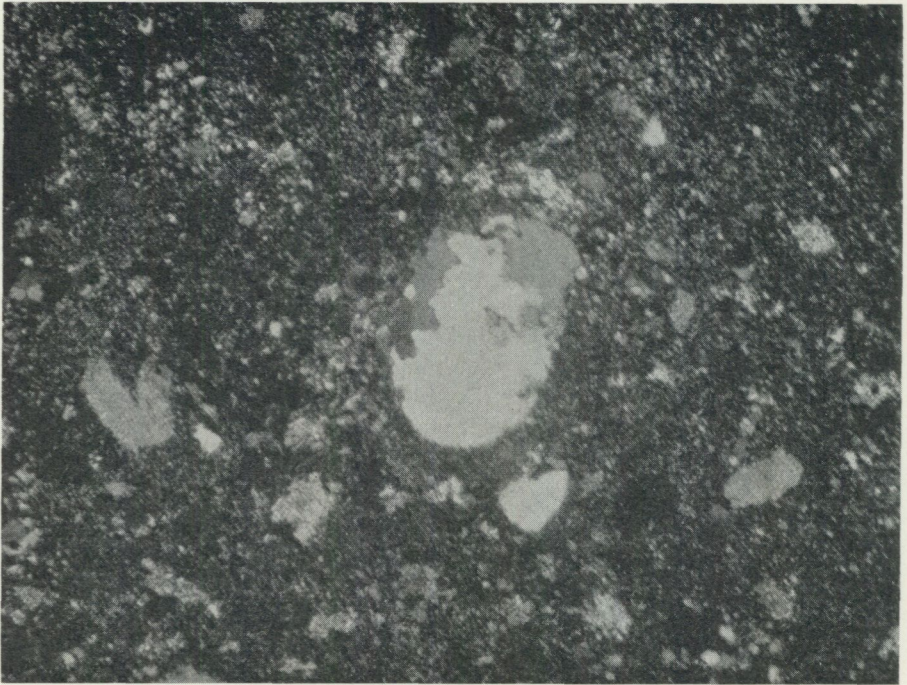


Fig. 3. Amygdule filled with quartz in porphyritic hälleflinta. Thin section magnified 50 ×, crossed nicols. 1.8 km S.E. of Börje church.  
Photo C. Larsson and P. H. Lundegårdh.

mediate varieties are quite frequent. (Compare Table 2 and the calcium-alkali determinations given below.)

The hälleflinta is as a rule rich in phenocrysts. Most of these consist of acid plagioclase. Quartz phenocrysts are also common, whereas phenocrysts of mafic minerals are comparatively rare. Porphyritic grains of microcline have been observed now and then.

Though the phenocrysts can often be easily perceived macroscopically, their lengths do not in ordinary cases exceed 1 mm, and grains larger than 3 mm are rare. The felspar phenocrysts are hypidiomorphic or idiomorphic, whereas the quartz phenocrysts are as a rule xenomorphic. Amygdules filled with quartz also occur (Fig. 3).

The porphyritic hälleflinta is a lava rock which frequently shows beautiful fluidal structure (Fig. 4) although its groundmass has apparently recrystallized. There are, indeed, strong reasons to suspect that much of the porphyritic hälleflinta was originally glassy.

Agglomeratic structure is common, both in the lava itself (agglomeratic lava) and in layers of acid tuff intimately associated with the lava (tuff breccias; see also p. 24, upper part). Both sorts of agglomerate are monomikt, the fragments being entirely composed of a porphyritic hälleflinta often but slightly different from that of the matrix enclosing them.

A great number of plagioclase phenocrysts show zonal growth. In these crystals, the kernels are richer in An than the margins. The average content of An is very low, however, in most cases less than 10 %. The plagioclase phenocrysts have as a rule suffered from sericitization to a certain degree, and many crystals have been completely sericitized. Simultaneously with this low-temperature alteration, the phenocrysts have become impregnated with microscopic grains of hematite.

The quartz phenocrysts have as a rule been cracked and thus consist of a variable number of irregular individuals showing slightly different optical orientations. The quartz contained in amygdules has altered similarly (Fig. 3).

The larger microcline grains are quite fresh and do not show any special characteristics indicating their mode of development. At least part of them have probably to be interpreted as recrystallized orthoclase or sanidine phenocrysts. Anyhow, the growth of microcline porphyroblasts does not seem probable in this low-metamorphic kind of rock.

The sparse mafic phenocrysts have altered to serpentine and/or chlorite and/or epidote, frequently in combination with iron ore.

The groundmass is essentially composed of quartz, potassic feldspar, and plagioclase. Furthermore, variable quantities of muscovite, sericite, chlorite, epidote, zoisite, and iron oxides are included in the groundmass. The red hällflintas have as a rule become strongly sericitized and impregnated with minute grains of hematite. A few accessory minerals have been observed, viz. titanite, apatite, zircon, and, sometimes, pyrite. In the intermediate hällflinta, biotite is quite common, and it may also appear in the dark varieties of the acid hällflinta. The fluidal structure (Fig. 4), as well as the occasional schistosity (compare below), are most frequently marked with this mineral.

Chemical calcium-alkali determinations on porphyritic hällflinta have revealed the following data:

Locality	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Analyst
3.7 km S.W. of G:la Uppsala church, near Husbyborg . . . . .	1.31	0.65	8.12	M. Stolpe
Husbyborg . . . . .	0.67	2.59	6.83	N. Sahlbom
G:la Uppsala . . . . .	1.00	3.20	4.86	»
Stångby S.E. of Vaksala church . . . . .	0.89	4.34	3.90	»

The first analysis was originally published by Stolpe in the memoir accompanying the previous edition of the geological map-sheet Uppsala (Stolpe 1869, p. 15). The following three analyses have been reprinted from E. Wiman's monograph (Wiman 1930, p. 14). The figures indicate that, in the volcanic area at Uppsala, the varieties richest in potassium will be found north-west of the town. Although Stolpe's analysis (see also Table 2) is quite old and thus probably less accurate than Sahlbom's determinations, it none the less bears evidence of a rock that has concentrated potassium to a very high degree. Rocks of this kind are in Sweden known as potassic leptites and are common in the



Fig. 4. Porphyritic hällflinta with fluidal structure. Thin section magnified  $50\times$ . 1.8 km S.E. of Börje church.

Photo C. Larsson and P. H. Lundegårdh.

Swedish Svecofennides. (Compare B. Asklund, 1929.) In the Uppsala region, they have also been found to the east of Storvreta stn and as inclusions in the red primorogenic granite W.—N.W. of Uppsala. (See 'Leptites' below.)

Like porphyries in other tectonized regions, the Uppsala hällflinta is very rich in joints and cracks. The remaining rocks of the volcanic district at Uppsala have also suffered markedly from shearing and tearing producing sets of joints. (Compare p. 64.) On the other hand, the Uppsala hällflinta is seldom schistose. Apart from an occasional fluidal structure, most hand specimens collected display structural isotropy.

As has been mentioned, porphyritic hällflinta also occurs in the volcanic area to the east of Storvreta stn. Thin sections of red grey schistose hällflinta collected 3 km to the east of Storvreta stn show a recrystallized rock with angular phenocrysts of quartz and plagioclase. The latter have to some extent altered to microcline and are frequently idiomorphic. Moreover, sparse idiomorphic phenocrysts of magnetite have been observed. The composition of the plagioclase phenocrysts ranges from oligoclase to andesine.

The schistosity is marked with flat aggregates and sparse blades of biotite in a granoblastic groundmass composed of very small quartz and felspar grains (both sodic and potassic felspar). The biotite aggregates may be interpreted as altered and flattened phenocrysts.

### Fragment-Bearing Volcanics. Non-Porphyrific Hällflinta.

As we have seen in the above text, the porphyritic hällflinta, or old Archean quartz-porphyry, in the neighbourhood of Uppsala often shows fluidal structure and should thus be interpreted as a lava. Between Börje church and Uppsala, however, it now and then contains numerous fragments of foreign rocks, such as quartzite and basic volcanics, as well as small inclusions of quartz-porphyrifics which have developed earlier. In these cases, fluidal structure is wanting, and the groundmass is certainly a tuff. Probably, part of the fragment-free quartz-porphyry has also been originally deposited as a tuff, viz. the varieties displaying no fluidal structure at all.

Non-porphyrific, tuffitic hällflintas have been observed in the Uppsala region, too, *inter alia* in a few outcrops between Uppsala and Börje church. Most pyroclasts of, at least, the central part of the Uppsala region are fragment-bearing, however. Both grains of minerals and pieces of rocks are represented among the fragments. Pure crystal tuffs have been met with now and then though agglomeratic or conglomeratic rocks are by far more common. The latter are most often polymikt and should then be classed as volcanic conglomerates, in accordance with F. von Wolff (1914, p. 403).

In the volcanic conglomerates at Uppsala, angular fragments predominate (Fig. 6) though many inclusions of soft rocks (epidotized limestone especially) have become rounded (Fig. 7). All sizes of rock fragments between 400 and 1 à 2 mm are represented. The majority of fragments does not exceed 100 mm in length, however. The maximum length of the crystal fragments amounts to about 3 mm. The groundmass is in most cases intermediate to basic and frequently plagioclase-porphyrific, owing to the fact that plagioclase is the leading crystal fragment mineral. As has been mentioned above, fragment-bearing pyroclasts with acid groundmass (porphyritic hällflinta) also occur. These are frequently monomikt. The groundmass of the acid fragment-bearing rocks is dense, and the groundmass of the intermediate to basic fragment-bearing rocks dense to fine-grained.

As is seen from Plate 1, the fragment-bearing rocks are concentrated to the area between Uppsala and Börje church though they have also been found W.N.W. of G:la Uppsala, 6—7 km to the east of Storrreta stn, and in restricted quantities at still other localities. The fragment-bearing rock W.N.W. of G:la Uppsala is interesting inasmuch as it displays monomikt character. (See below.)

It was mentioned above that most crystal fragments consist of plagioclase. Fragments of epidote are also frequent, whereas quartz fragments are common only in the acid pyroclasts. A typical crystal tuff is shown in Fig. 5.

The volcanic conglomerates (Fig. 6) contain numerous fragments of acid, intermediate, and basic volcanics as well as of epidotized limestone (Fig. 7) and quartzite. Part of the latter may be derived from cherts. Most quartzite fragments display clastic texture, however. Fragments of soft pelite, stratified psammite, and granite have also been seen, though psammite and granite only

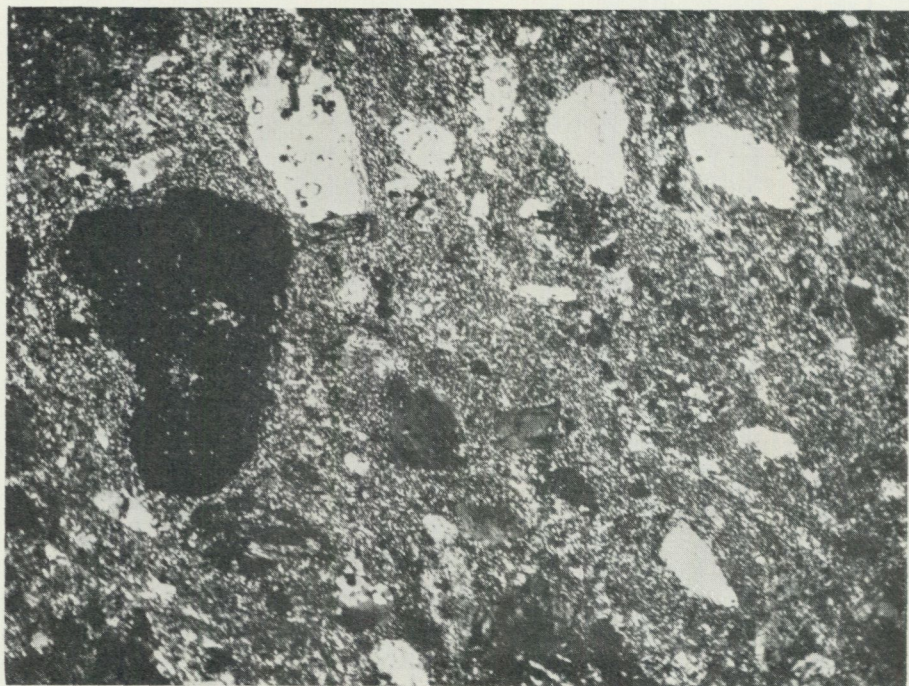


Fig. 5. Crystal tuff. Thin section magnified 25  $\times$ , crossed nicols. 3 km E.S.E.—E. of Börje church.  
Photo C. Larsson and P. H. Lundegårdh.

in rare cases. At two localities showing ordinary polymikt volcanic conglomerate with basic groundmass, all rock fragments  $\geq 5$  mm in length have been counted in two almost horizontal rectangles measuring 250  $\times$  500 mm:

Locality I. 2.8 km to the east of Börje church.

	Rectangle 1.	Rectangle 2.
Acid and intermediate volcanics (very often hällflintas).....	34	23
Basic volcanics (metabasites) .....	2	39
Quartzite .....	2	6
Epidotized limestone .....	2	1
Total number	40	69

Rectangle 1 is situated at a distance of 10 m N.W. of rectangle 2, viz. in a direction almost perpendicular to the stratification. Obviously, the two rectangular faces reflect the compositions of two different conglomerate layers. No fragments larger than 125 mm have been observed in the rectangles. The quartzite fragments are the smallest ones. Many of these have been excluded from the statistical tables here given since they do not reach 5 mm in length.

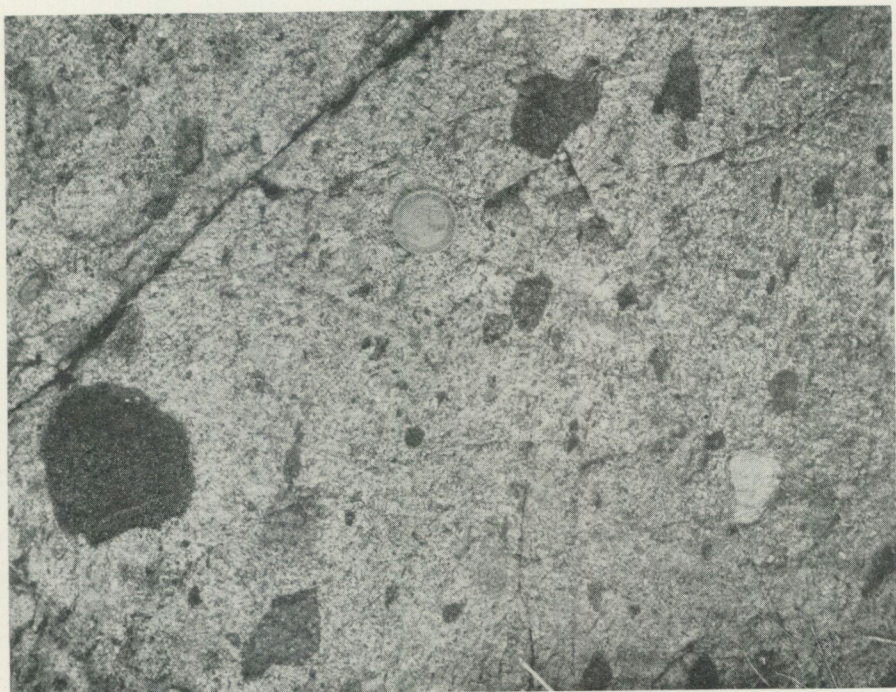


Fig. 6. Volcanic conglomerate, 3.4 km E.S.E. of Börje church.  
Photo P. H. Lundegårdh.

The bulk composition of the two rectangular faces now considered has been calculated thus:

Acid and intermediate volcanics . . . . .	52	%
Basic volcanics . . . . .	37.5	%
Quartzite . . . . .	7.5	%
Epidotized limestone . . . . .	3	%
	<u>100</u>	%

Locality II. 3.4 km E.S.E. of Börje church. (See also Fig. 6.)

	Rectangle 1.	Rectangle 2.
Acid and intermediate volcanics (often hälleflintas)	13	15
Basic volcanics (metabasites) . . . . .	30	33
Quartzite . . . . .	3	2
Soft pelite . . . . .	3	4
Epidotized limestone . . . . .	<u>11</u>	<u>13</u>
Total number	60	67

The distance between the two rectangles amounts to 35 m almost perpendicular to the stratification. Nevertheless, they seem to belong to the same conglomerate layer. They show the following bulk composition:

Acid and intermediate volcanics . . . . .	22	%
Basic volcanics . . . . .	49.5	%
Quartzite . . . . .	4	%
Pelite . . . . .	5.5	%
Epidotized limestone . . . . .	19	%
	100	%

The quartzite fragments are here, too, the smallest ones. No fragments exceeding 110 mm in length have been observed in the rectangles.

The acid and intermediate volcanics contained in the fragment-bearing rocks petrographically range from hällflintas to leptites. They include both quartz-porphyrries from the Uppsala district and from the older volcanic series represented to the north of Uppsala (at, *inter alia*, Stolvreta stn). W.N.W. of G:la Uppsala, an acid volcanic filled with angular fragments of the local porphyritic hällflinta occurs. E. Wiman (1930, p. 12—13) has interpreted this rock as a tuff breccia. It seems, however, difficult to reject the possibility that the rock in question might be an agglomeratic lava, especially as acid agglomeratic lava has been met with in other outcrops in the northern vicinity of Uppsala.

The basic volcanics, which have altered to fine-grained metabasites, are black or grey black and show the following bulk composition 3—4 km E.S.E. of Börje church: Biotite (aggregates of small individuals) > plagioclase pseudomorphs (composed of zoisite, sericite, primary and acid secondary plagioclase, and quartz) > titanite  $\geq$  epidote. Secondary pyrite is common. The ordinary accessory minerals are muscovite and apatite. Locally, the metabasite fragments have become strongly epidotized. Epidote is then the leading mineral.

The quartzite is grey white, white, or bluish white. The original clastic texture has frequently been preserved though recrystallizations into larger individuals seem to be more common.

The pelite is a soft and aphanitic, grey or greenish grey rock which it has been impossible to investigate in detail.

The inclusions of epidotized limestone are in most cases rounded (Fig. 7). The epidote is poor in iron and has often got associated with quartz having a decided tendency to gather into peripheric shells (Fig. 7). Cracks are quite common in the majority of epidote inclusions. These cracks have never been traced in the surrounding matrix. They have obviously developed during the alteration of the original mineral of the inclusions, which is calcite. Single epidote pebbles still contain some calcite.

The epidote pebbles show to us that the early Archean limestone layers *inter alia* encountered to the east of Stolvreta stn represent a lower stratigraphic level than the volcanic conglomerates in the neighbourhood of Uppsala.

The crystal fragments of epidote met with both in the crystal tuffs and in the groundmass of the volcanic conglomerates should be interpreted as altered calcite, too. Moreover, the volcanic district at Uppsala is very rich in cracks and joints filled with epidote. Solutions rich in calcium, aluminium, and silicic

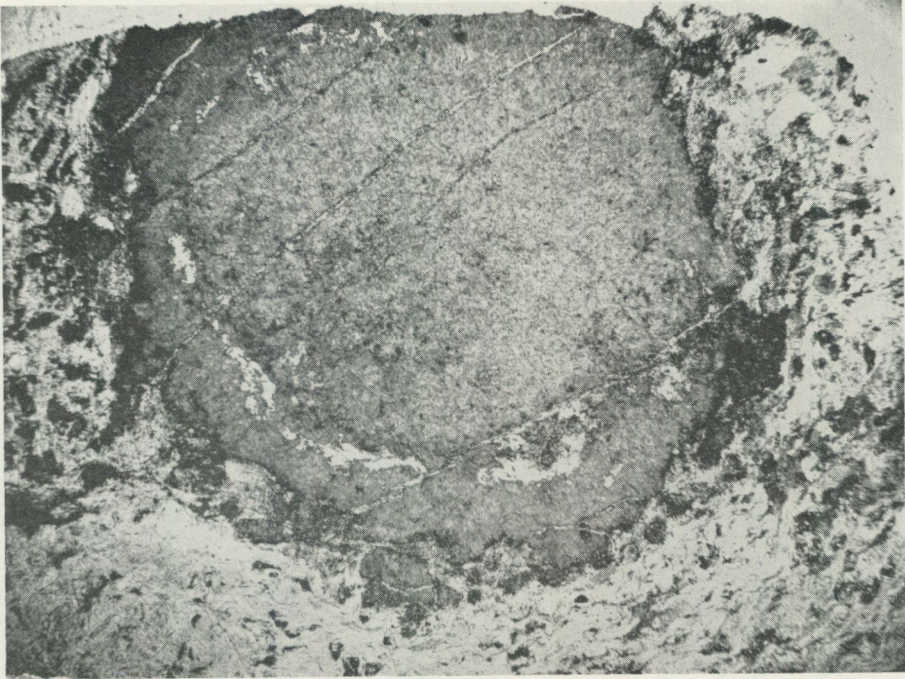


Fig. 7. Pebble of epidotized limestone with internal joints and marginal, concentric quartz. Thin section of volcanic conglomerate magnified  $6 \times$ . 2.5 à 3 km. E.—E.S.E. of Börje church. Photo C. Larsson and P. H. Lundegårdh.

acid have apparently been in action. Now and then, even the volcanic bed-rock itself has been subjected to epidotization. Diffuse alteration spots of epidote thus appear locally in the basic volcanics between Börje church and Uppsala, and the phenocrysts of the plagioclase-porphyrites have frequently undergone strong epidotization. As was mentioned before, the metabasite fragments of the volcanic conglomerates have also sometimes been epidotized.

On the whole, the epidotization has been concentrated to the basic volcanics of the Uppsala district, whereas most part of the intermediate and acid volcanics have been preserved from alteration. This is due to the chemical composition of the latter, however, and limestone fragments enclosed in porphyritic hälleflinta have thus been as strongly epidotized as elsewhere. (As regards epidotization, see also p. 55.)

In addition to the fragments already described, the sparse granite inclusions have to be mentioned once more. The first find was made by E. Wiman (1930, pp. 147—151). He reports the presence of a granite inclusion measuring as much as  $40 \times 20$  cm in the volcanic conglomerate about 4.5 km S.W. of G:la Uppsala church. According to Wiman, the granite is grey and coarse to medium-grained. It consists of quartz, basic oligoclase ( $An = 25-30\%$ ), and biotite. Secondary epidote is also common. Furthermore, Wiman mentions the following accessory minerals: Microcline, titanite, apatite, and ore. Mineralogically, the



Fig. 8. Fragment-bearing leptonite. Thin section magnified 20  $\times$ . Road-cutting 6.5 à 7 km E.—E.S.E. of Storvreta stn.

Photo C. Larsson and P. H. Lundegårdh.

granite differs decidedly from the grey primorogenic Svecofennian granite encountered in the neighbourhood of Uppsala, which is as a rule more basic (rich in hornblende) though it contains considerable quantities of microcline. (See p. 49.)

The origin of the granite xenoliths is unclear. They seem to have been derived either from an infracrustal equivalent to the earliest Upplandian volcanics or from the pre-Svecofennian substratum of the volcanics.

The groundmass of the volcanic conglomerates in the neighbourhood of Uppsala consists mainly of quartz, acid plagioclase, microcline, and biotite (uncommon in acid varieties). In the basic varieties, secondary epidote has frequently got a strong position. Owing to folding, the fragment-bearing rocks have become tilted, and their dip is now high. (See Plate 1.) Simultaneously, part of the conglomerate layers have become schistose. The schistosity is preferentially marked with thin layers of biotite though, in strongly tectonized varieties, the fragments, too, have been affected so that they now display lenses parallel to the schistosity. The strongest tectonization has been met with in the west-south-western corner of the volcanic district, near Börje church.

Volcanic conglomerates do not only occur at Uppsala. Rocks of this kind have also been observed E.S.E. of Storvreta stn (see Plate 1) though they have there developed in earlier Svecofennian time and thus show quite a different

petrographic character. 7 km E.S.E. of Störvreta stn, the red leptite contains the following kinds of fragments: 1. Pure quartzite (Fig. 8). 2. Iron-rich epidote + sericite + dispersed grains of magnetite. 3. Ore + titanite + iron-rich epidote often accompanied by sericite, serpentine, limonite etc. Fragments of sedimentary rocks thus predominate. The association ore (probably titanomagnetite)—titanite—iron-rich epidote indicates a metamorphic ultra-basic eruptive rock, however.

The granoblastic groundmass of the red volcanic conglomerate E.S.E. of Störvreta stn consists of quartz and microcline impregnated with minute hematite grains. Iron ore, too, is common. Further, some epidote has been observed. Sericite, chlorite, serpentine, and limonite are inferior constituents. A little zircon also occurs, whereas plagioclase is wanting. The groundmass is thus extremely potassic, and the rock as a whole should be classed as a potassic leptite. The heterogeneous mineralogical composition of the groundmass indicates an admixture with crystal fragments.

The non-porphyritic hällflintas are grey tuffitic rocks which in part display visible stratification. (Compare E. Wiman 1930, p. 17.) Non-porphyritic hällflinta has been observed in a few outcrops between Börje church and Uppsala, further 7 km E.S.E. of Störvreta stn, near the red fragment-bearing leptite just described.

According to Wiman (1930, p. 19), the non-porphyritic hällflinta in the neighbourhood of Uppsala consists mainly of plagioclase with 35 % An, quartz, potassic feldspar, and mica. The following accessory minerals have been reported: titanomagnetite, titanite, apatite, and orthite (allanite). During alterations of the rock, epidote, zoisite, sericite, and pyrite have developed. A chemical analysis of the rock has been quoted in Table 2.

The non-porphyritic hällflinta E.S.E. of Störvreta stn displays granoblastic texture without visible stratification and consists of the following minerals: Quartz > oligoclase (in part sericitized)  $\approx$  potassic feldspar > biotite  $\gg$  epidote.

### Plagioclase-Porphyrites.

In addition to the fragment-bearing volcanics just described, the area between Börje church and Uppsala displays no less than three varieties of plagioclase-porphyrite. Further, plagioclase-porphyrite (and basic leptitic derivatives) occupies at least half of the Vaksala—Åkerby area. (See Plate 1.) E. Wiman (1930) has classed the plagioclase-porphyrite in the neighbourhood of Uppsala as quartz-andesite, viz. a rock more acid than normal andesite (chemically corresponding to dacite) though it shows andesitic texture.

Plagioclase-porphyrites composed mainly of black, grey black, or green black groundmass filled with small phenocrysts ( $\leq 2$  mm in length) are most common though plagioclase-porphyrite with black, green black, or reddish grey green black groundmass and larger phenocrysts (2—10 mm in length) has also gained a strong position (Fig. 9). The former varieties are concentrated to the western part of the volcanic district at Uppsala, whereas the latter fills part of the bed-



Fig. 9. Plagioclase phenocryst in plagioclase-porphyrite. Thin section magnified  $25 \times$ . 1.5 km E.N.E. of Läby church.

Photo C. Larsson and P. H. Lundegårdh.

rock in the G:la Uppsala—Vaksala area. Furthermore, plagioclase-porphyrite with large phenocrysts has been observed 2.5—3 km E.N.E. of Börje church, 1.5 km E.N.E. of Läby church, and in a small outcrop about 2 km S.S.W. of Vaksala church.<sup>1</sup>

Two varieties of plagioclase-porphyrite with small phenocrysts have been distinguished, one often rather strongly altered rock which is frequently intimately associated with fragment-bearing volcanics, and one more basic, mostly well-preserved rock (Fig. 10) which occupies the area marked with 'G' in Plate 1, in the north-western vicinity of Uppsala. E. Wiman (1930, p. 15) has classed the latter as penetrating quartz-andesite and interprets it as a younger variety. (Compare p. 66.) It locally brecciates the porphyritic hälleflinta.

Plagioclase phenocrysts predominate in the two varieties now considered. Most often these show zonal growth, with rather acid margins and more basic kernels. The average anorthite percentage ranges between 30 and 45, but in the kernels it frequently amounts to 50 à 55. The highest An values have been met with in the penetrating variety. Sericitization is common, especially in the non-penetrative variety. Secondary epidote, clinozoisite, and zoisite also occur in many plagioclase phenocrysts.

<sup>1</sup> In Plate 1, this plagioclase-porphyrite has not been distinguished from the surrounding porphyritic hälleflinta.

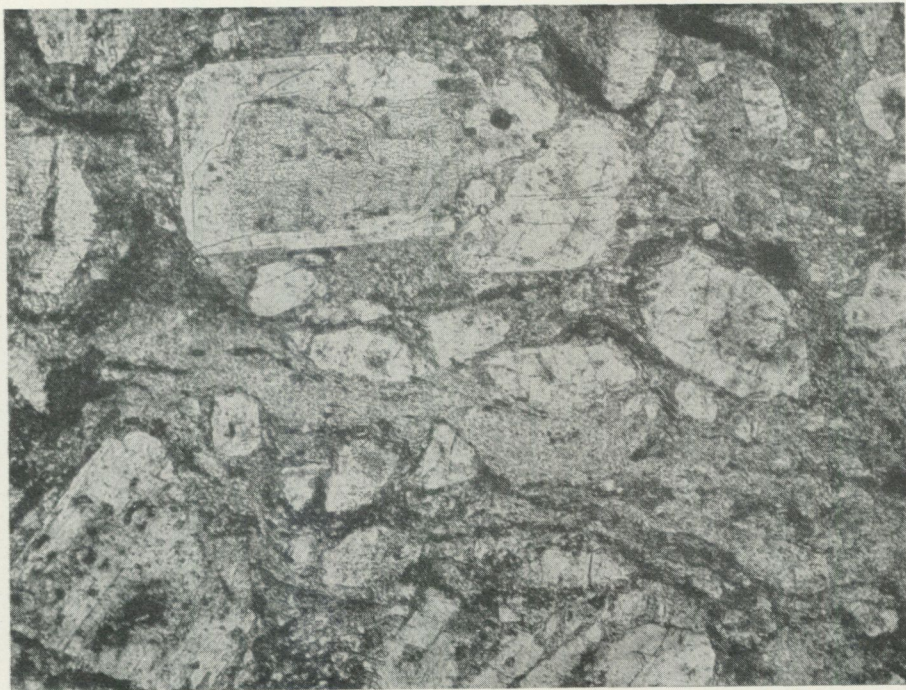


Fig. 10. Penetrating plagioclase-porphyrite with fluidal structure. Thin section magnified  $50 \times$ .  
4 km S.W. of G:la Uppsala church.  
Photo C. Larsson and P. H. Lundegårdh.

Quartz phenocrysts (in part amygdules) appear now and then though not in the penetrating variety. The latter on the contrary contains numerous phenocrysts of titanomagnetite and uraltized pyroxene. The titanomagnetite is often enclosed in a shell of some kind of secondary mineral rich in titanium and known as leucoxene. This mineral here seems to be composed mainly of titanite. The uralite shows the optical properties of common green hornblende.

Furthermore, the penetrating plagioclase-porphyrite locally contains numerous larger plagioclase phenocrysts (2—5 mm in length) and fragments (diameters greater than 5 mm). The fragments are as a rule light-coloured and acid though sparse basic inclusions are also known. According to E. Wiman (1930, p. 146), an inclusion of plagioclase-porphyrite with rather large plagioclase phenocrysts (5 mm in length,  $An = 45\%$ ) shall occur in the south-easternmost part of the area marked with 'G' in Plate 1. This fragment seems to have been derived from the coarse-porphyritic basic hypabyssals of the Uppsala district. (Compare below.)

The groundmass is composed essentially of biotite, plagioclase, potassic feldspar (less common in the penetrating variety), epidote, and quartz. Furthermore, chlorite, titanite, oxidic ore, and pyrite have been observed. Apatite and sometimes zircon, too, are accessory minerals. The grain size of the groundmass does as a rule not exceed 0.05 mm.

Beautiful fluidal structure is common, especially in the penetrating variety (Fig. 10), and certainly most of the plagioclase-porphyrite with small phenocrysts has to be interpreted as lava. Transitions between non-penetrative plagioclase-porphyrite and basic crystal tuff have been observed, however. It seems thus probable that part of this plagioclase-porphyrite variety forms a tuff. Besides, it is sometimes quite impossible to distinguish macroscopically between fragment-bearing basic tuff and plagioclase-porphyrite flows. In Plate 1, even basic volcanics with barely visible fragments have been included in the areas marked with small circles as soon as they fail to show fluidal structure.

Epidote is the leading secondary mineral, and the epidote content reflects the degree of alteration fairly well. Sericitization of the plagioclase is another sign of alteration.

The chemical analyses contained in Table 2 display the principal differences between the non-penetrative and penetrating varieties of plagioclase-porphyrite with small phenocrysts. The former variety is less basic, and it consequently contains higher quantities of alkali metals and lower quantities of calcium + magnesium than the latter variety. The average anorthite content of the former ranges from 30 to 40 %, whereas it amounts to 45 % in the latter. The non-penetrative variety has undergone stronger alteration than the penetrating one and thus shows higher relative contents of trivalent iron than the latter.

The coarse-porphyritic plagioclase-porphyrite is characterized by plagioclase phenocrysts sometimes measuring as much as 1 cm in length and always showing zonal growth. The kernels of the phenocrysts contain 40–45 % An. Owing to partial alteration into sericite and clinozoisite, most phenocrysts have got a greenish or yellowish hue.

The groundmass of the coarse-porphyritic plagioclase-porphyrite is black, green black, or reddish grey green black, and dense to fine-grained. It has as a rule recrystallized completely. It consists mainly of plagioclase (An = 30 %), hornblende (only in comparatively well-preserved varieties), biotite, epidote (most common in strongly altered varieties), and quartz. In addition, the rock contains variable quantities of chlorite, ore (most often enclosed in leucoxene), titanite, and apatite. The two last-mentioned minerals are sometimes wanting. Potassic feldspar is uncommon.

The chemical analyses (Table 2) indicate an intimate relationship between the coarse-porphyritic and the non-penetrative small-porphyritic plagioclase-porphyrites. Transitions between the two rocks have also been met with (2.5–3 km E.N.E. of Börje church). The contents of alkali metals are lower in the coarse-porphyritic variety, however.

The coarse-porphyritic plagioclase-porphyrite has on the whole undergone stronger alteration than the small-porphyritic varieties, especially near its contacts with the primorogenic granite. Accordingly, its relative percentage of trivalent iron is higher than that of the small-porphyritic varieties. The alteration has been caused by the primorogenic granite, the assimilative capacity of which is displayed by the transitions into plagioclase-porphyrite occurring to the west of Vaksala church.

In the area now mentioned, the coarse-porphyrific plagioclase-porphyrite has also been cut by a number of dikes of black uralite-porphyrite. As is seen from Table 2, the latter is more basic than the former. It has been supposed to represent a somewhat younger stage of the eruptive evolution of the Uppsala region. It will therefore be described in the next chapter.

Part of the plagioclase-porphyrite has been subjected to strong metamorphism and has been changed to quartz-diorite and basic leptite. In the central volcanic district at Uppsala, this kind of alteration has only been met with along the boundaries, for example south-east of Börje church and in the neighbourhood of Åkerby church.

Smaller masses of basic volcanics in the primorogenic granite, such as the ones E.N.E. of Läby church (see Plate 1), have changed nearly completely to quartz-diorite or basic leptite, which contain zonal-structured phenocrysts inherited from the original rock, however. The numerous small fragments of basic volcanics included in the basic primorogenic granite have also been strongly altered and have frequently become in part assimilated, too.

The secondary rocks now mentioned will be more fully dealt with in the following text.

#### Leptites.

During the Svecofennian orogeny, the volcanics became strongly heated and grew coarser. Simultaneously, the volcanic textures have been more or less affected, and they have often been wholly lost. The recrystallized hällflinta is a granoblastic rock known as leptite. It is most frequently fine-grained (average grain size ranging from 0.22 to 1 mm) though coarser varieties are also common. These strongly recrystallized volcanics often grade into primorogenic granites (compare p. 56) and may be classed as coarse leptites, or leptite granites.

Now and then, the recrystallization has been seen to have worked contemporaneously with a partial dissolution of the porphyritic hällflinta — water and mineralizers being added with the result of a lowering of the crystallization temperature. The secondary rocks thus obtained cannot be macroscopically distinguished from ordinary primorogenic granites. In the Uppsala region, only the occurrence of sparse plagioclase phenocrysts inherited from the pre-existing hällflinta and the appearance of fluorite revealing an addition of mineralizers give us hints regarding the origin of the rocks in question.

Leptites and leptite granites are most frequent in the northern and western parts of the Uppsala region. They make up the whole rock mass of the smaller volcanic inclusions in the primorogenic granites. In the supracrustal xenoliths in the neighbourhood of Störvreta stn, leptite is the leading rock, too, whereas the volcanic district at Uppsala has only been subjected to marginal leptitization. It is quite interesting that, at Uppsala, the western and eastern ends of the volcanic district display the strongest alteration. In the western end, to the north of Börje church, even leptite granite is frequently met with. The Uppsala xenolith apparently once belonged to a volcanic horizon of considerable exten-

sion, as is also indicated by the numerous lenticular bodies of leptitized volcanics in the western part of the Uppsala region. Most part of this horizon has lost its original character, however, and the porphyritic hällflinta has changed to Vänge granite (primorogenic acid granite), whereas the plagioclase-porphyrite (see the following text) has been split into a great number of small and often in part dissolved (assimilated) inclusions ('dark spots') in the intrusive Uppsala granite (primorogenic basic granite).

The winding Storvreta xenoliths were also larger in early Svecofennian time. In the east-south-easternmost part of the eastern xenolith, the leptite thus grades into primorogenic granite, and the limestone layers in the leptite can be traced as patches of epidote both in the transitional rocks and in the adjacent primorogenic granite.

In Plate 1, the coarsest leptite granites have been included in the brown areas of primorogenic granites. This seems correct especially as there are strong reasons to class much of the 'ordinary' primorogenic granites themselves as products of granitization *in situ*. (Compare the above text. For further information, see pp. 56—58.)

The leptites (and leptite granites) in the neighbourhood of Börje church are grey, grey red, or red rocks chiefly consisting of quartz, microcline, and oligoclase albite or acid oligoclase admixed with variable quantities of mica, biotite especially, but also muscovite. Violet fluorite often occurs. This mineral has not been observed in the porphyritic hällflinta and ought therefore to have been introduced in the rock secondarily, probably simultaneously with the formation of the primorogenic granites. (Compare p. 57.)

The following accessory minerals complete the petrographical picture: epidote, chlorite, serpentine, apatite, hydrozircon, and allanite pseudomorphs.

As has been mentioned above, the texture is for the most part granoblastic though both phenocrysts and porphyroblasts are met with now and then. The former in ordinary cases consist of plagioclase. They display strongly sericitized and  $\text{Fe}_2\text{O}_3$ -impregnated kernels enclosed in fresh, secondary plagioclase. Quartz phenocrysts have also been observed. These border idiomorphically upon the surrounding groundmass though they have recrystallized to aggregates of small grains with highly variable orientations.

In the western part of the Uppsala region, in the parish of Vänge<sup>1</sup>, the leptite sometimes contains grey, grey white, or blue quartz aggregates measuring 5—10 mm in length. (As a rule, the length of the quartz phenocrysts of the Uppsala volcanics does not exceed 3 mm.) These aggregates may be interpreted as metamorphic fragments of quartzite. As will be seen in the following text, the fragment-bearing volcanics in the western vicinity of Uppsala contain numerous small inclusions of quartzite which ought to reappear now and then in the westerly leptites.

The porphyroblasts encountered in the leptites consist of microcline.

The coarse leptites, or leptite granites, sometimes show granophyric texture,

<sup>1</sup> Boundaries of parishes have been marked with short dashes in Plate 1.



Fig. 11. Granophyric coarse leptite. Thin section magnified  $40\times$ , crossed nicols. 400 m to the north of Vaksala church.

Photo C. Larsson and P. H. Lundegårdh.

especially in the neighbourhood of Vaksala church. (See Plate 1.) To the north of the church, there appears a clear red metamorphic volcanic rock which is rich in granophyric intergrowths (Fig. 11) and plagioclase phenocrysts showing beautiful zonal growth. The plagioclase phenocrysts have undergone strong alteration to epidote and sericite. They have simultaneously been impregnated with microscopic hematite grains. The fine-grained groundmass consists of quartz, plagioclase, microcline and biotite in part transformed to chlorite. Ore, titanite, apatite, and various secondary minerals are accessory constituents.

The coarse leptite now described should be interpreted as a porphyritic hällflinta, the groundmass of which has dissolved and later recrystallized (in part as a granophyre), whereas its phenocrysts have been preserved. The necessary solvent has probably been derived from the intrusive Uppsala granite occurring immediately to the north of the granophyric rock.

The leptite area to the east of Störvreta stn includes volcanics with primary features, viz. a fragment-bearing rock close to the limestone in the east-south-eastern part of the area (p. 26) and porphyritic hällflinta (p. 20). However, the primary features of the rocks concerned have most frequently been destroyed during the metamorphism. Even leptite granite is locally met with, preferen-

tially in the vicinity of the eastern boundary of the mapped region. (Compare above.)

Coarse leptite also occurs in the red granite area S.E. of Ärentuna church and S.W. of Storvreta stn. (See Plate 1.) Both here and in the neighbourhood of Storvreta stn (immediately to the west of the railway), the metamorphic volcanics have become strongly tectonized so that they are now filled with cracks and joints and in part grade into tectonic breccias. (These have been marked with 'B' in Plate 1.) An old shear zone apparently runs from the vicinity of G:la Uppsala through Storvreta to the northern boundary of the mapped region. (See also p. 68.) The mobilized primorogenic granite has not been influenced by this shear, and the zone therefore ought to have developed before the final solidification of the granite.

The mineral compositions of the leptites and leptite granites in the north-eastern part of the Uppsala region are similar to those encountered in other parts of the region. Superior minerals are thus here, too, quartz, microcline, oligoclase, and biotite. Extremely potassic varieties have been locally met with. A chemical analysis will be found in Table II.

In addition to the acid and intermediate leptites above described, the occurrence of basic leptite has to be reported. When the quartz-bearing plagioclase-porphyrites and the basic crystal tuffs have been subjected to strong secondary heating, they have often recrystallized to this kind of leptite. The phenocrysts of the original rocks have been in part preserved, however. Basic leptite appears in the neighbourhood of Åkerby church and S.E. of Börje church, to the west of Uppsala. (Compare Plate 1.)

Alteration of plagioclase-porphyrites and similar basic rocks into quartz-diorite and kindred metabasites is also common in the Uppsala region, especially in the numerous basic inclusions in the basic primorogenic granite. (See p. 48 and p. 51.)

In the fault zone N.W. of Jumkil church, in the north-western part of the Uppsala region, strong schistosity has developed in the leptite xenoliths there occurring. Solutions have entered along the schistosity planes, and part of the original minerals have changed to sericite and epidote.

### Målar Series.

As has been mentioned in the introduction, Oldest Svecofennian is in Central Sweden overlain with synclinal deposits belonging to the Målar series. However, the contacts between the two series have been highly disturbed, or even destroyed, by folding, faulting, granitization, migmatitization, and intrusion of granitic magmas. In the Uppsala region, the younger supracrustal rocks form slices resting upon, or enclosed in, the primorogenic granites to the west and to the south of the town. (Compare Plate 1.) N.E. of Börje church, the red primorogenic granite has been interpreted as a granitized acid porphyritic hälleflinta (brown with black dots in Plate 1). It is there covered with grey

rocks belonging to the Mälars series, most of which have also been wholly granitized (brown without dots in Plate 1).

The principal younger supracrustal rock of the Uppsala region is a grey sedimentary gneiss. Thin disturbed intercalations of basic volcanics interpreted as tuffs are often met with, as exemplified by Figs. 13—14. Part of the gneiss has been mobilized, as is also seen in Figs. 12—13. Intrusions of uralite-porphyrite probably belonging to the Mälars series appear E.N.E. of Börje church and to the west of Vaksala church.

### Sedimentary Gneiss. Basic Tuff.

The grey sedimentary gneiss of the Uppsala region originally seems to have formed a dense, or very fine-grained, rock with moderate or poor stratification. Recrystallizations and flowage have most frequently produced strong alterations of the rock implying a weakening, or sometimes even a disappearance, of the stratification simultaneously with the development of a granitic rock with increased grain size (Fig. 12) and locally containing microcline porphyroblasts. Migrations and replacements of ions have also contributed to the alteration of the gneiss. Here, potassic metasomatism should be mentioned at first. (See below.) Locally, the sedimentary gneiss has been mobilized and has moved along opening joints (Figs. 12—13).

The alterations of the sedimentary gneiss ought to have proceeded as follows:

1. *Primorogenic alteration.* Part of the sediments have been subjected to a flowage the result of which is a granitic gneiss with winding structure (N.W. of Bergsbrunna stn; see Fig. 12). Another part of the gneiss has been subjected to strong recrystallization combined with metasomatism and now displays a medium-grained granite without visible parallel structure (N.E. of Börje church).
2. *Serorogenic alteration (migmatitization).* Acid and intermediate, mostly mica-rich, argillitic members of the gneiss complex have become plastically deformed and have in part been mobilized so that they now display intrusions along joints which have opened in more resistant parts of the gneiss complex. This phenomenon can be studied 2.5 à 3 km N.W. of Bergsbrunna stn (Figs. 13—14). We here observe intrusions of mobilized gneiss into a formerly incompetent, strongly recrystallized, granitic gneiss. The intrusions of mobilized gneiss cut the flowage structures of the latter. Furthermore, part of the mobilized gneiss has been dissolved and has penetrated the granitic gneiss along irregular cracks (Fig. 12).

The ordinary sedimentary gneiss is composed chiefly of quartz, oligoclase-albite or oligoclase, and biotite. In addition, considerable quantities of muscovite are frequently met with. Magnetite is the leading minor mineral though garnet, zircon, and apatite are also common. Now and then, hornblende, epidote, prehnite, pseudo-allanite, and titanite have been observed. The strongly granitized, medium-grained variety of sedimentary gneiss N.E. of Börje church contains a little fluorite and calcite. Part of the plagioclase of this rock has altered metasomatically to microcline. The fluorine has obviously entered into



Fig. 12. Secondary primorogenic granite with flowage structure, penetrated by and bordering upon mobilized supracrustal rocks belonging to the Målar series. The latter include rounded fragments of felspar quartzite. The penetrating veins are pegmatitic. 2.5 à 3 km N.W. of Bergsbrunna stn.

Photo P. H. Lundegårdh.

the rock simultaneously with the potassium necessary for the formation of the microcline. (Compare also p. 55.)

2.5 à 3 km N.W. of Bergsbrunna stn, we have already seen that a mobilized argillitic gneiss borders distinctly upon a granitic gneiss, cutting the winding flowage structures of the latter. The former is more acid than the latter, showing, *inter alia*, considerable quantities of mica and a sodic oligoclase. The latter contains much magnesium-rich hornblende with moderate pleochroism and also exposes to view a rather basic plagioclase ( $An \geq 30\%$ ), which often forms small porphyroblasts.

The mobilized gneiss has often been intercalated with thin beds of black or green black, fine-grained metabasite which is composed mainly of hornblende, biotite, and more or less altered plagioclase. The smallest ones of these beds have in part been folded plastically together with the surrounding gneiss (Fig. 14), whereas the remaining beds have been brecciated during the mobilization of the gneiss (Fig. 13). Narrow layers of pale grey, stratified, mica-bearing felspar quartzite have also been present in the gneiss before its mobilization. These layers have been displaced and now appear as small boudins in the



Fig. 13. Mobilized sedimentary gneiss with brecciated layers of basic volcanics. 2.5 à 3 km N.W. of Bergsbrunna stn.

Photo P. H. Lundegårdh.

mobilized gneiss. Most boudins have become rounded owing to marginal dissolution. (Compare Fig. 12.)

The metabasite layers have been interpreted as tuff beds. Manifestations of volcanic activity being thus established in the gneiss complex, it seems highly probable that part of the sedimentary gneiss itself has also been admixed with pyroclastic matter. Moreover, degradation products of pre-existing basic volcanics, such as the plagioclase-porphyrites of the Uppsala region, have certainly contributed to the formation of the sedimentary gneiss. The granitic gneiss 2.5 à 3 km N.W. of Bergsbrunna stn, with its calcic plagioclase and its high content of hornblende, should thus by no means be regarded as an abnormal rock. Besides, its admixture with basic volcanic matter is not only revealed by its mineral composition but also by its contents of certain minor elements. Spectrum analysis (Table 3), indeed, displays concentrations of chromium, cobalt, and nickel which differ markedly from those encountered in ordinary gneissic and granitic rocks. (Compare P. H. Lundegårdh, 1949.) The weight proportions of the three minor elements in question,  $Cr > Ni > Co$ , are on the contrary characteristic of early products of differentiating magmas (peridotites, lherzolites, basic gabbros) though the numerical values are much higher in the latter (P. H. Lundegårdh, *op. cit.*). This is, however, quite natural,



Fig. 14. Folded thin layer of basic tuff in sedimentary gneiss. 2.5 å 3 km N.W. of Bergsbrunna stn.  
Photo P. H. Lundegårdh.

because a dilution of the basic magmatic matter has of course occurred during the sedimentation.

As regards the sedimentary schists and gneisses of the Larsbo series, which should be interpreted as equivalents of the gneiss at Uppsala, S. Hjelmqvist (1937 and 1938) has pointed out their richness in matter emanating from degraded basic rocks and basic volcanic ash. The average An percentage of the Larsbo gneisses ranges from 25 to 30 %, and microcline is in most cases uncommon.

The slices of sedimentary gneiss in the Uppsala region have been separated from the Odensala/Norrunda—Vidbo—Husby Långhundra belt of supracrustal rocks during the intrusion of the primorogenic basic granite. In the Odensala/Norrunda—Vidbo—Husby Långhundra belt, which is stretching through the region S.E. of Uppsala, the Mälar series is in part much better preserved than in the slices at Uppsala. (Compare E. Wiman 1930, p. 56 ff.) The chief members of the Mälar series in the belt mentioned are pale grey, fine-grained mica schist grading into felspar quartzite rich in mica and dark grey, fine-grained mica gneiss. The latter should be classed as a tuffitic argillite (An = 30—35 %). Analogous sedimentary rocks occur in, *inter alia*, the Barknåre area, parish of Hållnäs, North-Easternmost Uppland. (See B. Sund, 1956.)

The younger supracrustal rocks of the Odensala/Norrunda—Vidbo—Husby Långhundra belt have been subjected to magnesia metasomatism involving the formation of cordierite and garnet in the tuffitic argillite. The potassium liberated during the magnesia metasomatism has been exuded, probably as

aluminate. (Compare P. H. Lundegårdh 1956, p. 341.) In the outer parts of the belt, it has been fixed as porphyroblasts of grey white microcline along the planes of stratification and schistosity. According to the principle of constant volume during synkinematic metasomatism (cf. H. G. Backlund 1943), the magnesium necessary for the formation of cordierite, garnet etc. should have been derived from the supracrustal rocks at present containing secondary microcline.

The porphyroblastic mica gneiss frequently grades into a certain kind of grey porphyritic granite known as Arnö granite (A. E. Törnebohm 1880 a, pp. 22—23; 1881, p. 11). This granite is met with in close vicinity of rocks belonging to the Mälars series, actually forming a broad belt stretching from the region to the north of the westernmost part of Lake Mälars to Southern Uppland. Furthermore, evidences of a granitization *in situ* are often seen in the marginal parts of this rock. The Arnö granite belongs to the final products of the primorogenic activity in the Central Svecofennides.

#### Uralite-Porphyrite.

As has been touched upon in the introductory chapter, the uralite-porphyrite dikes in the volcanic bed-rock to the west of Vaksala church have been studied in detail by E. Svedmark (1876, 1888 a). Later E. Wiman (1927, 1930) has observed a dioritic rock E.N.E. of Börje church. This basite has proved to be intimately related to the Vaksala dikes.

The uralite-porphyrite dikes are as a rule short ( $\leq 30$  m) and directed towards N.N.W. Their width is moderate, generally not exceeding 2 m. The dikes, as well as the surrounding volcanics, contain numerous joints and have frequently been dislocated along these. The dikes are older than the primorogenic granite of the Vaksala area.

Owing to the minor size of the dikes, it has been impossible to reproduce them in Plate 1. The bulk of the dikes will be found about 1 km to the west of Vaksala church, however. Furthermore, a few uralite-porphyrite dikes have been observed 2 km S.W. of G:la Uppsala church.

The uralite-porphyrite to the west of Vaksala church is a green black, dense rock without visible schistosity and showing moderate metamorphism. It is very rich in porphyritic grains of uralite (as a rule measuring 1—2 mm though sometimes larger, up to 5 mm) and phenocrysts of plagioclase (ranging from 1 to 5 mm). In addition, several ore phenocrysts occur. These are, however, frequently very small and cannot then be distinguished from the groundmass.

Two varieties of porphyrite have been observed, viz. a mafic one which is rather poor in plagioclase phenocrysts and a felsic one which is richer in plagioclase phenocrysts than in porphyritic grains of uralite. (Compare Svedmark 1888 a, p. 33 ff.)

The porphyritic grains of uralite should be interpreted as altered phenocrysts. They still now and then show kernels of the primary mineral, a pyroxene the optical properties of which most often correspond to those of a pigeonite

( $c : \gamma = 26-27^\circ$ ,  $2V\gamma$  rather small). The uralite itself is a common greenstone hornblende ( $c : \gamma = 16-20^\circ$ ,  $2V\gamma = 95-100^\circ$ ) with moderate pleochroism. Most porphyritic grains of uralite constitute single crystals. Uralite grains composed of several minor individuals with different optical orientations are, however, also common. Part of these grains seem to have grown at the expense of the groundmass during the alteration of the primary mineral, the pyroxene.

The plagioclase of the phenocrysts is a labrado-andesine ( $An = 50\%$ ) that has frequently changed considerably to epidote, zoisite, sericite etc. The ore grains have as a rule leucoxene rims and are thus probably composed of titanomagnetite. Svedmark (1888 a, p. 36) has observed grains of ilmenite, too.

Spectrum analysis of mafic uralite-porphyrite (Table 3) gives evidence of low contents of both chromium and nickel. Accordingly, the rock in question should be interpreted as a late product of fractional differentiation of a basic magma. High contents of titanium are always encountered in such rocks. (Compare P. H. Lundegårdh, 1950.) As a matter of fact, a determination of  $TiO_2$  in mafic uralite-porphyrite, by A. Aaremäe, has given 1.24 %.

The groundmass of the uralite-porphyrite consists of corroded, or sometimes wholly altered plagioclase and, further, of common hornblende. In addition, several small grains of ore (compare above), as well as minor quantities of pyrite, quartz (chiefly in the felsic variety), and apatite, have been observed.

The plagioclase of the groundmass has changed similarly to that of the phenocrysts, viz. to epidote, zoisite, sericite, etc. Among minerals originating from primary mafic constituents, biotite and chlorite have to be reported.

A chemical analysis of uralite-porphyrite rich in plagioclase phenocrysts is quoted in Table 2. The analysis is rather old, however, and  $TiO_2$  has not been determined though the available mineralogical data indicate a fairly high content of titanium. (Compare the  $TiO_2$  value given above.)

The environments of Uppsala do not only display dikes of early uralite-porphyrite. 2—3 km E.N.E. of Börje church, indeed, a massif of a kindred rock has been observed (at first mentioned by E. Wiman 1927, p. 17). The basite E.N.E. of Börje is a grey green black to green black, most frequently fine-grained, porphyritic rock rich in hornblende and often traversed by joints filled with this mineral. As regards the porphyritic grains, both uralite and plagioclase are represented. The marginal parts of the rock locally contain small angular fragments of older volcanics. A few minor dikes of acid exudates possibly originating from the intrusive oldest Archean granite have also been seen.

The central part of the massif shows a somewhat different petrographical character. The uralite-porphyrite there grades into a fine medium- to fine-grained diorite essentially composed of plagioclase ( $An = 50\%$ ; in part sericitized) and uralite with kernels of clinopyroxene. Quartz and biotite (late crystallization products), titanite, apatite, and zircon are inferior constituents. The biotite is sometimes accompanied by a little muscovite. Furthermore, the frequent occurrence of secondary epidote and chlorite should be reported. (Mineralogical data according to E. Wiman 1930, p. 22.)

In South-Western Finland, uralite- and plagioclase-porphyrites are quite common. (Compare A. Simonen, 1953, and the literature there quoted.) Svedmark compared these rocks with the uralite-porphyrite dikes in the northern neighbourhood of Uppsala as early as in 1888 (1888 b, p. 75 ff.), though he stressed more the differences than the similarities. Now the petrographical characters of equivalent eruptive rocks in orogenic belts often change considerably when we move from one district to another, owing to different compositions and courses of crystallization of the intruding magmas, as well as to variations of the modes and intensities of the deuteric and secondary alterations of the crystallization products.

Similar and probably equivalent basites do not only occur in Finland. In Easternmost Uppland (for example parish of Hällnäs; compare B. Sund, 1956) and in the Hamrånge syncline to the north of Gävle (P. H. Lundegårdh, 1956), both uralite- and plagioclase-porphyrites have been observed. As regards these porphyrites in general, it has to be pointed out that their frequency increases markedly when we move eastwards in the Central Svecofennides.

Many observations speak in favour of the location of the Bothnian geosyncline of the Central Svecofennides to South-Western Finland. (Compare Simonen, 1953, and part of the literature there quoted.) Turning westwards, this geosyncline points towards the Hamrånge region. The Mälars series would thus occupy a southern parallel syncline separated from the geosyncline by a belt of rocks belonging to Oldest Svecofennian (leptite-hälleflint series).

### Middle Svecofennian.

It has been evident from Table 1 that the introductory stage of the primorogenic phase of the Svecofennian cycle was the development of the rocks of the Mälars series. The infracrustal primorogenic rocks are as a rule of later formation than the Mälars series and are also intrusive in this.

The evolution of the Svecofennian infracrustal primorogenic rocks began with the crystallization of ultrabasites, mainly peridotite and lherzolite. Soon afterwards, gabbros and diorites appeared, and later we obtained basic granites (for example the Uppsala granite). The youngest products of the evolution are acid granites rich in microcline (such as the Vänge granite).

Formerly, the infracrustal primorogenic rocks of the Svecofennian cycle were interpreted as a series of differentiation products originating from a granodioritic parental magma (the *urgranit* series). Under the influence of various petrologists, such as J. J. Sederholm, E. Wegmann, and H. G. Backlund, the aspects of the genesis of these rocks have been strongly revised, however. Investigations by the writer (P. H. Lundegårdh 1949, p. 19, Table 2 and Table 6) have born geochemical evidences against the assumption of a successive magmatic differentiation comprising all Svecofennian infracrustal primorogenic rocks. Thus, at present, only part of the infracrustal basites (chiefly the gabbroic rocks) seem to have to be interpreted as differentiated

magmatic rocks, whereas most of the diorites and the granites probably display supracrustal rocks which have altered intensely *in situ*, or have been dissolved and mobilized as mainly resurgent solutions and secondary magmas. Mobilizations of supracrustal rocks in a plastic state followed by recrystallization (flowage) also seem to have contributed to the formation of Svenno-fennian primorogenic granites. The secondary diorites are often associated with other kinds of metabasites, viz. amphibolites and porphyritic rocks.

The aspects of orogenies emanating from Sederholm involve a complete dissolution and mobilization (palingenesis) of deep-folded older rocks. We should thus have to include in our calculations primorogenic granitic magmas which are wholly secondary. (Compare also H. Stille, 1940.) The condition of constant volume is here fulfilled, which has been considered important in view of the high pressures characterizing folding ranges.

Stressing the principle of constant volume during orogenies, E. Wegmann (1935) and H. G. Backlund (*inter alia* 1943) have advanced still another step on the path of rock metamorphism and have arrived at a 'reconstructive homogeneization' (Backlund 1943, p. 119) implying a granitization of various pre-existent rocks in the solid state. As the velocities of diffusion of the ions present in ordinary rocks seem to be very small even in orogenic *milieu*, we cannot, however, possibly accept large-scale migrations of undissolved ions. (See I. Th. Rosenqvist 1949, pp. 63—64.) On the other hand, gaseous or liquid solutions seem to be highly apt to serve as granitizers. (Compare P. Geijer 1934, p. 634, S. Hjelmqvist 1942, p. 85 ff., and I. Th. Rosenqvist, *loc. cit.*)

The composition of these solutions is open to discussion. Theoretically, we have to include in our computations a complete series of solutions ranging from water + mineralizers<sup>1</sup> to water + mineralizers + all elements necessary to originate a granite. After having studied in detail the Herräng field in Eastern Uppland, N. H. Magnusson (1940, pp. 42—43 and p. 74) has assumed that the latter kind of solutions have been at work there. He thinks that the mode of intrusion of the primorogenic Herräng granites, actually having permitted angular pieces as well as big slices and packs of the folded supracrustal rocks to remain well-preserved in their original stratigraphic positions, does not harmonize with the conception of slowly rising, viscose magmas showing high temperatures. Magnusson interprets the granitic solutions at Herräng as exudates from great masses of granite which should represent crystallized magmas.

Magnusson does not claim that his solutions have been originally granitic. He only states that they have been granitic when they intruded into the supracrustal rocks of the Herräng field (Magnusson 1940, p. 43). They might thus very well have been essentially composed of rocks which have melted or have been dissolved at deeper levels of the crust. (Compare above.)

Magnusson (1940, p. 43) also stresses the homogeneity of the great primorogenic granite masses of Uppland and adjacent provinces. These masses have been earlier analysed by P. Geijer, who has interpreted them as anticlinal

<sup>1</sup> Chemical compounds containing haloids, boron etc., which depress the temperature of and increase the ability to dissolution of solid rocks.

batholiths (Geijer 1916, p. 53). It is, indeed, unquestionable that the anticlinal primorogenic Svecofennian folds have frequently been filled with homogeneous granites which cannot possibly be interpreted as the products of a granitization *in situ*.

In the Uppsala region, the primorogenic basic granite (the Uppsala granite) displays intrusive characters, whereas the intermediate and acid, primorogenic granites to a large extent seem to have to be interpreted as the products of a granitization *in situ*. The plagioclase of the basic granite shows zonal growth, and, therefore, the rock cannot possibly have crystallized far below the surface of the Middle Svecofennian crust. Though many of its xenoliths have been strongly altered, the basic granite often contains well-preserved pieces of both acid, intermediate, and basic supracrustal rocks. The temperature of, at least, part of the mother magma of the primorogenic basic granite cannot thus have been very high. (Compare above.)

The intermediate and acid granites contain scattered grains of a strongly altered plagioclase, which has probably been inherited from the pre-existent supracrustal rocks. A granitization far below the surface of the ancient crust would scarcely have permitted the preservation of such remnants.

#### Lherzolite, Gabbro.

Infracrustal basites of gabbroic character are not very frequent in the Uppsala region. Peridotite and ultra-basic gabbro occur 4 km W.S.W. of Jumkil church, lherzolite grading into ultra-basic gabbro 4.5 km W.S.W. of Bergsbrunna stn, and common gabbro 4.5 km to the west of Bergsbrunna stn. (See Plate 1.) The ultra-basic rocks W.S.W. of Jumkil church are probably younger than the primorogenic granites and will therefore be described in the next chapter.

The ultra-basic rocks 4.5 km W.S.W. of Bergsbrunna stn are green black and coarse to medium-grained. The lherzolite shows a characteristic weathering to gravel (Fig. 15). Main minerals are hornblende (in part uralitic), augite, and often bytownite, too. The amphibole is a common greenstone hornblende showing pale pleochroic colours.  $2V\gamma$  amounts to  $90 \text{ à } 95^\circ$ . The larger individuals are penetrative and schillering, containing poikilitic grains of both augite and plagioclase. Part of the bytownite has altered, often to sericite and sometimes to clinozoisite. In the lherzolite, bytownite joins the inferior minerals, which comprise bronzite and olivine, too. The latter has as a rule changed to chlorite-serpentine pseudomorphs with the original cracks being still preserved. The bronzite, as well as the augite, have been strongly uralitized.

Small quantities of pyrite and iron ore have been observed. Sparse though rather large individuals of apatite complete the mineralogical picture thus given.

Emanations from the surrounding primorogenic granite have altered the ultra-basic rocks now described and have given origin to a transitional zone of monzonitic rocks. Inside this zone, the ultra-basic rocks often contain con-



Fig. 15. Lherzolite displaying strong selective weathering into gravel. 4.5 km W.S.W. of Bergsbrunna stn.

Photo P. H. Lundegårdh.

siderable quantities of quartz and microcline, which have been introduced along the paths offered by the intergranular film and which have grown metasomatically at the expense of the original minerals. We have thus obtained a rock containing both bytownite and microcline.

The largest massif of Svecofennian gabbro in the Uppsala region is situated 4.5 km to the west of Bergsbrunna stn (the Vipängen massif). The gabbro here met with is green grey black to grey black and fine medium- to medium-grained. It consists essentially of labradorite (60—65 % An), augitic or diopsidic clinopyroxene, uraltic hornblende, and titaniferous magnetite. E. Wiman



Fig. 16. Dike of primorogenic grey granite (oldest Archean granite) in gabbro. To the left a metasomatic hybrid rock. 4.5 km to the west of Bergsbrunna stn.

Photo P. H. Lundegårdh.

(1930, p. 35) mentions that the uralite surrounding the clinopyroxene is sometimes actinolitic, thus reflecting the diopsidic character of part of the latter. The labradorite is often rich in alteration products: sericite accompanied by clinozoisite and zoisite.

The Vipången gabbro borders upon two kinds of primorogenic granite, viz. grey basic and red grey intermediate granite, the latter with numerous microcline porphyroblasts. (See Plate 1.) Dikes of primorogenic grey granite have also been observed within the gabbro (Figs. 16—17). In the marginal parts of the massif, the composition of the gabbro has become strongly influenced by exudates from the primorogenic granite. Secondary biotite and quartz are always present here, the former mineral in large quantities (20 %, or more), whereas microcline is less common. Biotite often appears in more central parts of the massif, too, though it is there an inferior constituent.

Chemical analysis of the Vipången gabbro (Table 2) shows a very basic rock ( $\text{SiO}_2 = 44.08\%$ ) with high lime content ( $\text{CaO} = 14.68\%$ ). The calcic character of the above-mentioned ultra-basic gabbro grading into lherzolite is also pronounced, as is evident from the composition of its plagioclase. Similar ultra-basic mafic gabbro has been observed in other parts of Uppland, too, for example in the Norrtälje region, N.E. of Stockholm. Pyroxenitic-hornblenditic gabbro from an outcrop 11 km to the south of Norrtälje thus displays a plagioclase with no less than 88 % An (P. H. Lundegårdh 1946, p. 36). In the neighbourhood, the primorogenic basic granite locally contains as much as 7 % CaO

(op. cit., p. 48). The lime content of the Uppsala granite is in normal cases lower, about 4 %. (Compare Table 2.)

The parental magmas of the infracrustal primorogenic basites have as a rule differentiated into early, ultra-mafic rocks which have enriched chromium especially, and nickel, into middle, common gabbros with moderate contents of nickel and moderate or low concentrations of chromium, and into late norites and diorites with little nickel and little or no chromium present. (Compare V. M. Goldschmidt, 1945, and P. H. Lundegårdh, 1949.) A great number of spectrographic determinations on Svecofennian primorogenic plutonic basites will be found in the second paper just cited (Lundegårdh 1949, p. 43). The ultra-mafic rocks here examined contain up to 800 parts per million (p.p.m.) Cr and 400 p.p.m. Ni. The order of atomic frequency of Cr, Co, and Ni is in these rocks always  $Cr > Ni > Co$ .

As regards the gabbroic rocks to the south of Uppsala, the spectrographic data obtained reveal a remarkable deficiency of chromium (Table 3).  $Cr = 100$  p.p.m. is, indeed, a very low concentration to be found in a primorogenic Svecofennian lherzolite, and  $Cr = 5$  p.p.m. in a calcic, pronouncedly basic gabbro is quite an abnormal figure. For the purpose of comparison, I shall quote a few data from my paper of 1949, viz.  $Cr = 800$ ,  $Ni = 400$ , and  $Co = 60$  p.p.m. in a lherzolite from the parish of Möklinta, about 70 km W.N.W. of Uppsala, and  $Cr = 650$ ,  $Ni = 400$ , and  $Co = 35$  p.p.m. in another lherzolite from the parish of Söderbärke, about 60 km to the south of Falun, in Dalecarlia. These are both typical first-differentiated Svecofennian primorogenic ultra-basites.

In view of these data, we cannot possibly interpret the lherzolic gabbro to the south of Uppsala as an early product of a normal differentiation of a primary (juvenile) magma. The content of phosphorus as displayed by the presence of large apatite grains also speaks against such an interpretation. Early differentiation products of basic magmas are, indeed, always very low in phosphorus. (Compare P. H. Lundegårdh, 1950.)

Turning to the Vipången gabbro, the high concentration of lime, between 14 and 15 %, is quite abnormal of a differentiated primorogenic plutonic rock containing insignificant amounts of chromium. On the other hand, the low chromium content corresponds very well to the  $Mg : Fe$  ratio, which is 0.58 ( $Mg$  and  $Fe$  calculated as percentages by weight from the analytical data contained in Table 2). I have earlier classed the plutonic basic rocks showing  $Mg : Fe > 1$  as early, those showing  $Mg : Fe = 0.5-1$  as middle, and the ones showing  $Mg : Fe < 0.5$  as late differentiation products of basic magmas (P. H. Lundegårdh, 1950).

Being thus classified, the Vipången gabbro displays a late middle differentiation product of a basic magma, and, as above mentioned, such a rock contains little chromium. The very moderate nickel content is also in harmony with this classification, as well as the  $TiO_2$  value obtained, 0.70 %. (Early products of basic magmatic differentiation are very poor in titanium. Compare P. H. Lundegårdh, 1950.) The abnormal concentration of lime may very well



Fig. 17. Dikes of primorogenic grey granite in gabbro. 4.5 km to the west of Bergsbrunna stn.  
Photo P. H. Lundegårdh.

be due to assimilation of early Svecofennian limestone. The lherzolitic gabbro to the south of the Vipängen gabbro seems to have crystallized from a similarly contaminated magma portion.

Since long, the primorogenic gabbroic Svecofennian rocks have been regarded as plutonics still displaying part, or most, of their original minerals and crystallization textures. This conception has in Sweden been repeatedly doubted by H. G. Backlund. (See, for example, his paper of 1943.) Backlund has been inclined to interpret the basites in question as altered ophiolites, viz. eogeo-synclinal basalts which have changed to gabbroic rocks simultaneously with the evolution of the primorogenic granites.

Recent investigations on spilites, in the Hamrånge syncline, North-Eastern Gestríkland (P. H. Lundegårdh, 1956), have shown the growing of pyroxene + olivine under the influence of strong magnesium metasomatism contemporaneously with partial felsparizations of quartzites and the development of secondary primorogenic granites in the neighbourhood. In the Hamrånge syncline, these processes do not seem to have occurred at high depths. (Compare the zonal growth of many plagioclase individuals contained in the Uppsala granite, p. 50). Although the geochemical data obtained in various primorogenic Svecofennian basites indicate a strong differentiation of their parental magma (cp. P. H. Lundegårdh, 1949, and the above text), we are therefore not allowed

to state that these rocks have originally always crystallized as lherzolites, gabbros etc. Perhaps early primorogenic metasomatic processes have been at work, such as an advancing 'basic front' emanating from the intruding primorogenic basic granite. On addition of magnesium, calcium, and iron, a normal gabbro can have thus altered to the present ultra-basic rock. We have, indeed, already seen that the late solutions exuded from the crystallizing primorogenic granite have caused metasomatism in the lherzolite to the south of Uppsala, though an acid one implying the development of quartz and microcline.

### **Diorite, Quartz-Diorite, Metabasite.**

Small massifs of dioritic and amphibolitic, primorogenic Svecofennian rocks have been found in various parts of the Uppsala region (Plate 1). Moreover, the primorogenic basic granite is often rich in fragments of similar rocks ('dark spots'). Great part of these basites have evidently been altered all through and should be classed as metabasites. The quartz-diorite has very often revealed textural characters inherited from porphyritic volcanics.

The colour of the dioritic and amphibolitic rocks varies between grey black and dark green; the grain size ranges from fine-grained to coarse, though medium- to fine-grained varieties dominate.

The dioritic and amphibolitic, primorogenic rocks are as a rule enclosed in primorogenic granites, and the contacts with these are in general distinct. Transitions have also been observed, however. The dioritic rocks display irregular hypidiomorphic to xenomorphic textures, whereas the amphibolitic rocks are in most cases granoblastic. Furthermore, part of the quartz-diorite and amphibolite are porphyritic. The former thus often contains plagioclase phenocrysts (see below) and the latter porphyroblasts of common hornblende.

Main minerals are plagioclase (An = 35—55 %), common hornblende, and in most cases biotite, too. The plagioclase has frequently been in part sericitized and sometimes impregnated with minute hematite grains (near contacts with primorogenic granite). Strongly altered phenocrysts inherited from porphyritic volcanics appear at many places in the quartz-diorite especially, evidencing the secondary character of part of the basites now dealt with. These phenocrysts often show zonal growth.

The kernels of the hornblende individuals of the dioritic rocks now and then contain fragments of clinopyroxene, mostly augite. The large hornblende individuals of the porphyritic amphibolite are as a rule poikiloblastic.

Minor minerals are quartz, titaniferous iron ore, pyrite, epidote, titanite, and apatite. In the quartz-diorite and part of the amphibolitic rocks, quartz is quite common and often attains the position of a main mineral.

One of the largest massifs of diorite and associated rocks met with in the Uppsala region is situated at Bärby stn, to the east of the town. The diorite here grades into both amphibolite and porphyrite with hornblende porphyroblasts. N.W. of Bärby stn, the latter has in part become impregnated with minute grains of secondary hematite. Near the northern contact with primorogenic

granite, a white grey transitional rock consisting mainly of plagioclase and quartz has been observed.

N.W. of Skogs-Tibble church, in the south-western corner of Plate 1, a coarse diorite with beautiful hornblende prisms can be studied. This diorite no doubt represents a wholly recrystallized and perhaps also metasomatic rock. Similar coarse diorites in the margins of the serogenic Svecofennian gabbro massifs in Eastern Uppland have been shown to have originated under the influence of residual solutions exuded during the final crystallization of the parental magma of this gabbro.

To the east of Ärentuna church, small-grained amphibolitic-dioritic derivatives of Oldest Svecofennian basic volcanics are quite common. As is usual in masses of secondary primorogenic granites, these ancient beds of lava and tuff have been divided into lens-and-slice-shaped boudins running parallel to the general plane structure.

The above data have made clear that part of the dioritic and amphibolitic-porphyrific rocks are evidently secondary. Trace element determinations carried out on various xenoliths of Early Svecofennian basites in primorogenic and serogenic granites in Eastern Uppland and South-Easternmost Gestrkland have revealed very low contents of chromium especially (0—8 parts per million), and nickel (trace—35 p.p.m.). (See P. H. Lundegårdh 1949, p. 42.) The mother rocks of these xenoliths have thus to be interpreted as very late differentiation products of basic magmas. Similar low concentrations of chromium and nickel have been found both in beds of basic volcanics in Oldest Svecofennian and in the final products of the differentiation of the parental magma of the primorogenic plutonic basites (P. H. Lundegårdh 1949, pp. 42—43). From a geochemical point of view, it is therefore impossible to find out the origin of the basic xenoliths.

### Basic Granite (Uppsala Granite).

In Central Uppland, Oldest Svecofennian has mostly been separated from the Mälar series and in part brecciated by an intrusion of a primorogenic basic granite known as Uppsala granite and in Plate 1 classed as oldest Archean basic granite. In the Uppsala region, the Uppsala granite as a rule displays an almost non-deformed, coarse medium- to medium-grained rock with blue quartz. (Compare P. J. Holmquist 1906, pp. 182—86.) Varieties which have undergone visible lineation occupy minor areas, especially in the south-easternmost part of the region.

The Uppsala granite has been frequently penetrated by solutions moving along joints and cracks. The penetration makes itself visible by a red-colouring of the rock caused by impregnation with hematite chiefly in the plagioclase, which has simultaneously been strongly sericitized.

The contents of  $\text{SiO}_2$  (Table 2) and microcline of the Uppsala granite are much higher than those observed in normal basic granites. Hornblende is quite



Fig. 18. Fragment of leptite in primorogenic basic granite (oldest Archean basic granite, or Uppsala granite). 4 km E.S.E. of Storvreta stn.

Photo P. H. Lundegårdh.

common, however (mostly  $\geq 5\%$  of total rock), and the plagioclase has a high content of calcium ( $An = 35-45\%$ ). Moreover, the latter is the leading mineral of the rock, followed by quartz and biotite. Microcline and hornblende are equally common. Minor minerals are ore, apatite, zircon, and allanite. Now and then, pyrite, titanite, and fluorite also appear.

The plagioclase mostly tends towards tabular development and often shows zonal growth, with strongly calcic kernels, indicating a rather rapid crystallization. Sericitization is common, especially in the above-mentioned red-coloured variety. Alteration to epidote and zoisite has also been observed in many thin sections (preferentially in the kernels of the plagioclase individuals). Calcite occurs locally.

The hornblende is a common one with rather strong pleochroism. The extinction angle  $c : \gamma$  ranges from  $14$  to  $17^\circ$ . According to E. Wiman (1930, p. 29), the birefringence amounts to  $0.021(\gamma - a)$ .

The biotite has now and then undergone slight chloritization. In the red-coloured variety, both biotite and hornblende have changed considerably, or, often, completely, to chlorite etc.

Typical Uppsala granite from the neighbourhood of Ekeby bruk stn, in the western part of Uppsala, shows the following mineral composition (geometric analysis; concentrations given in percentages by weight):

Andesine with deuteritic and secondary sericite .....	42.5
Quartz .....	34.0
Biotite .....	8.5
Common hornblende .....	7.8
Microcline .....	6.0
Epidote .....	0.5
Chlorite .....	0.25
Apatite .....	0.25
Zircon .....	0.10
Ore .....	0.07
Titanite .....	0.05
	100.0

The Uppsala granite contains numerous xenoliths which evidence the intrusive character of the rock. The xenoliths mostly appear as swarms which are often dense. The bulk of the xenoliths consist of basic supracrustal rocks though leptonite, grey sedimentary gneiss, and plutonic basites have also been observed (Figs. 18—19). Part of the xenoliths are angular and border distinctly upon the surrounding granite. Many fragments have undergone partial assimilation, however, and the granite itself has obviously been strongly contaminated with wholly assimilated (dissolved) rocks. This seems to hold true of the leptonites and sedimentary gneiss especially. (Compare below.)

Dikes of Uppsala granite have also been observed, both in the supracrustal rocks and in the infracrustal greenstones (Figs. 16—17).

Two chemical analyses of Uppsala granite will be found in Table 2. The samples analysed are, however, taken from outcrops situated in an area characterized by higher percentages of quartz than the normal Uppsala granite. The concentration of lime as displayed by the analyses is rather high, though, in Uppland, similar figures are not rare. Porphyritic primorogenic Svecofennian granite from the region to the south of Norrtälje, N.E. of Stockholm, thus contains 3.98 % Ca(SiO<sub>2</sub> = 69.26 %, microcline common; data from P. H. Lundegårdh 1946, p. 60).

The Uppsala granite from Ekeby bruk above subjected to geometrical analysis has been analysed by means of quantitative spectrography, too. (General sample. Analyst: P. H. Lundegårdh.) Part of the data obtained are included in Table 3. A complete list of the elements investigated will be given here:

Li .....	150 parts per million
B .....	< 10 » » »
V .....	40 » » »
Cr .....	25 » » »
Co .....	45 » » »
Ni .....	20 » » »
Cu .....	150 » » »
Zn .....	200 » » »
Sr .....	300 » » »



Fig. 19. Fragment of grey sedimentary gneiss in primorogenic basic granite (Uppsala granite), 900 m S.S.E. of Låby church.  
Photo P. H. Lundegårdh.

We immediately observe that cobalt is decidedly more common than both chromium and nickel. This order of frequency characterizes late differentiation products of crystallizing basic magmas. (Compare V. M. Goldschmidt, 1945, and P. H. Lundegårdh, 1949.) In pure final products of basic magmatic differentiations, chromium and nickel even disappear. (See, *inter alia*, L. R. Wager and R. L. Mitchell, 1943, P. H. Lundegårdh, 1946 and 1949, S. R. Nockolds and R. L. Mitchell, 1948.)

In the primorogenic magmatic evolution of the Svecofennian, the Uppsala granite enters among the latest products. If we accept a purely primary magmatic origin of the granite, its contents of chromium especially, and nickel, would thus seem to be too high. When discussing the xenoliths of the Uppsala granite, I pointed out, however, that large quantities of early Svecofennian rocks have most probably been assimilated by the intruding granite. Among these rocks, we have to reckon the grey sedimentary gneiss to the south of Uppsala. In the neighbourhood of Bergsbrunna, the sedimentary gneiss has a composition strongly favouring an increase of the contents of chromium and nickel of the assimilating granite as compared with its cobalt content ( $Cr = 70$ ,  $Co < 10$ ,  $Ni = 60$  p.p.m.)

The intrusive character of the Uppsala granite, as displayed by the xenoliths



Fig. 20. Bands of felspar and quartz in primorogenic basic granite (Uppsala granite). Road-cutting 4.5 km W.N.W. of Bergsbrunna stn.

Photo P. H. Lundegårdh.

especially, omits the assumption that a granitization *in situ* should have given origin to the rock. As regards its mother magma, the problematic factor will be the ratio juvenile matter: resurgent (palingenic) matter. We have, indeed, little chance to state with any degree of certainty the quantitative contribution of older rocks to the mother magma of the Uppsala granite though we may guess that resurgent (palingenic) matter originating from the bottom of the Svecofennian range predominates. (Compare p. 42, upper part.)

Locally, the Uppsala granite shows banding (Fig. 20 and 'Ba' in Plate 1). The length of the bands does as a rule not exceed 2 m, and their width is quite moderate ( $\leq 5$  cm). The bands are grey white or white. They consist of basic andesine ( $An = 40-45\%$ ), microcline, and quartz. In addition, inferior quantities of biotite are mostly present. The minor minerals of the bands are the same as have been observed in the ordinary Uppsala granite.

The plagioclase of the bands has developed as medium-grained tabular individuals. No *Regelung* has been traced — the plagioclase has either gathered to swarms of individuals of different orientations (often with small quartz grains of late formation) or has been embedded in large microcline poikiloblasts. When the plagioclase is bordering upon quartz, a narrow rim of microcline is in most cases present.

The banding seems to form a fluidal structure developed during an early

stage of the crystallization of the granitic magma. Apparently, plagioclase has originally been the dominating mineral of the bands. The quartz and the microcline most probably derive their origin from the magmatic residuum.

I have already mentioned that the primorogenic basic granite of the Uppsala region seldom shows schistosity of macroscopically visible strength and that the quartz of the normal Uppsala granite is as a rule blue. In varieties having suffered from more pronounced deformation, the quartz has lost its blue colour and has become greyish. The blue quartz grains are composed of a number of small individuals showing nearly the same optical orientations, whereas in the greyish quartz the orientations differ decidedly, owing to the stronger deformation. Similar though otherwise interpreted observations have been made by P. Ljunggren in South-Western Dalecarlia (Ljunggren, 1954).

### Intermediate Granite.

The primorogenic intermediate granite of the Uppsala region is concentrated to the areas N.W.—N.—N.E. of the town (the oldest Archean intermediate granite in Plate 1). The rock is in ordinary cases red grey and medium-grained though purely grey varieties also occur. It contains almost equivalent quantities of microcline and plagioclase (oligoclase or oligoclase-andesine). The former has sometimes developed as porphyritic individuals and contains dispersed hematite grains of microscopic size. The latter is slightly sericitized and as rule richer in microscopic hematite grains than the microcline. The reddish colour of the rock is due to the hematite impregnation of the feldspar.

Quartz and biotite form the remaining superior minerals, whereas hornblende is less common. Indeed, most specimens of intermediate granite contain no hornblende at all. The minor minerals are on the whole the same as have been reported to be present in the basic granite.

Slight schistosity can be traced in part of the areas occupied by primorogenic intermediate granite. In most cases, this granite is, however, structurally isotropic.

The contacts with the primorogenic acid granite are always diffuse, whereas the intermediate granite at least locally borders distinctly upon the basic granite. No penetrative contacts have been observed, however.

Contrary to the basic granite, the intermediate one is poor in xenoliths. Moreover, the diffuse character of most xenoliths enclosed in the latter may indicate that metasomatic, granitizing processes have been at work. On the other hand, we cannot disregard the fact that an intermediate differentiation product of the parental magma of the primorogenic granites ought to have been enriched in volatiles (mineralizers) and should thus have had a strong assimilative capacity. Now and then, the intermediate granite contains strongly altered, roughly tabular though frequently penetrated (corroded) plagioclase individuals which may be interpreted as either early crystallization products or relics of pre-existing rocks, most probably some kind of volcanic belonging to the leptite-hälleflint series.

One variety of intermediate granite here and there observed is filled with porphyritic individuals of microcline. This variety will be described later (p. 58). Another variety, which is pure grey, should be referred to as Sala granite, in accordance with the definition given by A. E. Törnebohm (1880 a, p. 23; 1881, p. 12). The Sala granite mostly contains a little hornblende and is in the Uppsala region concentrated to a restricted number of outcrops in the westerly areas.

Furthermore, a pale grey, fine to coarse medium-grained, primorogenic granite appears W.N.W. of Uppsala, about 2 km N.E. of Börje church. This granite is as a rule free from hornblende and grades into a grey, sedimentary rock with brecciated beds of basic volcanics belonging to the Mälär series. (Compare p. 35.) The contents of microcline of the granite N.E. of Börje church is rather high. The microcline is, however, evidently secondary, actually penetrating the plagioclase both marginally, as reaction rims, and centrally, as metasomatic spots. The content of microcline gradually decreases when we approach the kernels of preserved sedimentary rock, and the latter themselves display a typical re-crystallized derivative of some kind of tuffitic argillite with low content of potassic felspar. The granite N.E. of Börje church has thus to be interpreted as a product of a granitization *in situ*.

The intermediate granite bordering upon the younger volcanics in the neighbourhood of Uppsala, such as the granite to the west of Vaksala church, often contains granophyric intergrowths between quartz and felspar.

2.5 km E.N.E. of Börje church, the Uppsala volcanics have been intruded by a grey, fine-grained, intermediate to acid granite composed mainly of quartz, orthoclase, plagioclase, and biotite. Secondary epidote is rather common, too. Minor constituents are hornblende, titanite, ore, apatite, and allanite pseudomorphs. The orthoclase is penetrative and has sometimes crystallized as Carlsbad twins. It seems probable that this granite, which is almost non-deformed, belongs to the primorogenic granite group although orthoclase is there quite rare. The comparatively high content of epidote indicates that residual solutions emitted from the primorogenic granites have contributed largely to the low-temperature alteration of the volcanics, where at least two generations of epidote have been traced. (Compare p. 25.)

The granitization processes assumed to have been at work in the areas of intermediate primorogenic granite will be more fully discussed in the following paragraph (pp. 56—58).

#### Acid Granite (Vänge Granite).

In the western part of the Uppsala region, grey red to red, coarse medium-grained to coarse, as a rule non-deformed primorogenic acid granite has got a wide distribution (the oldest Archean acid granite in Plate 1; see also Fig. 25, p. 66). This granite appears in the north-eastern part of the region, too, though it is there coarse to fine medium-grained. It has been distinguished as Vänge granite by A. E. Törnebohm (1880 a, p. 23; 1881, p. 10). The chemical analysis

given in Table 2 shows that the Vänge granite is very acid. P. J. Holmquist (1906, p. 188) paralleled it with the Älö granite near Oskarshamn in South-Eastern Sweden. According to recent investigations, this granite might be interpreted as a granitized felspar quartzite. (Compare T. Du Rietz, 1949, and H. G. Backlund, 1950.)

The Vänge granite is composed mainly of quartz, microcline (individuals measuring up to 2 cm in length), and sodic plagioclase (oligoclase-albite or oligoclase, An = 10—25 %). Biotite (mostly altered to chlorite) is an inferior constituent.

Among minor minerals, we have to mention at first muscovite, calcite, allanite pseudomorphs, and zircon. Hornblende, fluorite, secondary epidote, ore, and titanite appear occasionally.

The plagioclase has been strongly impregnated with microscopic hematite grains and has simultaneously altered in part to sericite. The microcline, too, contains hematite grains of microscopic size though the frequency of these inclusions is not so great as in the plagioclase. The red colour of the rock is due to the hematite impregnation.

A geometric analysis of a number of pieces of Vänge granite from an outcrop situated 150 m N.W. of Brunna stn, near Vänge church, runs as follows (concentrations given in percentages by weight):

Quartz .....	39.3
Microcline .....	32.6
Plagioclase with deuteric and secondary sericite .....	26.5
Chlorite with remnants of biotite .....	1.4
Calcite .....	0.1
Muscovite .....	0.1
	100.0

The Vänge granite often carries strongly or wholly altered plagioclase individuals. These seem to be inherited from some older rock and are as a rule surrounded by a rim of rather fresh plagioclase of the same age as the rest of the granite. (Compare P. J. Holmquist 1906, p. 187.) N.W. of Börje church and in other parts of the area to the west of Uppsala, the Vänge granite grades into red leptite. The transitional rocks should be characterized as red, granitic, strongly re-crystallized leptites ('coarse leptites', or leptite-granites). The red leptite has been interpreted as a metamorphic derivative of Oldest Svecofenian hällflinta (quartz-porphry and associated fragment-bearing rocks). It is quite frequent along the western boundary of the central volcanic area at Uppsala. Moreover, it appears as large inclusions in the Vänge granite to the west of this area. Now and then, the red leptite displays porphyritic quartz grains measuring up to 1 cm in length. We do not know whether this quartz is blastoporphyrific or represents re-crystallized quartzite fragments. Microcline porphyroblasts are also common.

Large inclusions of quartzite and greenstones have also been met with in the Vänge granite, whereas small xenoliths are quite rare. The quartzite has been described in an earlier chapter (p. 15). The greenstones include gabbro, diorite, and amphibolitic metabasite. As will be seen in the next chapter (p. 59), gabbro intrusions also seem to occur in the Vänge granite.

In the Uppsala region, the Vänge and Uppsala granites seldom border distinctly upon each other. Most frequently, they are separated by broad zones of intermediate primorogenic granite. In the neighbourhood of Läby church, sharp contacts have been observed, however, and locally (500 à 600 m N.W. of Läby church), dikes of Vänge granite cut Uppsala granite.

Part of the primorogenic acid granite has thus crystallized from solutions. Angular remnants of leptite have also been seen, though only in restricted parts of the areas occupied by the granite in question. As already mentioned, the Vänge granite, on the contrary, mostly grades smoothly into leptite and often carries strongly altered plagioclase individuals which seem to be inherited from some older rock, probably porphyritic leptite. As a matter of fact, such 'early' individuals have never been observed in the intrusive Uppsala granite.

The transitional rocks situated between the Vänge granite and the porphyritic hälleflinta to the west of Uppsala contain secondary fluorite. The Vänge granite itself, too, now and then contains some fluorite, whereas this mineral is wanting in the non-affected hälleflinta. Fluorine is a common element in magmas and solutions developing granites, and compounds containing fluorine are known as mineralizers. (Compare the foot-note on p. 42.) Thus N. H. Magnusson (1940, p. 59) reports the presence of considerable amounts of fluorite in association with sulphide ore minerals emanating from the mother solutions of the primorogenic granites in the Herräng field, Eastern Uppland.

The presence of fluorite in the transitional, 'granitized' volcanics as well as in the Vänge granite shows rather clearly that foreign compounds have been introduced during the primorogenic phase of the Svecofennian folding. The concentration of fluorite to the transitional rocks indicates that a real front of highly mobile primorogenic magma exudates has existed in the neighbourhood of Uppsala (though sulphide ore minerals are rare here).

A glance upon the petrological map, Plate 1, immediately shows that the bulk of the primorogenic acid granite has been concentrated to the west of the central volcanics in the Uppsala region. This space has earlier been occupied by supracrustal rocks of the same kind as the acid volcanics at Uppsala, as shown by several large inclusions in the Vänge granite and, furthermore, in agreement with the position of the fold axis of the Svecofennian range in Eastern Sweden. This axis was in general directed towards the east, with slow dip. (The weak lineation now and then appearing in the Uppsala region is apparently of somewhat later formation and has probably developed simultaneously with the thrust faults along the limb planes of the primorogenic folds. Compare p. 71.)

On considering the principle of constant volume during primorogenic foldings (before the development of thrust faults), the volcanics once existing at and to the west of Börje church ought to have been either dissolved by rising primorogenic granitic solutions similar to those advocated of by N. H. Magnusson (1940) in the Herräng field, or transformed into granite by strong metamorphism under the influence of late-magmatic water solutions containing some fluorine-bearing compound. (Compare above.) In the first case, they should have been transported upwards and should then have been consumed by later degradation. In the second case, they should be still present in the region investigated, though in the shape of acid granite. (The compositional differences between the porphyritic hälleflinta and the primorogenic acid granite are insignificant.) The Uppsala region contains both kinds of primorogenic acid granite. Owing to the high frequency of plagioclase relics, the second kind seems to predominate.

The primorogenic intermediate granite earlier described should have developed similarly.

### Porphyritic Granite.

The primorogenic porphyritic granite (the oldest Archean porphyritic granite in Plate 1) shows a bulk mineral composition which is similar to that of the intermediate granite. Its potassic feldspar, however, mostly forms coarse porphyroblasts. Moreover, its hornblende content is frequently higher than that of the intermediate granite. This is due to the fact that primorogenic basic granite has now and then been transformed into porphyritic granite, owing to potassic metasomatism.

The groundmass of the porphyritic granite is fine to coarse medium-grained, and its colour is red grey to grey. The microcline porphyroblasts are pink or red. As is shown in Plate 1, the granite in question is quite common though it does never form large bodies.

When studied microscopically, the secondary nature of the large microcline grains is quite obvious. The grains have grown at the expense of the surrounding minerals. Chemical reactions implying exchanges of ions have made this process possible. Potassium has been added, probably as aluminate, whereas, *inter alia*, sodium has been removed. We do not exactly know, when this metasomatism was at work. We may, however, presume that residual solutions rich in mineralizers have locally attacked the basic and intermediate, primorogenic granites shortly after their crystallization, having thus originated the scattered masses of porphyritic granite displayed in Plate 1.

At Kåbo gårde, in the south-western part of Uppsala, an orbicular variety of the porphyritic granite has been described by E. Wiman (1927; 1930, p. 32). This rock forms a lenticular inclusion in Uppsala granite. Its orientation is N.N.W.—S.S.E. It is composed of perthitic microcline porphyroblasts, plagioclase, quartz, biotite, and minor minerals. The porphyroblasts are orbicular and display pink kernels enclosed in red shells. Their total diameter is *c.* 3 cm, with a shell thickness amounting to about 1 cm.

### Late Svecofennian.

After the consolidation of the oldest Archean granites, sets of joints developed in the crust. The lines of weakness thus offered in part opened and became filled with rising magma. In an earlier stage of this evolution, basic magma was introduced, differentiating and crystallizing as gabbroic rocks, hypabyssic basites (altered; described as metabasites), and sparse final porphyries. In a later stage, great part of the crust of Central Sweden was subjected to migmatization. In the Uppsala region, swarms of granite-aplite and pegmatite dikes appeared, and small masses of these rocks also developed. (Compare Plate 1.)

#### Peridotite, Gabbro.

4 km W.S.W. of Junkil church, in a big forest, two small outcrops of ultra-basic rocks have been seen. (See Plate 1.) One of these outcrops shows a green black to grey black gabbro, the other outcrop a green black peridotite. Both rocks are coarse to medium-grained. The neighbouring outcrops consist of primorogenic acid granite. No contacts are visible.

The main minerals of the ultra-basic gabbro are bytownite, hypersthene, and olivine. In the peridotite, the mafic minerals dominate and bytownite forms an inferior constituent. The hypersthene and the olivine are poor in iron, and the former mineral shows penetrative growth visible as schillering reflections when light is thrown upon the cleavages. The olivine is associated with green spinel.

Magnetite is a common accessory mineral, whereas apatite is rare, in harmony with the rules governing the differentiation of basic magmas. This means that, in early products of basic magmatic differentiation, Mg is always greater than Fe and no or very little P is present. (Compare P. H. Lundegårdh, 1950.)

In part of the gabbro, the hypersthene and the olivine have altered to penetrative common greenstone hornblende with pale pleochroic colours and  $2V\gamma = 90-100^\circ$ . In hypersthene pseudomorphs, cummingtonite has been locally observed. This mineral here represents an intermediate alteration stage between hypersthene and common greenstone hornblende. (Compare B. Asklund 1925, pp. 21-22, and S. Hjelmqvist 1937, p. 30.)

During the amphibolization, much bytownite has been consumed, and part of the remaining plagioclase has changed to sericite and zoisite, or clinozoisite. In addition to the amphibole, the metagabbro contains some biotite, chlorite, and serpentine.

It is impossible to judge whether the alteration now described is secondary or deuteric. Moreover, the age relation to the surrounding primorogenic granite is unclear. 2.5 ÷ 3 km N.W. of the small gabbro massif, a dike of grey green black, fine- to fine medium-grained, ultra-basic uralite gabbro with hypidiomorphic bytownite, sparse pyroxene pseudomorphs, and schillering uralite porphyroblasts has been recently observed, however. The dike runs in a north-

western direction and measures 2 à 3 m in width. The dike gabbro is rich in magnetite, whereas apatite is lacking. Both the mineralogical data and the general appearance of the dike gabbro indicate a relationship to the massive gabbro, and the latter would thus have to be interpreted as intrusive in the primorogenic granite, too.

This suggestion is strongly supported by the spectral analysis given in Table 3. The concentrations of chromium, cobalt, and nickel obtained in the massive gabbro differ decidedly from those encountered in primorogenic ultra-basic intrusions (which show  $Cr > Ni > Co$ ; compare below.) On the other hand, they are similar to the figures met with in many serorogenic, or late-kinematic, ultra-basic intrusions. Among these, I will call attention to the serorogenic Svecofennian Roslagen gabbro, intrusion I, which includes a peridotitic gabbro composed as follows:  $Cr = 5$ ,  $Co = 90$ ,  $Ni = 250$  parts per million (P. H. Lundegårdh 1947, p. 40). It is not impossible that the gabbro W.S.W. of Jumkil represents an intrusion of the same magma that has given origin to the ultra-basic gabbro of Roslagen.

In series of rocks developed by normal differentiation of juvenile (primary) basic magma, the geochemical rules claim high concentrations of both chromium (especially) and nickel in the earliest, ultra-basic stages (V. M. Goldschmidt, 1945). Rocks such as the gabbro W.S.W. of Jumkil are thus abnormal and probably derive their origin from secondary magmas<sup>1</sup>. Intrusions of secondary basic magmas are concentrated to serorogenic and postorogenic periods in the evolution of the crust. (Compare P. H. Lundegårdh, 1950.)

### Hypabyssal Metabasites, Porphyry.

In the central and western parts of the Uppsala region, a great number of basic eruptive dikes have been observed. Most of these run towards north to north-west though east-west dikes also occur. In Plate I, several minor dikes have been omitted, and neighbouring parallel dikes have been represented as one single dike. Moreover, small dislocations and strike fluctuations have been neglected.

The width of the dikes seldom exceeds 10 m, and dikes narrower than 1 m are very common (Fig. 21). Basic dikes are quite dominant. As a matter of fact, only a few porphyry dikes exist in the Uppsala region.

The basic dikes have one feature in common: Their main mafic minerals have altered to hornblende. In other respects, however, their petrographic characters are highly variable. Thus, ophiolitic varieties (diabases) are found in some dikes, granoblastic varieties (amphibolites) in others, and porphyritic varieties in still others. The third kind of dikes displays both porphyritic plagioclase and blastoporphyratic, or porphyroblastic, hornblende. The blastoporphyrates can frequently be seen to have originally contained porphyritic pyroxene and should then be classed as uralite-porphyrates.

<sup>1</sup> In the case of the Jumkil gabbro most probably a primary magma that has been deprived of some of its original components.



Fig. 21. Dike of metabasite in primorogenic granite (oldest Archean granite). Road-cutting 1100 m to the south of Låby church.

Photo P. H. Lundegårdh.

The hypabyssal metabasites are as a rule black, green black, or deep green. Varieties showing aphanitic to fine-grained groundmass predominate though fine medium- to medium-grained rocks have also been found. Several dikes are slightly schistose. The majority of dikes are, however, macroscopically distinguished by structural isotropy.

Chief components are common greenstone hornblende and a plagioclase ranging from andesine to acid labradorite. In certain dikes, most part of the feldspar has been sericitized. Biotite often joins the main minerals. Now and then, the latter has altered to chlorite (as a rule penninite). Accessoric minerals are ore and apatite, further various alteration products, preferentially chlorite (compare above) and/or epidote. In addition, titanite and deuteric, or secondary pyrite may occur. Certain varieties are rich in quartz.

In many cases, the hornblende has been seen to have originated from pyroxene, whereas no olivine pseudomorphs seem to be present.

The mutual age relations between the various kinds of metabasite dikes

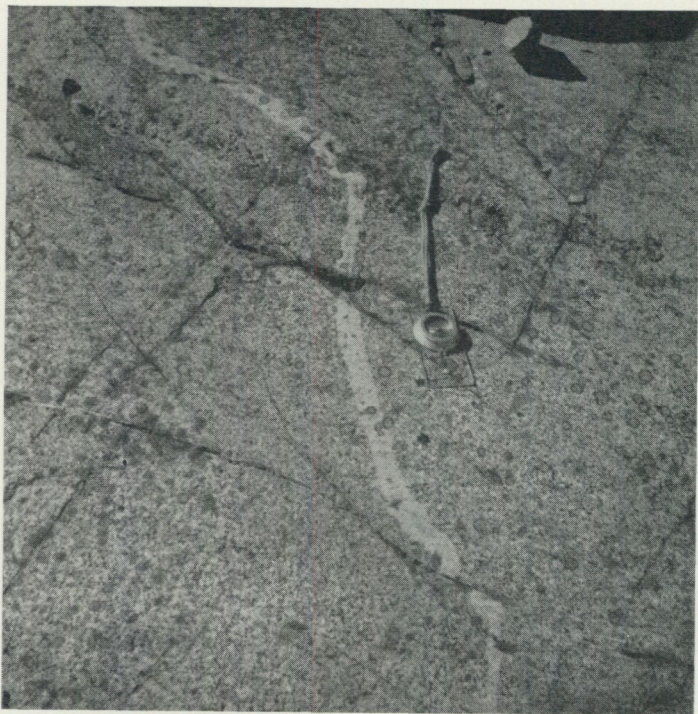


Fig. 22. Acid dike in primorogenic basic granite (Uppsala granite). 1.5 km E.S.E. of Danmark church.

Photo P. H. Lundegårdh.

are unknown, owing to the fact that neighbouring dikes normally run parallel to each others. The dike crosses displayed in Plate 1 are mostly covered with Quaternary deposits. A few observations made on the dike system S.W. of G:la Uppsala church indicate little or no difference in age. These dikes show a uniform fine-grained metabasite, however.

Crossing dikes of metabasites and final Svecofennian pegmatitic-granitic-aplitic rocks are also rare. Only in the south-westernmost part of the region, the latter have been reported to cut the former at a few places. The age position of most dikes is, however, unclear, though the data given below speak in favour of the correctness of their location to the period ranging from the consolidation of the primorogenic granites to the final Svecofennian migmatitization.

In the Söderfors region, northernmost Uppland, a number of metabasite dikes cut the bed-rock in a north-westerly direction (B. Asklund, 1948). These dikes are most frequent in the south-eastern corner of the mapped region (nearest to the Uppsala region), there actually displaying a swarm. The dikes show variable petrographic characters and are associated with acid dikes. Part of the metabasites are porphyritic. Though final Svecofennian granite occupies the northern part of the Söderfors region, this granite has never been seen to cut metabasite dikes. On the other hand, no metabasite dikes occur in

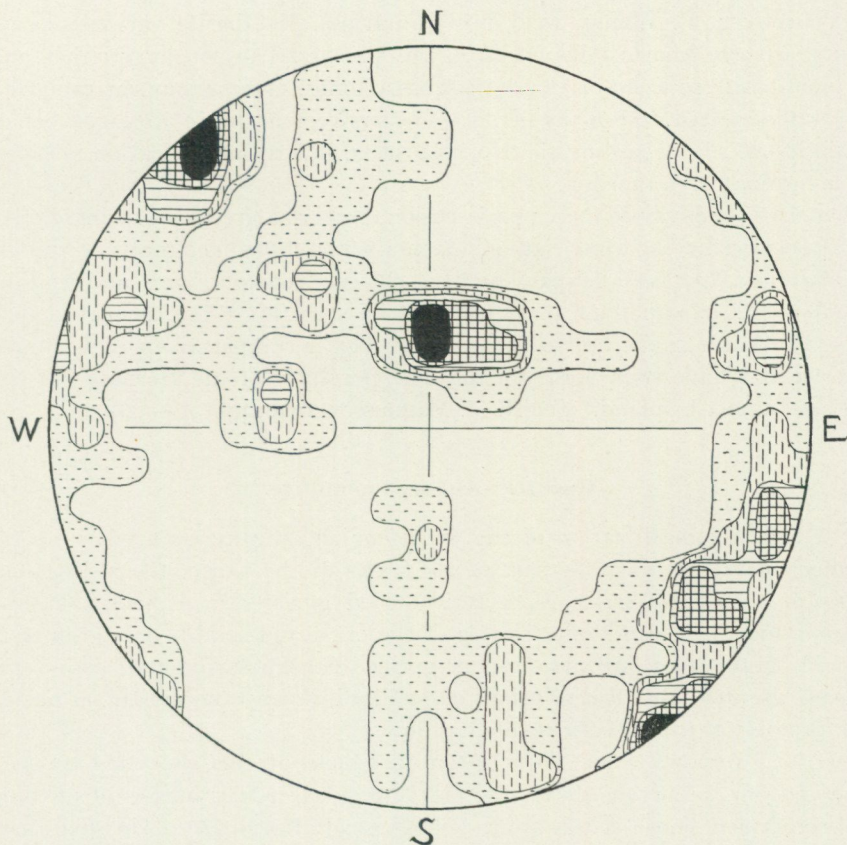


Fig. 23. Stereographic projection of 75 poles of joints in penetrating plagioclase-porphyrite. Frequency fields = (7—6)—(4—5)—3—2—1—0 poles. Artificial cave about 3.5 km S.W. of G:la Uppsala church.

the young granite itself. The dikes have therefore to be interpreted as older than the final Svecofennian granite.

Similar dikes occur in Easternmost Uppland. These dikes are strongly differentiated and have clung together as swarms (the Herrång ore field in Northern Roslagen, described by N. H. Magnusson in 1940; the Norrtälje-Bergshamra region in Central Roslagen, described by P. H. Lundegårdh in 1946).

The prevailing orientation of the dikes in Easternmost Uppland is east-west. They cut the ultra-basic gabbro of Roslagen though a few of them, viz. the most basic ones, have been shown to be intimately related to this rock. (Compare also P. H. Lundegårdh, 1948.) Furthermore, the dikes of Easternmost Uppland cut the Vätö granite, a red microcline-granite which is associated with the ultra-basic gabbro and has been interpreted as a final differentiation product of the parental magma of this rock (P. H. Lundegårdh 1946, pp. 80—86, 136—138, and 1954).

As already touched upon, the Uppsala region displays a few dikes containing

acid porphyry (E. Wiman 1930, pp. 50 and 52). Metabasite varieties rich in quartz are also known (Wiman 1930, pp. 50—51). The porphyry either joins the metabasite so as to originate diaschistic dikes, or occurs as separate dikes. The differentiated dike rocks in the Söderfors region and in Roslagen behave similarly, which, regarding the Uppsala dikes, is a strong indication in favour of an intimate relationship.

The dike porphyry of the Uppsala region displays a grey rock sprinkled with small porphyritic oligoclase individuals in a very fine-grained matrix composed of oligoclase, potassic feldspar, quartz, chlorite, epidote, ore, and titanite. (Compare E. Wiman 1930, p. 52.) As will be seen from the chemical analysis quoted in Table 2, the lime content of the rock is comparatively high. Similar observations have been made on the dike porphyry of the Herräng ore field in Easternmost Uppland. (See N. H. Magnusson 1940, pp. 31—32.)

### Granite—Aplite, Pegmatite.

The final migmatitization of the Svecofennian orogeny changed the petrographic characters of great part of the rocks of the range, the sedimentary rocks of the Mälars series especially. Veined gneisses developed, palingenic magma intruded into higher levels of the crust and solidified as granites of variable grain sizes (medium- to fine-grained Stockholm granite, coarse Fellingsbro granite). Residual solutions crystallized, slowly, and mostly, as pegmatite, rapidly (at the eutectic point) as aplitite.

In the Uppsala region, only distant products of this process have been observed, viz. numerous dikes (Fig. 22) and sparse minor masses of medium- to fine-grained, more or less aplitic granite, and of pegmatite. The dikes most frequently appear as swarms (Plate 1). The granite is sometimes porphyritic.

The final Svecofennian rocks of the Uppsala region are mostly red or reddish. They consist mainly of quartz, oligoclase, and microcline. Further, variable quantities of biotite are always present. The following accessory minerals complete the petrographical picture: Secondary epidote, ore, muscovite, titanite, apatite, and pseudo-allanite.

The rocks now described are in most cases non-deformed. Now and then, the granite and granite-aplites display a slight schistosity microscopically visible as granulation of major quartz individuals, *S-Regelung* of biotite blades, and bending of single feldspar laths.

### Joints, Faults, Shear Zones.

The oldest cracks of the Uppsala rocks seem to be those encountered in the rounded epidote inclusions in the volcanic conglomerates (Fig. 7). Part of the joints and cracks in the porphyritic hällflinta and the plagioclase-porphyrites have also developed quite early, viz. the epidote-bearing ones mentioned on p. 24. E. Wiman (1930), who has investigated the jointing of the Uppsala region

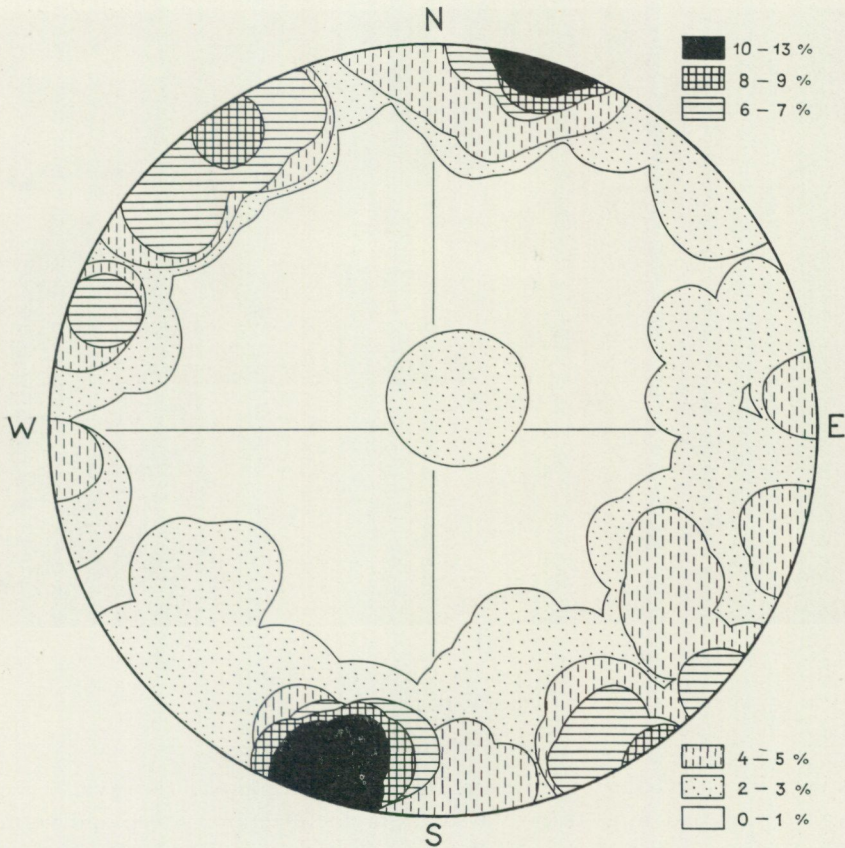


Fig. 24. Stereographic projection of 100 poles of joints in primorogenic basic granite (oldest Archean basic granite, or Uppsala granite). Sommaro, South-Western Uppsala.

in detail, has been able to distinguish in the volcanics at Uppsala between six generations of cracks and joints, filled with the following minerals (from oldest to youngest): 1. Epidote. 2. Quartz + microcline. 3. Prehnite. 4. Quartz. 5. Chlorite. 6. Laumontite. 1 and 2 are intimately associated and seem to display crystallization products of residual solutions emerging from the magma of the older plagioclase-porphyrites near Uppsala. The cracks and joints containing these minerals seem to have developed during the cooling of the hälleflinta beds and porphyrite intrusions.

Another set of early joints is displayed by the uralite-porphyrite dikes to the west of Vaksala church and at a few other localities. The uralite-porphyrite dikes have been interpreted as members of the Mälars series. (See p. 34.) They are stretching towards N.N.W., with fairly high dips. Cross joints are common, and the dikes have frequently been displaced along these during some later phase of the Svecofennian orogeny.

In the penetrating plagioclase-porphyrite 3-4 km S.W. of G:la Uppsala church, an artificial cave blasted at Husbyborg during the second world war



Fig. 25. Primorogenic acid granite (oldest Archean acid granite, or Vänge granite) with regular cleavages. 3 km W.N.W. of Börje church.

Photo P. H. Lundegårdh.

has been investigated by the writer. In Fig. 23, all joints of the cave,  $N = 75$ , have been plotted so as to give a stereographic diagram.<sup>1</sup> Steep and vertical joints tending towards N.E. and flat-lying east-west joints here predominate. 17 joints are filled with laumontite, or laumontite + calcite, 4 with quartz, and 1 with pyrite. About  $\frac{1}{4}$  of the remaining 53 joints contain calcite. Owing to dissolutions, we cannot tell the exact number of joints that have originally been calcite-bearing, however.

The age relations between the various mineralizations seem to be as follows (from oldest to youngest): 1. Pyrite. 2. Quartz. 3. Laumontite and calcite. The oldest mineralizations present in the joints of the porphyritic hällflinta and the non-penetrative plagioclase-porphyrites are wanting, in agreement with the supposed younger age of the penetrating plagioclase-porphyrite.

E. Wiman (1930, p. 105) has measured a great number ( $N = 158$ ) of joints in the plagioclase-porphyrites at Uppsala. According to Wiman, the leading system of joints is N.—N.N.W., about  $90^\circ$ , and E.—W., about  $90^\circ$ . This is the same Mohr system that dominates the bed-rock of Central and Eastern Uppland. (Compare below.)

Most joints of the porphyritic hällflinta (total number here = 166) vary between N.W. and N.E., with high or vertical dips (E. Wiman 1930, p. 104).

<sup>1</sup> It has to be regretted that only 75 joints were available. From a statistical point of view, this is an insufficient number.

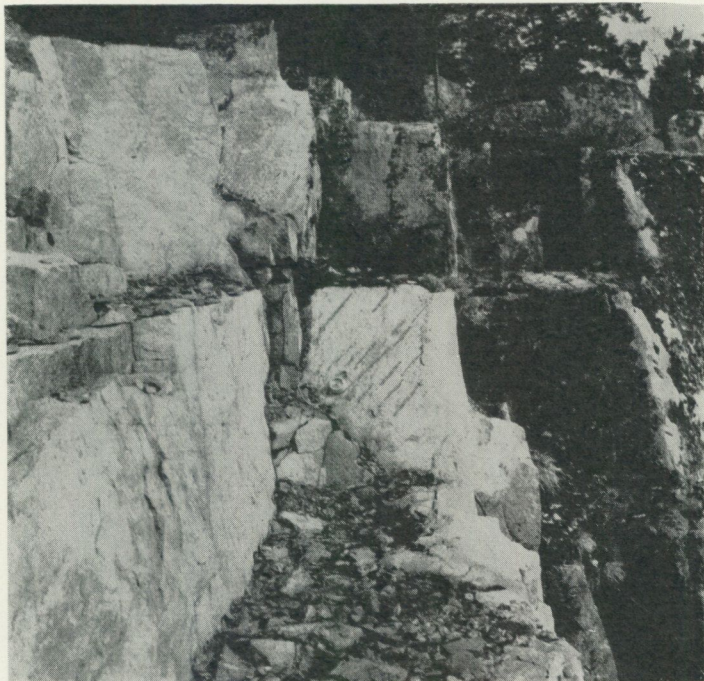


Fig. 26. Regular jointing in coarse leptite grading into primorogenic acid granite (Vänge granite). Compass placed on a joint surface with fault striae. 2 km S.S.W. of Åkerby church.

Photo P. H. Lundegårdh.

The orientations of the mineralized joints of the primorogenic basic granite near Uppsala (the Uppsala granite;  $N = 102$ ) are in part similar to the joints of the penetrating plagioclase-porphyrite (E. Wiman 1930, p. 108). Wiman has shown that steep N.—E.N.E. joints and N.—N.W. joints with moderate dips predominate though E.—E.N.E. joints with moderate dips are also frequent. He gives the following scheme of the mineralizations there encountered (from oldest to youngest): 1. Epidote (rare). 2. Calcite. 3. Prehnite (very common), laumontite, and chlorite. 4. Fluorite (rare). (See Wiman 1930, pp. 96 and 108.) All these minerals seem to belong to the same mineralization epoch, however, and Wiman suggests their hydrothermal or pneumatolytic origin (1930, p. 98). According to our present knowledge, it seems most probable that the mineralization has been caused by residual solutions emerging from the primorogenic magma — solutions related to the granitizing ones that have been supposed to have given origin to part, or most, of the Vänge granite. (Compare p. 57.) The joints should thus have developed shortly after the solidification of the Uppsala granite.

Recently, the writer measured 100 joints in the Uppsala granite 500—1000 m E.S.E.—S.E. of Ekeby Bruk stn, in the south-western part of Uppsala. (See Plate 1 and Fig. 24.) Steep joints stretching towards W.N.W. and N.N.E.—E.N.E. here dominate. A few distinct vertical  $N 10^{\circ}W$  fissures belonging to 5†—561906. *S. G. U., Ser. C. N:o 544.* Lundegårdh.

the younger system described immediately below have also been observed. Part of the dominating joints are filled with calcite and/or prehnite.

In later Svecofennian time, a regional Mohr system of joints and fissures was produced. In Central and Eastern Uppland, we then obtained one set of joints and fissures tending towards N.—N.N.W. and another set running in an eastern to east-north-eastern direction. Both sets of joints mostly show high or vertical dips. The system in question cuts the ultra-basic gabbro of Roslagen (P. H. Lundegårdh 1943, p. 386), whereas it is older than the metabasite and porphyry dikes, having actually opened after the consolidation of the ultra-basic gabbro and enabled the intrusion of the dike-producing magma. Although it cuts the ultra-basic gabbro, it has, however, most probably been established earlier. The general strike of the Svecofennian range is here E.N.E.—E., and obviously this direction has to be reproduced as the strike of the longitudinal cleavage of the primorogenic granites. The cross cleavage should then be directed towards the north. In South-Eastern Uppland, the Svecofennian range tends towards N.E. The longitudinal joints of the granites, both the primorogenic and serorogenic ones, there tend towards N.E. and the cross joints towards N.N.W.—W.N.W.

In the area to the west of Uppsala, the longitudinal cleavage of the primorogenic granite here met with — the Vänge granite, is directed towards N 30—70°W. The cross cleavage tends towards N 20—60°E. Both cleavages show high or vertical dips (Fig. 25). The longitudinal cleavage runs parallel to the strike and dip of the sparse supracrustal inclusions, another support in favour of the conception of a regional granitization *in situ* to the west of Uppsala. (Compare pp. 56—58.)

Faulting has occurred along certain fissures. (See Plate 1 and Figs. 26—27). The greatest fault zones pass through Uppsala and meet N.W. of the town. These zones seem to have originally developed in Archean time. Forces produced by later orogenies have, however, certainly been released by movements along these zones, too. The deep depression in the central and south-eastern parts of Uppsala (Fig. 28;  $\geq 100$  m as compared with the neighbouring outcrops in S.W. and N.E.) may thus indicate a very late (Tertiary?) rotation of the edge-shaped block stretching towards Bergsbrunna, implying a sinking of the bed-rock under Central Uppsala and a raising of the bed-rock S.E. of Bergsbrunna. (Compare Plate 1.) It has to be pointed out, however, that the partial brecciation of the rocks under Central Uppsala may have made these apt to deep-weathering.

Shear zones have also been observed in the Uppsala region. 2—3 km N.N.E. of G:la Uppsala church, the primorogenic secondary granite, or leptite granite, is strongly penetrated by shear joints and has become in part brecciated ('B' in Plate 1). (Compare p. 34.) Similar jointing and brecciation occurs in the leptite N.N.E. of Storvreta stn. The shear zone seems to stretch approximately parallel to the river Fyris from G:la Uppsala towards N.N.E. On the geological map-sheet Salsta, to the north of the Uppsala region (A. L. Th. Pettersson, 1871), the shear zone can be followed to Lake Dannemora. The movements having



Fig. 27. Fault surface in porphyritic hälleflinta. 2 km E.S.E. of Börje church.  
Photo P. H. Lundegårdh.

occurred along the zone are no doubt responsible to the structural discordance met with in the leptite-hälleflint complex at Knivsta, between Salsta and Lake Dannemora.

### Summary of Orogenic Events.

Finds of quartzitic and pelitic fragments in Oldest Svecofennian volcanics indicate the former existence of pre-Svecofennian rocks in the substratum of these rocks and make necessary the conception of pre-Svecofennian formations being still present in and, especially, around the Central Swedish and Finnish Svecofennides. In the first hand, it seems indispensable to re-examine in detail the older rock complexes of Southern Sweden. In the vicinity of Göteborg (Gothenburg), we have thus three supracrustal series, viz. the late Gothian<sup>1</sup> Åmål series, the early Gothian Stora Le—Marstrand series, and a pre-Gothian series. (Unpublished investigations by the writer. Compare also P. H. Lundegårdh, 1953, and W. Larsson 1956, pp. 10, 12 ff., and 23 ff.)

Moreover, to the east and south-east of the Göteborg (Gothenburg) region, W. Larsson (personal communication, 1956) has been able to establish the existence of two pre-Gothian supracrustal series.

<sup>1</sup> See foot-note, p. 7.



Fig. 28. The Uppsala depression from S.E. In the front of the church in the centre of the photo, the thickness of the Quaternary deposits amounts to 100 m or more.

Photo P. H. Lundegårdh.

The petrographic characters of the Mälars series give full evidence of orogenic activity during the final stages of Oldest Svecofennian, and simultaneously with the formation of the sediments, spilites etc. of the Mälars series the orogenesis grew stronger and stronger.

Its culmination was Middle Svecofennian being characterized by the development of a complete series of primorogenic rocks at present displaying plutonic characters and ranging from lherzolite to acid granite. Formerly, this series ('urgranit series'<sup>1</sup>) was interpreted as the consecutive products of some kind of differentiation within one single magnum magma. As has been evident from the above text, this hypothesis does not harmonize with the petrological and geochemical data recently collected in the Uppsala region. We have there been forced to interpret the gabbroic rocks as separate members of the primorogenic series and the granites as mainly secondary rocks (crystallized mainly secondary magmas, or solutions, and products of granitizations more or less *in situ*). Moreover, we have been forced to doubt to some extent even the primarity of the lherzolitite-gabbroic character of the basic plutonics.

Turning to the structural geology of the Uppsala region as developed during the primorogenic phase of the Svecofennian orogenesis, we have to accept an anticline to the north (leptite-hällefliint series) and a syncline to the south

<sup>1</sup> Also classed as the oldest Archean granite series, although we do not know if these granites really are the oldest Archean ones. (Compare the granite fragments in Oldest Svecofennian volcanics mentioned on p. 25.)

(Mälar series), with flat-lying fold axes. Thrust faults have apparently occurred along the limb planes of the faults, thus dividing the supracrustal rocks into sheets. When the horizontal compression relaxed, mainly secondary magma and solutions could rise along the thrust planes, crystallizing as Uppsala granite and granitizing part of the rock content of the sheets. Simultaneously, the latter were subjected to differential movements and plastic deformations. The result can be seen in Plate 1: Winding slices of supracrustal rocks in masses of primorogenic granites.

The lineation now and then met with in the Uppsala region as a rule shows high dips. (Compare Plate 1.) This structure probably reflects the direction of movement of the thrust faults. Similar lineations have been observed in the Caledonides of Western Norway (A. Kvale 1948, p. 248) and Scotland (E. M. Anderson, 1948).

In the Svecofennides, we have several indications pointing in favour of the assumption of serorogenic (late-kinematic) movements, too, along the thrust planes. Among these indications, I should mention the occasional plane and linear schistosity encountered in the serorogenic Svecofennian granites.

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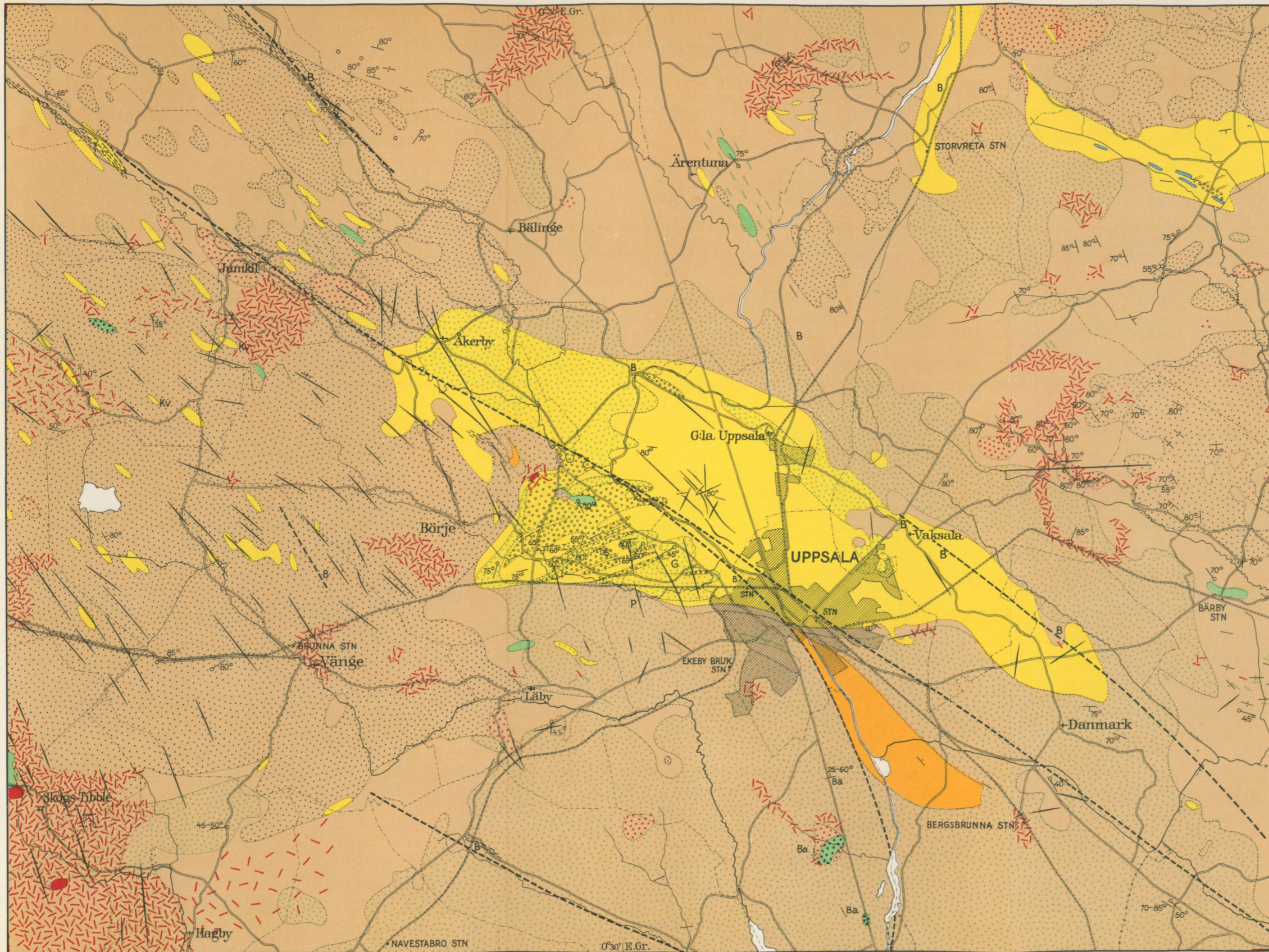
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# BERGGRUNDEN INOM KARTBLADET UPPSALA

PETROLOGICAL MAP OF THE UPPSALA REGION

P. H. LUNDEGÄRDH 1955



- Breccia  
*Breccia*
  - Förkastning  
*Fault*
  - Stark förskifring  
*Strong schistosity*
  - Granit-aplit, pegmatit, gångsvärmar  
*Granite-aplite, pegmatite, swarms of dikes*
  - Granit-aplit, pegmatit, smärre massiv  
*Granite-aplite, pegmatite, small masses*
  - Metabasit och porfyr (P), gångar  
*Metabasite and porphyry (P), dikes*
  - Urgranit, gångar  
*Oldest Archean granite, dikes*
  - Urgranit, mikroklinporfyrisk  
*Oldest Archean granite, porphyritic*
  - Urgranit, sur  
*Oldest Archean granite, acid*
  - Urgranit, intermediär  
*Oldest Archean granite, intermediate*
  - Urgranit, basisk, vanligen hornbländerik  
*Oldest Archean granite, basic, generally rich in hornblende*
  - Kvarstdiorit, diorit, uralitporfyr, metabasit  
*Quartz-diorite, diorite, uranite-porphyr, metabasite*
  - Peridotit, lherzolit, gabbro  
*Peridotite, lherzolite, gabbro*
  - Sedimentgnejs (med basiska tufflager)  
*Sedimentary gneiss (with layers of basic tuff)*
  - Metabasit, stora brottstycken  
*Metabasite, large inclusions in younger rocks*
  - Plagioklasporfyr (genombrytande varietet = G), basisk leptit (delvis porfyrisk)  
*Plagioclase-porphyr (penetrating variety = G), basic leptite (in part porphyritic)*
  - Fragmentbergarter (huvudsakl. vulkaniska konglomerat)  
*Fragment-bearing rocks (mainly volcanic conglomerates)*
  - Kalksten  
*Limestone*
  - Porfyrisk hälleflinta, sur till intermediär leptit, delvis grov; kvartsit (Kv)  
*Acid and intermediate hälleflinta, porphyritic, and leptite, in part coarse; quartzite (Kv)*
- Skiktning, skiffrihet, bandning *Stratification, schistosity, banding*
- 40° Stupning med känt gradtal *Dip with known degree*
  - " " , brant *Steep*
  - " " , lodrät *Vertical*
  - " " , obekant eller starkt växlande *Unknown or variable*
  - Ba Bandning *Banding*
- Stänglighet *Lineation*
- 40° Lutande *Inclined*
  - o Lodrät *Vertical*

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