INTERNATIONAL GEOLOGICAL CONGRESS
XXI SESSION NORDEN 1960

ARCHEAN GEOLOGY OF VÄSTERBOTTEN AND NORRBOTTEN, NORTHERN SWEDEN

GUIDE TO EXCURSIONS NOS. A 32 AND C 26

By

G. KAUTSKY, P. QUENSEL, E. ÅHMAN, R. FRIETSCH, AND P. GEIJER

The Swedish geological guide-books

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Key map: see inside of back cover.

Excursion No. A 32: Aug. 3rd — Aug. 13th, 1960
Excursion No. C 26: Aug. 26th — Sept. 5th, 1960

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Kartorna äro för spridning godkända i Rikets allmänna kartverk den 20/5 1960, där ej annat datum angivits.

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Introduction

Our knowledge of the Archean rocks of Norrland is closely related to mineral prospecting. Almost all geological discoveries in Norrbotten and Västerbotten are the work of geologists concerned with the prospecting programmes. As a consequence the mineralized areas are better known geologically than the barren ground in between.

The excursion is arranged so that a general impression of the Archean rocks, their stratigraphy and tectonics may be gained. Naturally much time will be devoted to the ores, their paragenesis and geological setting. Localities shown on the excursion lie for the most part in areas of economic interest.

Only the more recent literature is given here. In contributions by Gavelin 1955 SGU Ser. Ca 37 and Ödman 1957 SGU Ser. Ca 41, however, may be found maps and a more complete bibliography.

The Skellefte field

By

G. Kautsky

On account of the occurrence of sulphidic ore bodies the Skellefte field has been the subject of detailed geological studies. Geological maps on the scale 1 : 8 000 and 1 : 20 000 and covering almost the whole field have been prepared by the Boliden Mining Company and by the Geological Survey of Sweden. Extensive areas have been investigated geophysically employing electro-magnetic, magnetic and gravity methods. As a result the sub-outcrop distribution of the electrically conducting rocks and their inclinations are known in moraine covered parts of the field. Summary maps have been published by A. Högbom 1937 and S. Gavelin 1955.

During the excursion, the stratigraphy of the central part of the Skellefte field will be demonstrated. These rocks are in low grades of metamorphism and their structure well preserved.

Following G. Kautsky 1957 (fig. 1) the Skellefte field is made up of two supracrustal series — the Maurliden Series and the Elvaberg Series — separated by the intrusion of the Jörn granite and a tectonic phase marked by gentle folding.

The Maurliden Series' oldest sediments (the Maurliden phyllites) consist of thick greywackes, phyllites, slates and sandstones with intraformational conglomerate containing, among others, pebbles of porphyry. Porphyries together with tuffs and tuffites occur as layers in the sediments but are quantitatively of minor importance. The sediments are often beautifully banded whilst graded-bedding and rhythmic banding are common. Porphyry (a Maurliden volcanic rock) rests on the Maurliden schists whilst upon it comes a

Sorselegranit

Revsundsgranit
MIGMATITISIERUNG, METAMORPHOSE u. ERZBILDUNG
VERSCHIEFERUNG
FALTUNG

ELVABERGSERIE

Elvabergschiefer
Psammite u. Grauwacken

Menssträskkonglomerat Marine Fazies	kalkzementierte Felsitkonglomerate u. sedimentäre Breccien. Selten einzelne Jörngranit- oder bunte Gerölle. Einlagerungen von Psammiten u. Schiefern mit Sedimentationszyklen u. »graded bedding». Effusive Grünsteine	polymikte bunte Konglomerate u. Sandsteine mit Diskordantschichtung. Keine Sedimentationszyklen. Granitgerölle sehr selten.	Dömanberg Kongl.	Vargforskonglomerat Fluviatile Fazies
		WINKELDISKORDANZ		
		polymikte Konglomerate mit reichlich Jörngranitgeröllen u. nur einzelnen bunten Geröllen. Einlagerungen andesitischer Lavabänke im Konglomerat.	Abborrtjärn Kongl.	

TIEFGEHENDE VERWITTERUNGSRINDE
BEDEUTENDE DISKORDANZ u. HIATUS

WEICHWELLIGE FALTUNG und
Bildung von Jörngranit u. Arvidsjaurgranit
schwache Sulfidinvasion

MAURLIDENSERIE

Skogshedenvulkanite Porphyrite und Mandelsteine; ehemalige Basalte u. o. Andesite.

Petikträskschiefer Graphitschiefer mit Einlagerung von ca. 50 % Quarzporphyr.

Maurlidenvulkanite Felsite, Quarzporphyre, Feldspatporphyre und deren Tuffe

(Arvidsjaurporphyr)

Maurlidenschiefer graue u. schwarze Schiefer, Psammite, Grauwacken u. Konglomerate. Die Sedimente häufig mit Sedimentationszyklen u. »graded bedding». Konforme Einlagerungen von sauren u. intermediären Vulkaniten

Fig. 1. Stratigraphy of the Skellefte district, according to Kautsky 1959.

mixed sequence of alternating porphyry, graphitic schist, tuff, sandstone and tuffite (the Petikträsk schists). Above the Petikträsk schists comes an extensive greenstone formation with well preserved amygdaloidal lava of andesitic composition for the most part (the Skogsheden volcanics). The formation includes even sedimentary intercalations in the form of phyllites and tuffites.

The Jörn granite is younger than the supracrustal rocks of the Maurliden Series as it transects these rocks with intrusive contacts. The granite has a porphyritic outer zone and is to some extent schistose.

After intrusion of the Jörn granite and a gentle folding of the rocks a period of denudation followed. During this period the Jörn granite and deep stratigraphic levels of the Maurliden Series were exposed.

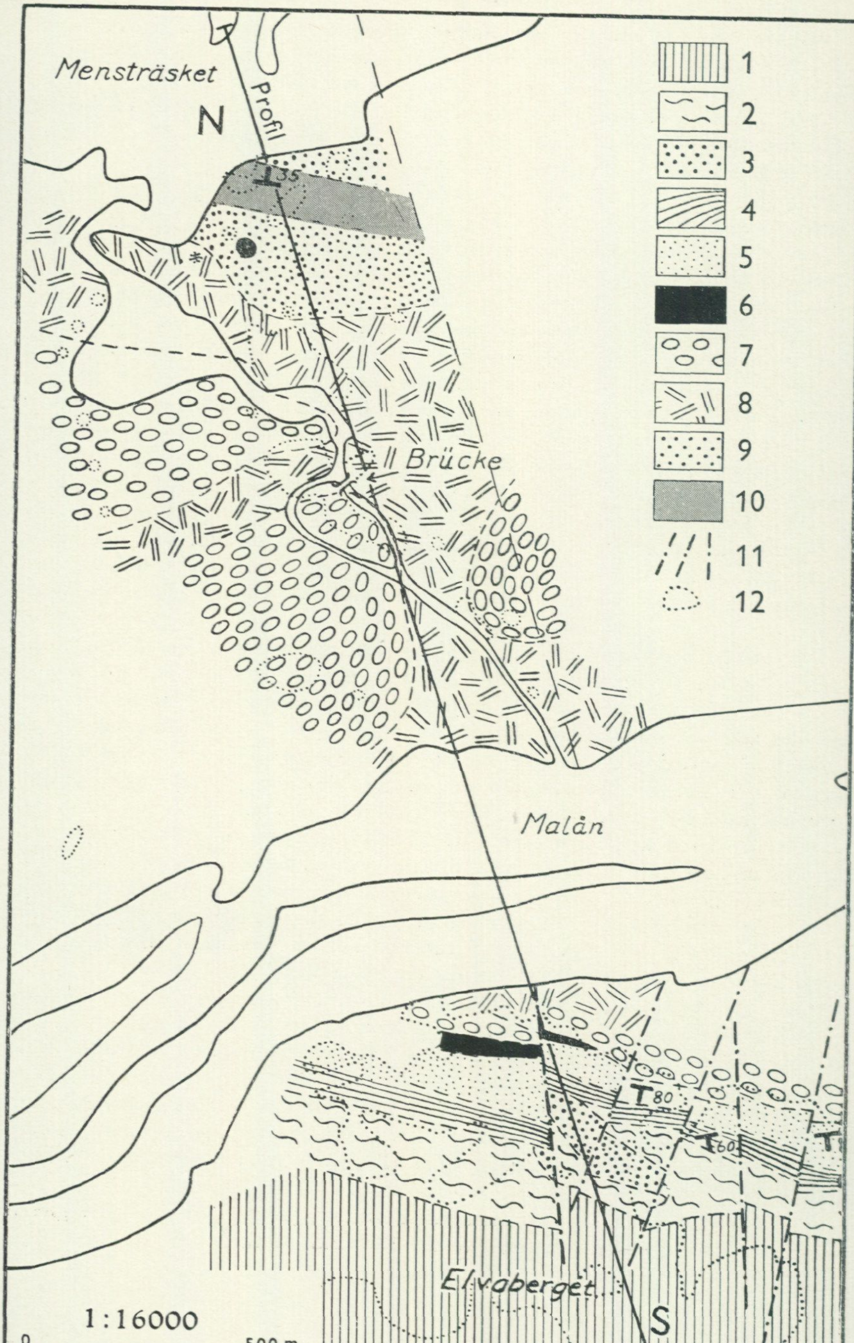
The Elvaberg Series rests on different members of the Maurliden Series and on the Jörn granite. The lowermost layers include first a little redeposited weathering debris from the underlying rocks. The older layers of the Elvaberg Series have been partly deposited under marine conditions (the Mensträsk conglomerate) and consist of fluviatile sediments and/or deltaic deposits (Vargfors conglomerate, the conglomerate at Ledfat). The marine deposits are rich in lime with carbonate cemented sedimentary breccias, limestones, conglomerate, calciferous sandstones and bituminous phyllites and slates. Graded-bedding and rhythmic banding are usual in the marine sediments. In contrast, the Vargfors conglomerate contains no sedimentary limestone except for certain layers transitional to the Mensträsk conglomerate. Cross-bedding is normal in the sandstone intercalations of the Vargfors conglomerate. All the rocks of the Maurliden Series and the Jörn granite occur as pebbles. In addition pebbles of Arvidsjaur porphyry also occur showing that the reddish Arvidsjaur porphyry is older than the Elvaberg Series. Extrusive greenstones of andesitic composition are present as intercalations in the lowermost layers of both the Mensträsk and Vargfors conglomerates.

The fluviatile deposits of the Vargfors conglomerate can be divided into two sections which are discordantly related to each other, a lower — the Abborrtjärn conglomerate consisting of polymictic conglomerate rich in Jörn granite pebbles and only an occasional red pebble; an upper — the Dömanberg conglomerate consisting of mottled bright red and green coloured conglomerates as well as red cross-bedded sandstones. In the Dömanberg conglomerate granite pebbles are exceptionally rare. These two conglomeratic sections which are mostly associated with each other, are probably not separated by a great time interval and no tectonic phase of significance occurs between the two types. The Ledfat conglomerate corresponds stratigraphically with the Dömanberg conglomerate most probably. Uppermost in the Elvaberg Series occur thick units of sandstone and phyllites (The Elvaberg phyllite). Some of these beds are good electrical conductors. The formation has a wide distribution.

The supracrustal rocks and the Jörn granite are schistose but the intensity of the schistosity varies in strength in different parts of the area.

The schistose Maurliden Series and the Elvaberg Series are cut by the Revsund granite which is commonly coarsely porphyritic but non schistose. Even younger, according to A. Högbom (1936), are a number of even-grained granite massifs with diorite marginal facies. They occur as minor elements in the supracrustal rocks of the Skellefte field. They are referred to as the Sorsele granite.

The ore formation is epigenetic and clearly younger than the regional schistosity. Ore geologists relate it to the Revsund granite.


Mensträsket
N
Profil
35
1
2
3
4
5
6
7
8
9
10
11
12
Brücke
Malån
80
60
Elvaberget
S
55
1:16000
0
500 m

The presence of mineralization in the area was first indicated by glacial boulders found in 1921 and the area was then investigated geologically and geophysically. In 1930 the first ore body was discovered. Development work started in 1941 and the mine came into production in 1944. Mining is carried out by the room and pillar method.

The predominant structural feature of the Adak area is that of a dome. The oldest rocks in the centre of the dome are the 'ore quartzites' which are of metasomatic origin. Over them follow banded sediments mainly of tuffitic character and sometimes containing layers of limestone. A thick series of basic volcanics divides the banded sediments into two groups.

The supercrustal rocks are framed by granites, which are considered to represent the youngest group of pre-Cambrian granites in the Skellefte District and its environment. To a certain degree these granites lie conformable with the stratification, and thus appear to rest on the supercrustal rock complexes.

The sulphide mineralization is mainly concentrated in the inner parts of the dome characterized by cordierite- and mica-quartzites, and to the boundary zones between these rocks and the overlying banded complex. Up to the present, five deposits of economic importance have been located, viz. the deposits of Adak, Lindsköld, Karlsson, Brännmyran and Rudtjebäcken. Besides the deposits already mentioned there occur in several places mineralization of a smaller extent. Mineralogically, the sulphide mineralization is characterized in the majority of

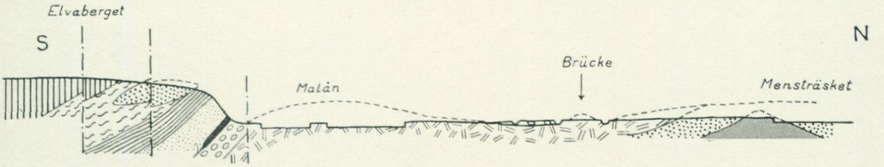


Fig. 3. Profile through the Elvaberget—Mensträsket region. For location and explanations see map on Fig. 2.

Fig. 2. Map of the Elvaberget—Mensträsket region.

1. Black graphitic phyllites and psammites
2. Knobby gray phyllites
3. Conglomerates in gray phyllites
4. Layer of graphitic phyllites
5. Metamorphic sandstones
6. Amphibolite
7. Mensträsk conglomerate; calcite-cemented breccia
8. Maurliden volcanics
9. Psammites in Maurliden phyllites
10. Maurliden phyllites
11. Faults
12. Outcrops

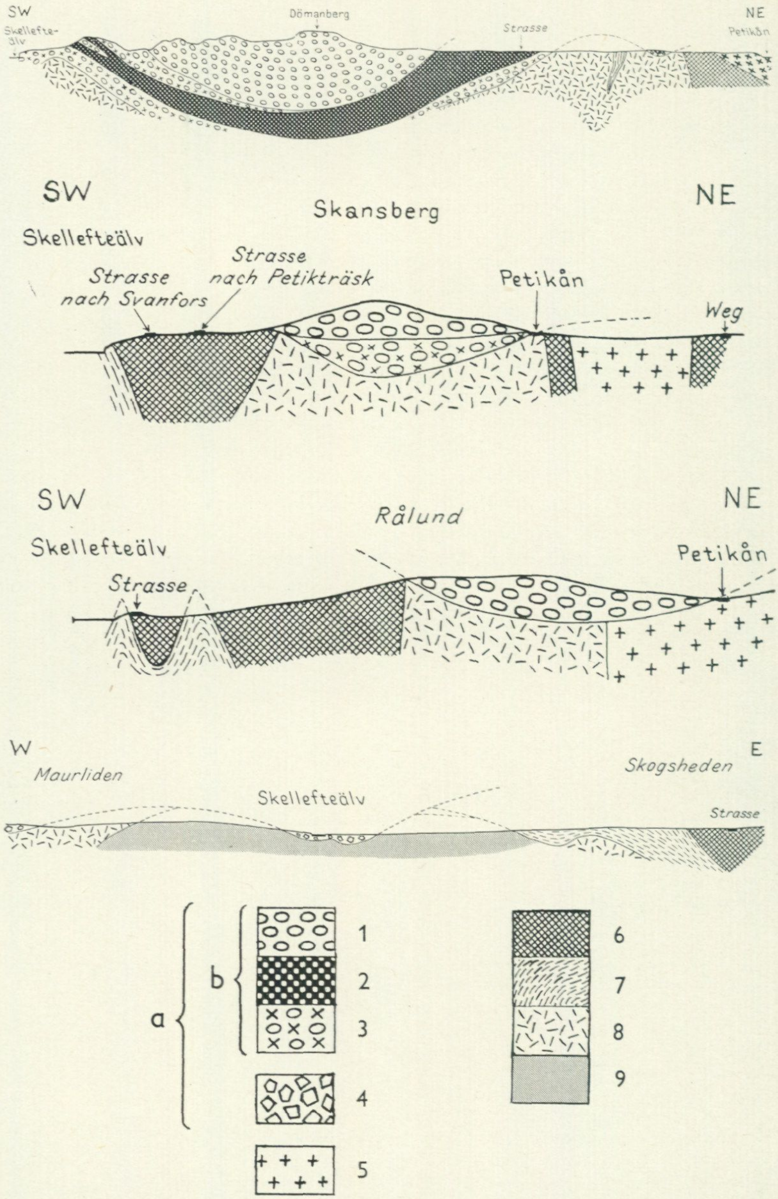


Fig. 4. Profiles through the Vargfors—Kusfors region.

a. Elvaberg series. b. Vargfors conglomerate. 1. Dömanberg conglomerate. 2. Vargfors andesite. 3. Abborrtjärn conglomerate. 4. Mensträsk conglomerate. 5. Jörn granite. 6. Skogsheden volcanics. 7. Petikträsk phyllites. 8. Maurliden volcanics. 9. Maurliden phyllites.

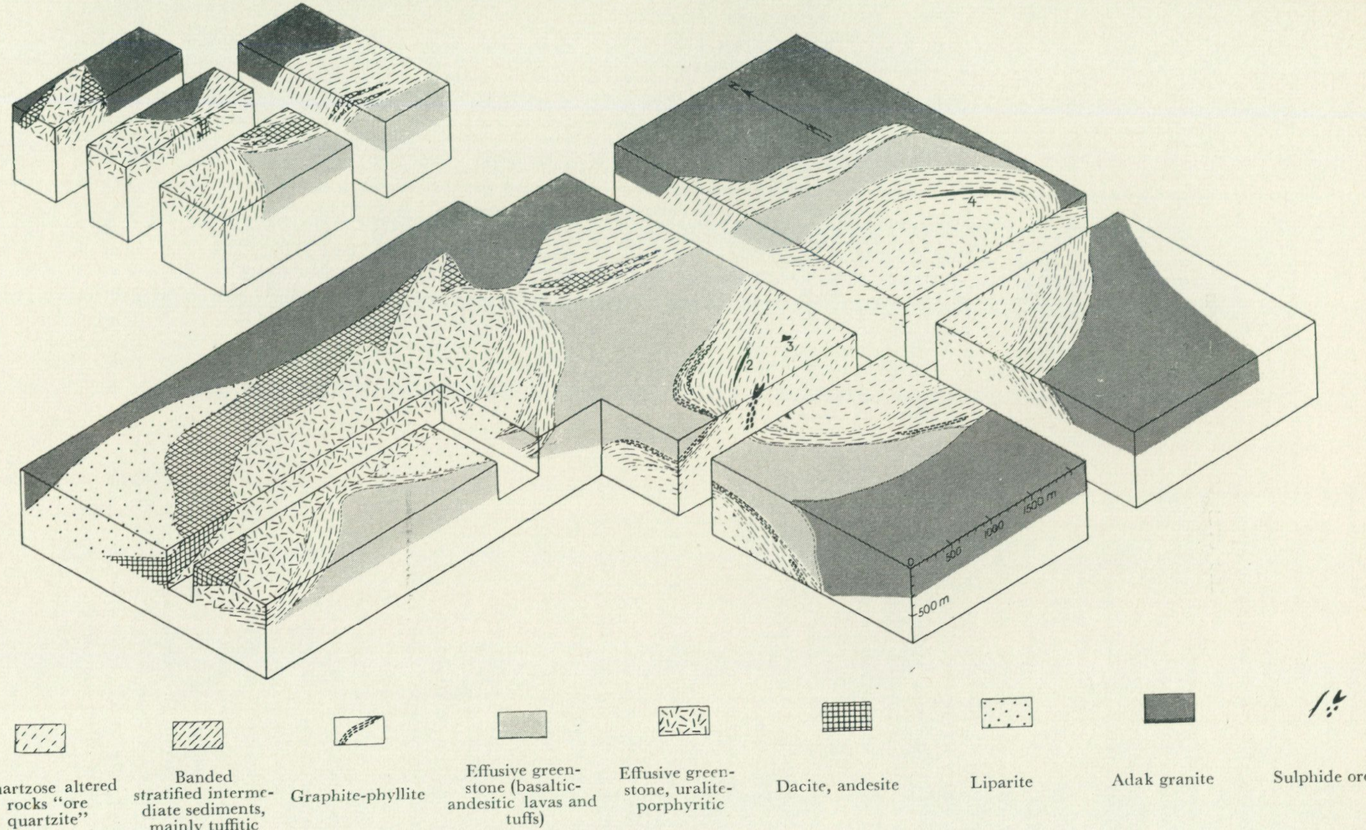


Fig. 5. Block diagram demonstrating the structure of the Adak area. After Gavelin 1955.

cases by chalcopyrite and pyrrhotite, as a rule accompanied by more or less arsenopyrite. Pyrite also occurs in subordinate amounts and then as a rule in parts that are poor in chalcopyrite. The Rudtjebäcken ore is an exception, as it constitutes a compact ore where pyrite is quite predominant, while pyrrhotite, chalcopyrite, and sphalerite appear only in subordinate quantities.

The country rock of the ores consists of "ore-quartzite" containing quartz, cordierite, cummingtonite, micas and sometimes almandite. In some cases the sulphide invasion has been accompanied by a fairly extensive lime-silicate formation.

Two main types of structural development are discernible:

1) The Adak-Karlsson ore where the sulphides constitute impregnations, breccias, networks, and minor concentrations of compact sulphides. In these cases the outlines of the ore bodies will be very irregular and only to a small degree determined by the stratification of the dome.

2) The Lindsköld and the Rudtjebäcken ores constitute pronounced "plate-formed" ore bodies. The ores are localized at the boundary zone between the massive "ore-quartzites" and the overlying banded rocks and the bodies are orientated parallel to the stratification of the dome.

There is assumed to be an intimate genetic relationship between the granites and the formation of the ores. A support for such a view is found in the fact that in a few places pegmatites, which are supposed to belong to the granites, seem to be closely connected with the metamorphic processes leading to the sulphide mineralization.

THE RAKKEJAUR ORE BODY

Rakkejaur has the largest area of ore in the Skellefte District (about 20 000 m^2). The ore body, which is 550 m long and maximum 65 m wide, is known from outcrops, diamond drillings from the surface, drifts into the ore on the 160 m, 240 m and 320 m levels, and from a net of horizontal drill holes from these drifts.

The eastern limit of the vertical dipping ore consists of quartz-porphyry or its tuffaceous equivalent altered to sericite schist and belonging to the Maurliden series in the stratigraphic scheme. The western limit of the ore is a calcareous weathering breccia and a polymict conglomerate with granite pebbles stratigraphically belonging to the basal parts of the Elvaberg Series. These coarser sediments are overlain by slates partly enriched in graphite. The pitch of the ore is about 80° NNW. Fragments of quartzite in the ore are elongated in the same direction.

The ore body consists of a lean pyrite ore with varying contents of zinc, copper and arsenic. In general, the boundary between the pyrite ore and the wall rock is sharp but towards the SSE the ore fans out or grades into an impregnation variety. The ore is seldom compact and contains considerable amounts of material from the bedrock. In the pyrite ore body are some lenses of arsenopyrite. Younger than the pyrite ore is a copper ore containing pyrrhotite, sphalerite, arsenopyrite and tetrahedrite brecciating the bedrock. Youngest of all are dark carbonates often containing sulphominerals such as falkmanite and tetrahedrite.

THE BOLIDEN MINE

(According to O. H. Ödman 1941)

The first indication of the deposit was a glacial ore boulder found in 1921 5 km E of Boliden. After geological and geophysical work the deposit was finally located by electrical prospecting and drilling in 1924. Mining operations started in 1925. Mining methods: open cut down to 90 m level, then cut and fill with pillar retrieving. Deepest level is 570 m. Total output 7.2 mill. metric tons grading 15 ppm Au, 49 ppm Ag, 1.5 % Cu, 7.0 % As, 26 % S. Reserves 0.8 mill. tons. Production in 1959 120 000 tons.

The host rock is composed of acid to intermediate volcanic and sedimentary rocks overlain by phyllites and graywackes. A massif of Revsund granite intrudes the supercrustal rocks a few km south of the mine. The supercrustal rocks are folded and strike approximately E—W and dip steeply S.

The deposit is chiefly made up of two large ore bodies, the Western Ore and Eastern Ore, which have been brought into contact with each other by a fault. They have a total length of about 600 m and a maximum width of about 40 m. Originally the two bodies had an "en échelon" position and overlapped to the right. The deposit is composed of three main types of ore, 1) arsenopyrite ore, 2) lamprophyres with quartz-tourmaline and sulphide ores, and 3) pyrite ore. These represent three stages in the mineralization and were formed in the above order. Each main type is composed of various kinds or ore of varying mineralogical composition. The ores are made up of a large number of minerals and the paragenetic conditions are exceedingly complex.

The development of an independent dragfold in the contact between the volcanic and the sedimentary rocks is of fundamental importance for the ore deposition. It was caused by shearing stress, acting in the direction north-side-west and south-side-east. The axis of the dragfold pitches 50—60° E and this direction has exercised a structural control on the deposition of the ores.

In the dragfold the stress formed suitable channelways for ascending hydrothermal solutions wich brought about an alteration of the bedrock. The process was complicated and began with a thorough sericitization, resulting in the formation of various quartz-sericite schists. Some types also contain pyrite and chlorite. The alteration continued and the next phase was marked by the development of a pure sericite rock. During the third phase the sericite was broken down and andalusite rocks were formed. During the sericitization large amounts of CaO, MgO, and FeO were liberated and they partly migrated into the surrounding fresh rocks where they brought about a recrystallization and a formation of basic plagioclase, hornblende, biotite, etc. The altering solutions are considered to have been hydrothermal and from the beginning weakly acid or alkaline; in the final phase of the alteration the solutions were probably of a decidedly acid nature. The shearing in combination with the alteration produced a schistose bedrock well suited for the formation of channelways, especially as the shearing stress was still acting on the dragfold. The formation of the altered rocks was largely accomplished before the appearance of the ore solutions but it is believed that hydrothermal solutions were also given off during the different stages of ore deposition, thus widening the zone of alteration. Strong sericitization was particularly evident during the second stage but during the third stage, on the other hand, the alteration seems to have been very unimportant.

Along channelways in the schistose rocks the solution of the first, or arsenopyrite stage of mineralization now ascended. The ore bodies formed have the shape of elongate lenses with their long axes pitching steeply to the east, parallel to the axis of the dragfold. The solution of the arsenopyrite ore was presumably fairly concentrated and of a comparatively high temperature and was characterized as pneumotectic. The solution was very complex and contained a large number of metals, gangue-forming oxides, and volatiles. The crystallization began with the formation of various types of arsenopyrite ore in which the main component is arsenopyrite. The remaining solution was partly retained in pores in the arsenopyrite ore but the main part was squeezed out by the stress into fissures in the solidified arsenopyrite ore, forming a breccia. In some places the residual solution was pressed out as apophyses into the wallrock. The arsenopyrite ore is in some places accompanied by separate mineral associations, viz. rutile rock, pyrite-apatite ore, and quartz-plagioclase veins, which are considered to be differentiates of the original ore solution. They sometimes form separate bodies. After the displacement of the ore solution replacement set in and the pneumotectic solution tended to pass over into a hydrothermal solution which replaced the wallrocks.

The second stage was initiated by the intrusion of lamprophyres on fissures formed by a stress with the same direction as that which formed the dragfold and the channelways for the arsenopyrite solution. The lamprophyres are largely altered, mainly by chloritization, and the primary nature of the rocks cannot be ascertained. It can only be said that they were basic dyke rocks. The continued stress formed fissures, partly in the lamprophyres and partly in the surrounding altered rocks and arsenopyrite ore bodies, on which the quartz-tourmaline ore solution was brought in by displacement. Emanations from this solution brought about the chloritization of the lamprophyres and a sericitization of the andalusite rock. During the latter process corundum, diasporite, and kaolin were also formed. The ore solutions contained SiO_2, MgO, Al_2O_3, alkalis, B, F, and other components but only relatively small amounts of metals. Arsenic is comparatively rare. Characteristic components are Bi, Te, and Se, elements which are comparatively rare in the solutions of the first and third stages. Also Cr is a characteristic component of the ore solution; it enters into the hydrothermal mineral mariposite. The ore solution is considered have been fairly concentrated and of a high temperature and has been classed as pneumotectic. Compared with the arsenopyrite solution, the quartz-tourmaline solution contained more gangue-forming components and was heavily loaded with B and H_2O. The ores formed by the solution are chiefly quartz-tourmaline veins and lenses. In some cases quartz is the predominant component, in others tourmaline forms almost the sole constituent. In local concentrations a number of metallic minerals are found, including some rare minerals characteristic of this locality, such as "selenocosalite", "selenokobellite", tellurobismuthite, and tetradymite. One of the tourmaline lenses in its upper portion passes over into a sulphide ore composed of pyrrhotite and chalcopyrite. It forms a sulphide fraction which was squeezed out from the quartz-tourmaline solution. The range of temperature of the solution was exceptionally wide, as high temperature minerals occur side by side with such low-temperature minerals as pyrargyrite.

The last stages are characterized chiefly by the formation of pyrite ores, forming two large ore bodies and a number of smaller ones. The pitch of the Eastern Ore is on the whole parallel to the axis of the dragfold and the pitch of the older ores. The ore bodies contain brecciated lenses of arsenopyrite ore and in some places replaced remnants of wallrock and lamprophyres. The pyrite solution entered the ore zone along several channelways formed by a stress with the same direction as before. The solution was brought in by displacement but replacement is very pronounced at this stage and from the channelways the solutions largely replaced the intervening portions of wallrock, lamprophyres, and bodies of older ore. The replacement resulted in the formation of the two large ore bodies. The ore solution is considered to hava been of a pneumotectic character at the time of the displacement but its strong replacing ability indicates that in some respects it was different to the earlier solutions. It probably changed rapidly to a hydrothermal condition. The crystallization began with the formation of pyrite and some other minerals, the remaining solution being enriched in chalcopyrite, pyrrhotite, and quartz. Part of this solution crystallized as groundmass in the ore but a large part was squeezed out towards the margins of the ore bodies or into the wallrocks, where apophyses were formed. Another fraction of the ore solution formed veins of quartz, plagioclase, and sulphide at the contacts of the ore bodies. Also in the pyrite stage the range of temperature was exceptionally wide as is evident from the appearance of apophyllite, which constitutes the last manifestation of mineralization in the deposit.

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The Varuträsk pegmatite

By

PERCY QUENSEL

The Varuträsk pegmatite is situated 22 km S.E. of the Boliden mine and 15 km from Skellefteå town on the Baltic coast. It is assumed to be genetically connected with the so called Skellefte granite, representing a fine-grained variety of the more widespread Revsund granite.

The pegmatite forms a trough-like to tabular body, striking N.N.E.—S.S.W. In the eastern wing the dip is about 30° W.N.W., whereas the western wing lies all but horizontal. The exposed outcrop is about 350 m in length. The thickness varies from some few meters up to 30 meters, bounded both above and below by an amphibolitic rock (cp. Fig. 6).

The parts of the pegmatite, containing lithium-bearing minerals, are separated in two lenses, intersected by a part, devoid of these minerals. The two lenses lie about 50 m apart.

Four stages in the mineralogical development of the pegmatite can be distinguished. The first, named *the pegmatitic stage,* is taken to represent the original zonal structure of the pegmatite body, formed by fractional crystallisation from the walls inwards. This is assumed to have taken place in a closed system under epimagmatic conditions, *i.e.* above 600°.

The second stage, named *the pneumatogenic stage,* is taken to include all replacement units, succeeding the pegmatitic stage. Subsequent alterations, due to activity of thermal water of hypogene origin, are attributed to a third *hydatogenic stage.* A final development, due to the activity of percolating ground water or to superficial weathering, can be included as *a stage of supergene alterations.*

In the following, the principle minerals, representative for each of these stages will be given.

The pegmatitic stage can be divided into four divisions, the border zone, the wall zone, the intermediate zones and the core, denoting the sequence of fractional consolidation.

The mineral assemblage of the *border zone* is simple and uniform. The only minerals of primary origin are a fine-grained assemblage of quartz and muscovite. This zone seldom attains more than some 10 cm in thickness, often it is less than a few cm thick.

The *wall zone* may vary from some 5 dm to several meters in thickness. In one sense one may say that the border zone and the wall zone co-ordinate, inasmuch as the bulk mineral composition is the same, though the minerals of the wall zone are developed in large individuals. Muscovite can now occur in large silvery white books, up to one dm in width. Additional minerals of this zone are b l a c k t o u r m a l i n e and b e r y l, the former a characteristic mineral of this stage and principally restricted thereto. Beryl crystals up to several dm in length have been found. L ö l l i n g i t e is found in some amount in one locality within the wall zone (between H_2 and K in the centre of the map).

The *intermediate zones* include the zonal development of the pegmatite between the wall zone and the core. At Varuträsk, as is the case in most other complex pegmatites, it forms the greater mass of the pegmatite. A sub-division into two phases can be made, denoted as an outer and an inner intermediate zone. The difference is that the outer zone has a simpler mineral composition than the inner zone.

The difference between the mineral assemblage of the wall zone and the outer intermediate zone is that m i c r o c l i n e p e r t h i t e now enters as the dominant mineral, developed in crystals or anhedral masses of great size. A single crystal measured 3 m in length and was then only partly exposed.

In the inner intermediate zone the mineral assemblage is the same as in the outer zone with the addition of some pronounced lithium-bearing minerals, evidently due to a content of lithium in residual solutions of the pegmatitic stage. The essential minerals in this respect are s p o d u m e n e and amblygonite (m o n t e b r a s i t e), both present in large amounts.

Attention may be called to the considerable amount of rubidium in the microcline perthite. The medium of nine analyses from the eastern wing of the pegmatite gave 1.55 % Rb_2O (maximum 3.3 %). In other respects the outer and inner intermediate zones show no further dissimilarities and grade imperceptibly into each other.

As recorded from many other zonal pegmatites the *core* of the Varuträsk pegmatite is not centrally located but displaced towards the southern foot wall of the eastern wing, where it occupies a lens-formed body, about 50 m in length and 15 m in breadth. The core is almost exclusively composed of pure milky quartz. Though surrounded by mineral assemblages of later replacement units and locally intersected by minerals of the same, the core on the whole shows but insignificant signs of replacement by invading solutions of succeeding phases of mineralisation.

The pneumatogenic stage is used to denote the phases of replacement which followed the zonal consolidation of the pegmatite. Whereas the temperature prevailing during that stage was taken to have exceeded the 600° limit, the replacement units of the pneumatogenic stage are postulated to have taken

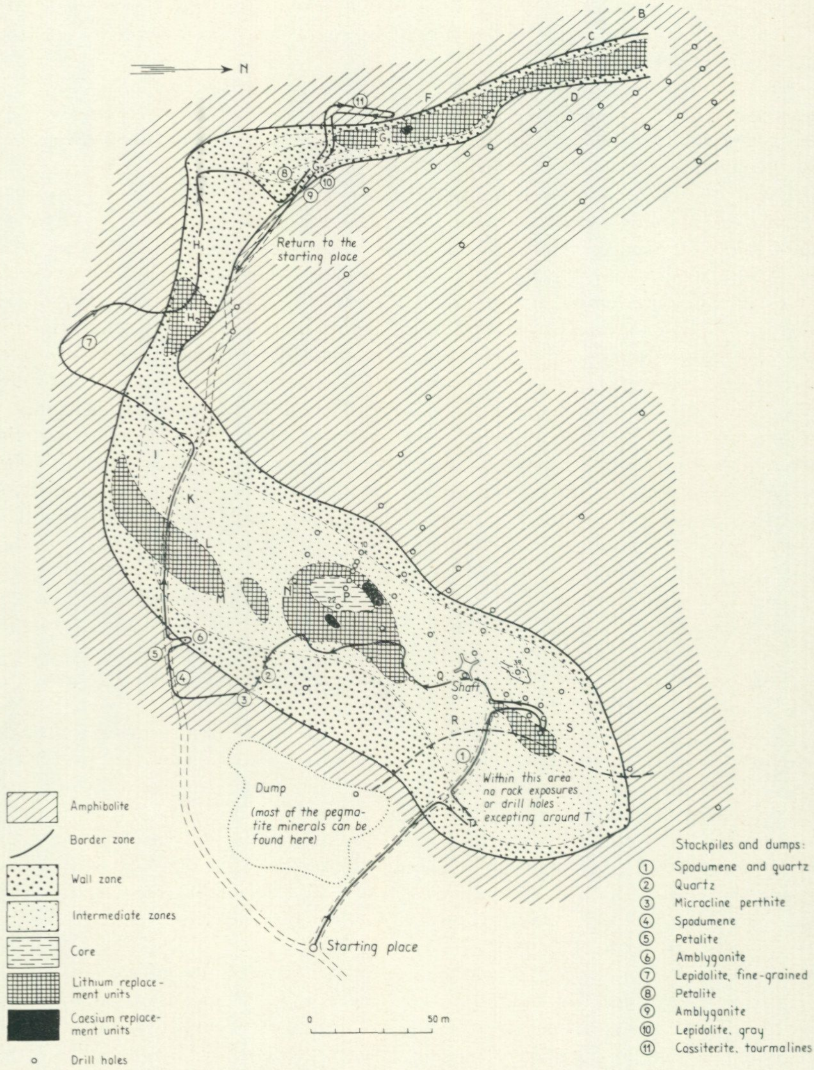


Fig. 6. Geological map of the Varuträsk pegmatite.
För spridning godkänd i Rikets allmänna kartverk den 27 april 1960.

place between this limit and the critical temperatures of the co-operating solutions, *i.e.* between approximately 600° and 400°. This stage has been divided into a higher and a lower temperature phase, each characterized by its own mineral assemblages.

The higher temperature phase has again been sub-divided into two stages, the lithium replacement unit and the caesium replacement unit, each characterized by specific mineral assemblages.

The lithium replacement unit is taken to represent the first epoch of renewed mineralisation after the final consolidation of the pegmatitic stage. The name is, however, only meant to indicate that the main concentration of lithium occurs within this unit, verified by the abundant occurrence of lepidolite, petalite, and a second generation of spodumene.

The greatest concentration of lepidolite is found in the form of a mauve-coloured fine-grained massive rock in the western wing together with some manganapatite (quarry H_2 on the map). Inclusions of pure white beryl with a vitreous lustre and granular texture, very different from the beryl of the pegmatitic stage, can there be found. The lepidolitic rock is in parts speckled with small grains of cassiterite and invaded by cleavelandite, pertaining to replacements of the lower temperature phase of this stage.

Together with lepidolite, petalite is the most abundant mineral of this unit. Though in general of rare occurrence in other lithium pegmatites, it is present in great quantities at Varuträsk.

The third lithium silicate mineral of quantitative importance in this unit is a second generation of spodumene. When now recurring in this unit, it is developed in an obviously different habit. Instead of the tabular masses of the pegmatitic stage, the mineral now occurs in the form of compact slender laths, which when uncontaminated, are semi-translucent. It is not unusual that the spodumene of this unit is highly altered to a mixture of clay minerals (rotten spodumene) which is never found to be the case with the earlier generation of the mineral in the pegmatitic stage.

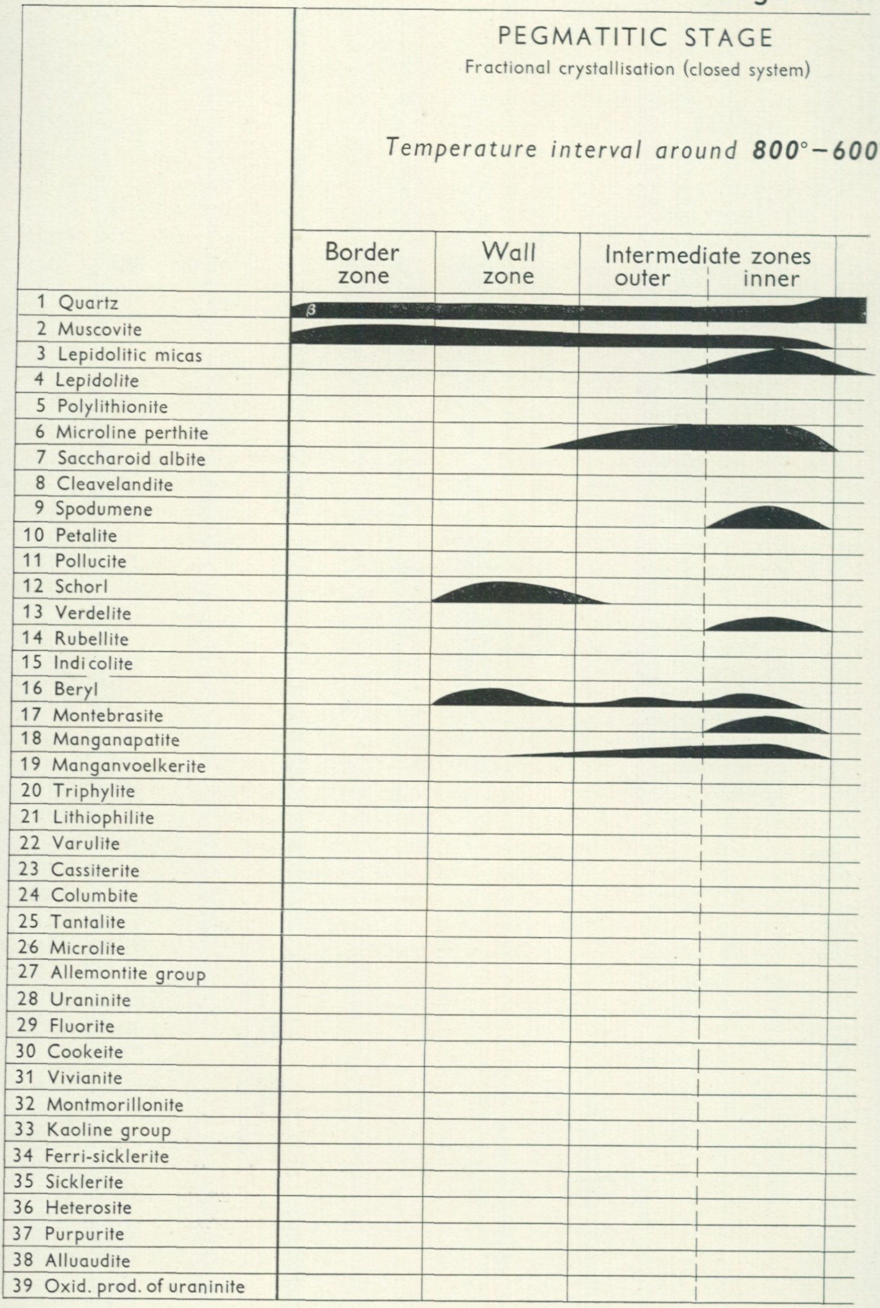
Other minerals of this unit only occur in small quantities. They consist of a second generation of montebrasite, manganapatite, and of green tourmaline. A new type of beryl now is found in the form of small vitreous crystals.

The great masses of pollucite in the Varuträsk pegmatite seem to call for a separate replacement unit within the high temperature phase of the pneumatogenic stage. It seems hardly plausible that solutions of the same phase in some parts of the pegmatite have carried lithium as the main alkali component and close by have deposited great amounts of caesium in the form of the mineral pollucite. The localized distribution of the largest deposit along the core margin likewise seems indicative of new replacement channels. The quartz core has, however, not succumbed to any replacement by the invading solutions of this unit.

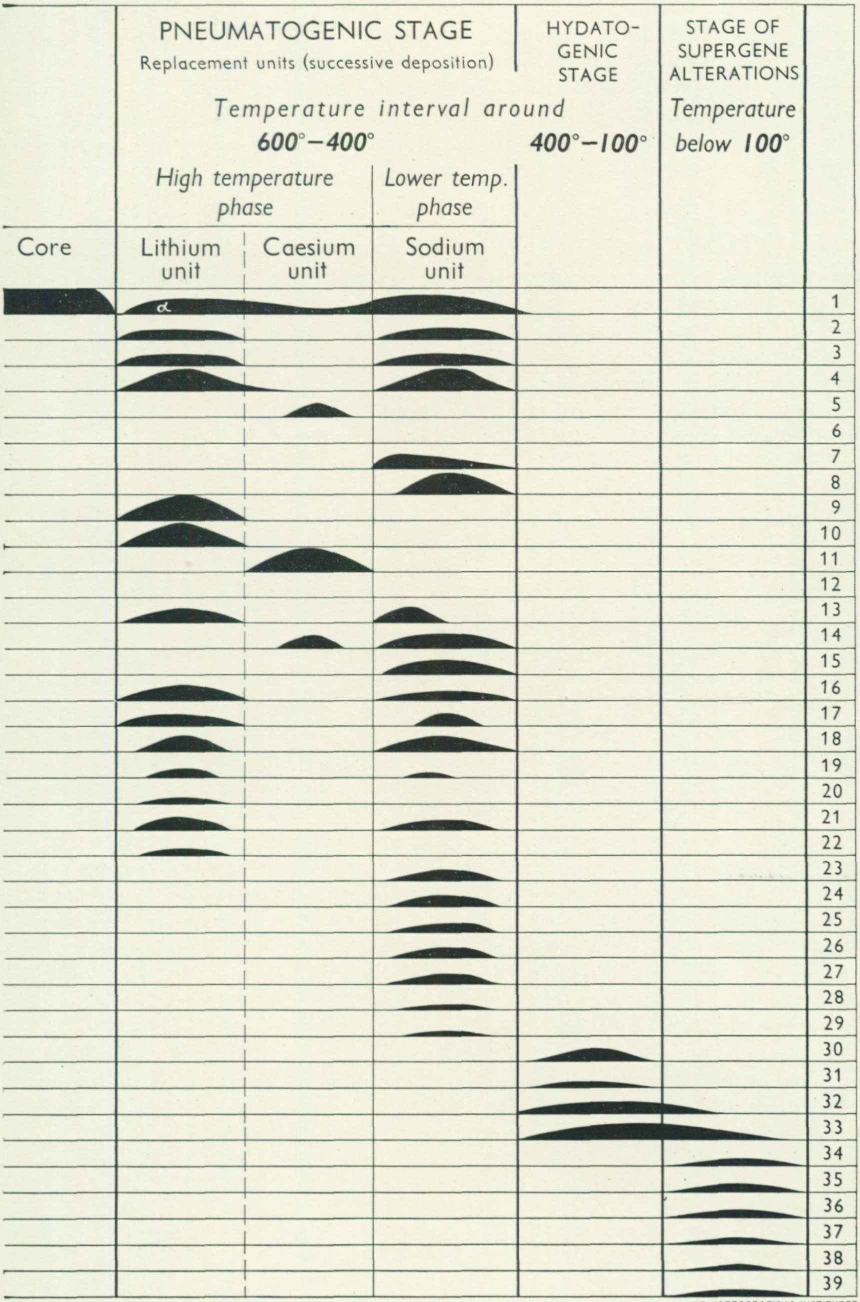
The lower temperature phase of the pneumatogenic stage expressively indicates that a further break in the mineralisation of the pegmatite now occurred. The solutions of this unit are universally found to traverse and replace all earlier mineral assemblages. Furthermore the mineralisation of this unit includes many minerals not before represented in the previous zones or units. With regard to the content of alkalies, sodium now enters as the principle component. As a result thereof the dominant mineral of this unit is an almost pure albite, predominantly in the form of cleavelandite, generally developed in spheroidal bursts or large radiating sheaves. In other parts, principally restricted

Table I

THE VARUTRÄSK
Paragenesis of



PEGMATITE
the minerals



AB KARTOGRAFISKA INSTITUTET

†3—600799

to the peripherical parts of the pegmatite, the mineral can occur in the form of a fine-grained saccharoid albite.

Next in importance of the minerals of this unit are several different modifications of mica minerals. Remarkable are the large purple crystals of lepidolite, up to 2 cm in breadth, principally to be found around a small prospecting pit in the eastern wing (T on the map). Other modifications are a delicately rose-coloured to nearly colourless lepidolite, forming concentric bundles as well as a medium-grained gray lepidolite, found as veins and in accumulated masses. Muscovite recurs, now in the form of a fine-grained rose-coloured species as well as in a cryptocrystalline form (oncosin), often traversing larger masses of pollucite.

The red and blue tourmalines (rubellite and indicolite) are characteristic minerals of this unit. Rubellite is often found in zonal development with the green tourmaline (verdelite). In that case the red type forms the core with an outer green shell. The red core is often completely altered to cookeite or replaced by albite.

Manganapatite recurs in this unit in the same aspect as in previous phases. The rare mineral *manganoan voelckerite* seems, however, to be restricted to this unit, connected with the gray lepidolite. It can easily be distinguished from manganapatite on account of that, on exposed surfaces, it is always found to occupy well-defined cavities, in contrast to manganapatite yielding to weathering.

The Li—Fe and Li—Mn phosphates are represented by the minerals *triphylite* and *lithiophilite*. They are, however, not found coordinated in the field. The natural cause is that triphylite is restricted to such occurrences where iron-containing solutions have circulated, whereas lithiophilite is found in connection with manganese concentration in the replacement units.

Triphylite has been rarely encountered in replacements within the wall zone. The usual occurrence of lithiophilite has on the other hand only been found in a small prospecting excavation (G_1 on the map) together with cleavelandite and its mineral assemblage. It is, however, there mostly altered to sicklerite → purpurite.

It has now been proved that the new mineral varulite itself is an alteration product of lithiophilite in replacements within the wall zone.

In the same small excavation, where lithiophilite was first found (G_1 on the map), many other minerals occur. A third generation of beryl as well as cassiterite are there relatively abundant. The only occurrence of uraninite is this locality. It mostly occurs in minute, generally oxidized crystals. Only one larger specimen has been found.

The rare minerals allemontite and stibiotantalite also belong to this unit, only found in an excavation near G_1. Several large specimens of both these minerals have been disclosed there.

Columbite and tantalite also belong to this unit. Columbite is not uncommon, though generally only found between cleavage planes of cleavelandite. Tantalite was seldom found during earlier stages of mining operations. Later large quantities of the mineral came to light in underground workings around the shaft in the eastern wing of the pegmatite, together with some few specimens of microlite.

Fluorite has only been found in two small vugs. As vugs are in the pegmatite all but absent this may explain the scarcity of fluorite. The want of fluorine in such minerals as montebrasite, voelckerite, and hydroxyl-apatite indicates that at no time during the deposition of the minerals of the pegmatite was there any excess of fluorine present.

The hydatogenic stage is taken to represent all processes, which may be ascribed to the influence of ascending hydrothermal water percolating throughout the consolidated mineral assemblages of the previous stages. During this stage the juvenile water seems not to have introduced new material of any importance. The residual fluids of the preceding stages have apparently concluded the transfer of soluble matter.

The most pronounced feature of the minerals pertaining to this stage is their high content of hydroxyl radicals.

A characteristic mineral of this stage is montmorillonite, mostly found as an alteration product of petalite. The decomposition of the younger generation of spodumene to kaolinite and to other kaolin minerals is also to be referred to this stage. Pollucite has in underground working also been found to have succumbed to an intense alteration to a soft white clay substance.

The alteration of the red core of the zonal tourmaline to cookeite should also be attributed to the thermal activity of this stage as well as to the formation of cookeite in independent depositions. The lower temperature prevailing during this stage would favour the formation of cookeite rather than the less hydrous micas.

The rare mineral mangan-hydroxylapatite, assumed to be a decomposition product of varulite, contains 2.56 % H_2O+ against about 1 % in the host mineral varulite. This would represent a typical example of hydration during the hydatogenic stage.

The stage of supergene decomposition represents an oxidation of selective minerals due to superficial weathering or to the action of phreatic water.

A good example of such processes is the successive oxidation of triphylite, lithiophilite, and varulite. In a first phase the bivalent iron ions in these minerals become trivalent, whereas the manganese ions remain bivalent, resulting in the formation of the minerals ferrian sicklerite—manganoan sicklerite, and manganoan alluaudite. Ultimately both the iron and the manganese ions become trivalent, forming the fully oxidized minerals heterosite and purpurite.

Arsenostibite (arsenian stibionite), an oxidation product of the alloy allemontite, must also be considered as an alteration product of this stage.

There hardly remain any further alteration products, than a frequent incrustation of manganese oxides on minerals containing manganese in their composition or on adjacent minerals. It must, however, be taken into consideration, that glacial erosion may have removed many products of weathering on exposed outcrops, which otherwise might have increased the mineral assemblage of this stage.

Attempts have been made to determine the age of the Varuträsk pegmatite. A determination of the lead isotopes in a specimen of uraninite has given an approximate age of 1.70×10^9. A determination with the Rb/Sr method gave an age of 1.74×10^9. The two determinations tally well within the limits of experimental error. On the other hand a determination on lepidolite with the K/Ar method gave an age of 2.06×10^9 and on the same material with the Rb/Sr method likewise 2.06×10^9. This is a singularly good correspondence, but of some reason probably giving a co-equal too high age.

The approximate age of the pegmatite is taken to be around 1.80×10^9 years, which would correspond with approximate ages, found in equivalent formations in middle Sweden.

In Table I the paragenetic association of the minerals is recapitulated. In Table II a list of the minerals is given in order after Strunz' tables (with the exception of alteration products, placed after their host mineral). Names in spaced types indicate those minerals which can be readily found.

Table II. List of described minerals from the Varuträsk pegmatite, in numerical order after Strunz' tables (with the exception of alteration products, here given after host mineral).

Elements: allemontite, stibarsen (alteration product: arsenostibite).

Sulphides: l ö l l i n g i t e.

Halides: fluorite.

Oxides: q u a r t z, c a s s i t e r i t e, c o l u m b i t e, tantalite, stibiotantalite, microlite, uraninite.

Phosphates: triphylite (alteration products: ferrisicklerite, heterosite), l i t h i o p h i l i t e (alteration products: m a n g a n o s i c k l e r i t e, p u r p u r i t e), varulite (alteration products: alluaudite, purpurite), triplite, amblygonite (var. m o n t e b r a s i t e), m a n g a n a p a t i t e, mangan-hydroxylapatite, mangan-voelckerite, vivianite.

Silicates: b e r y l, tourmaline (green, blue, and red; alteration product in red kernel of zonal tourmaline: cookeite), s p o d u m e n e (alteration product: k a o l i n m i n e r a l s), muscovite (w h i t e and r e d), lepidolite (p i n k - g r a y, and white), cookeite, p e t a l i t e (alteration product: m o n t m o r i l l o n i t e), p o l l u c i t e, albite (c l e a v e l a n d i t e and s a c c h a r o i d), m i c r o c l i n e p e r t h i t e.

The Kalix area

By

E. Åhman

In the Kalix area which is topographically flat occur flat-lying sediments and basic volcanics alternating rapidly with each other. The latter are dominant in the lower parts of the formation. Contacts with the underlying 'basement' are not exposed. Above the volcanics carbonate rocks occur and associated with these are sandstones and shales with occasional volcanic horizons. These are succeeded by a transitional zone consisting of a thick succession of mixed pelitic sediments. The volcanic horizons are noticeable throughout the whole formation which is folded about flat-lying fold axes orientated NE—SW. The metamorphic grade is relatively low.

The volcanics are developed both as lavas and tuffs. Amongst the first may be noted pillow lavas but also lavas with amygdaloidal texture and fine-grained greenstones. Graded and banded tuffs frequently alternate with layers of lava. Transitions from tuff to schist appear sometimes as well as quartzitic deposits in the tuffs. In these occur thin carbonate horizons at many places which have been disrupted by thrusting and now occur as long narrow lenses parallel to the lamination of the tuffs.

The carbonate rocks are made up partly of limestone and partly of dolomite. They are fine-grained and yellowish white in colour. Within the volcanics thin limestones often occur as alternations between tuff and limestone. The dolomitic limestone is partly exposed for more than 30 km in the coastal district. In this dolomitic limestone occur cabbageshaped lime algae which locally, as for example on Vitgrundet, are developed in giant forms. The shales are represented by phyllites and mica-schists with occasionally significant amounts of graphite and pyrite. Sometimes they are beautifully banded and show 'seasonal banding'.

Quartzitic sediments occur together with the limestones in a poorly exposed area in the easterly part of the formation which there has the character of a jasper quartzite.

The rocks of the Kalix Series are cut by granite dykes in peripheral areas. Otherwise occur only a few dykes of red porphyry and kimberlite. This unusual dyke rock is known in Norrbotten only in the Luleå—Kalix skerry area (= skärgård) and a few isolated localities NW of Kalix. These ultra-basic dykes have in general a N—S strike and number about 50. On V. Gräddmanhällan occur blocks of kimberlite breccia probably deriving from the NW.

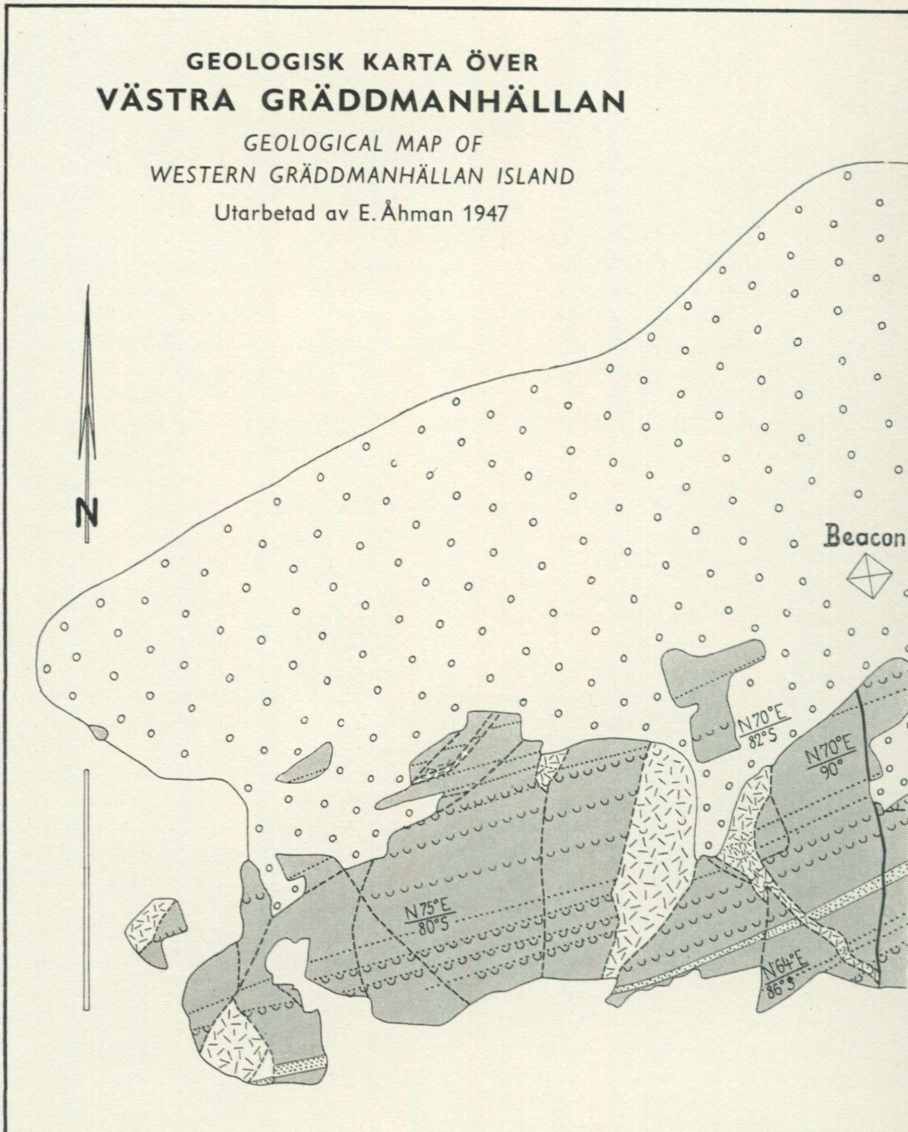
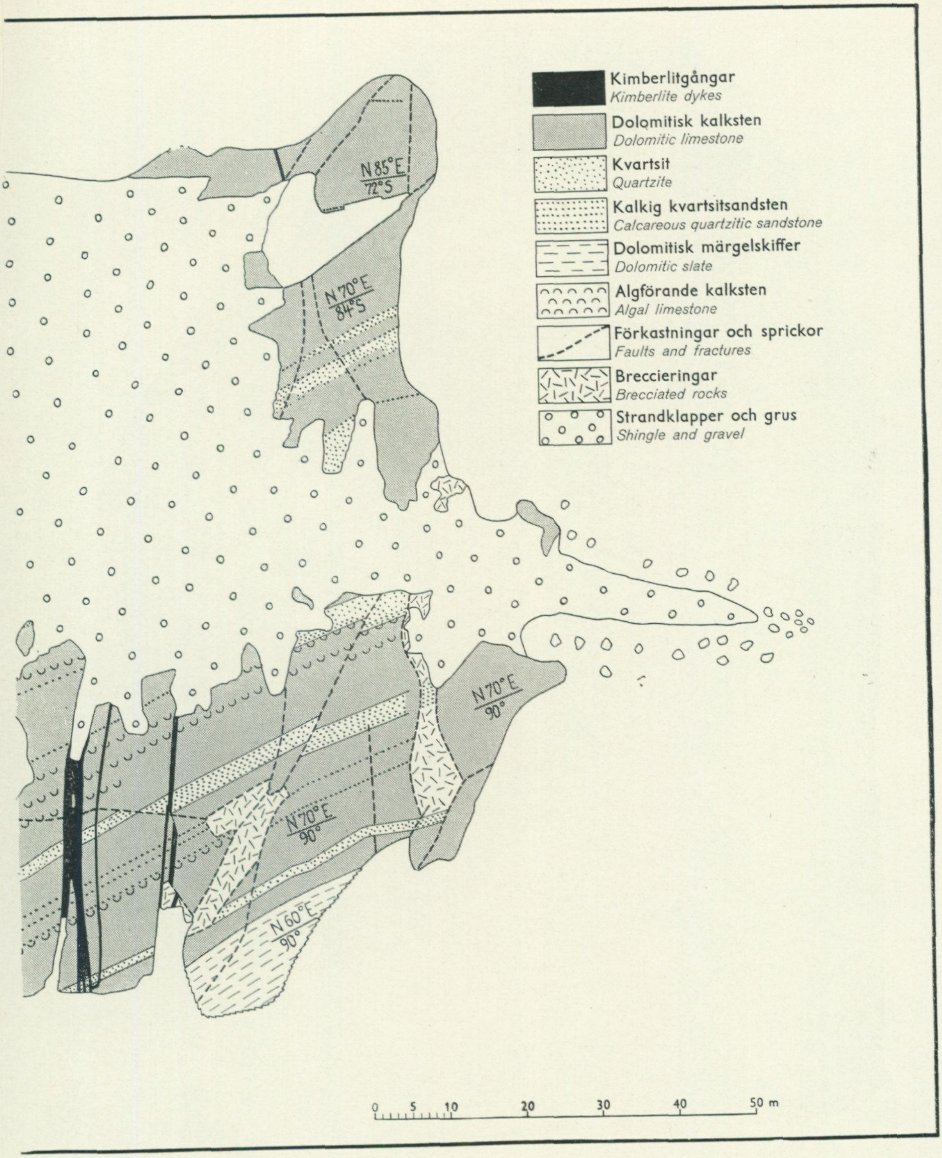


Fig. 7. För spridning godkänd i Rikets



allmänna kartverk den 13 september 1957.

Fig. 8. Algal structures in dolomite. Nat. size.

Brief description of the Pre-Cambrian of Norrbotten

By

R. Frietsch

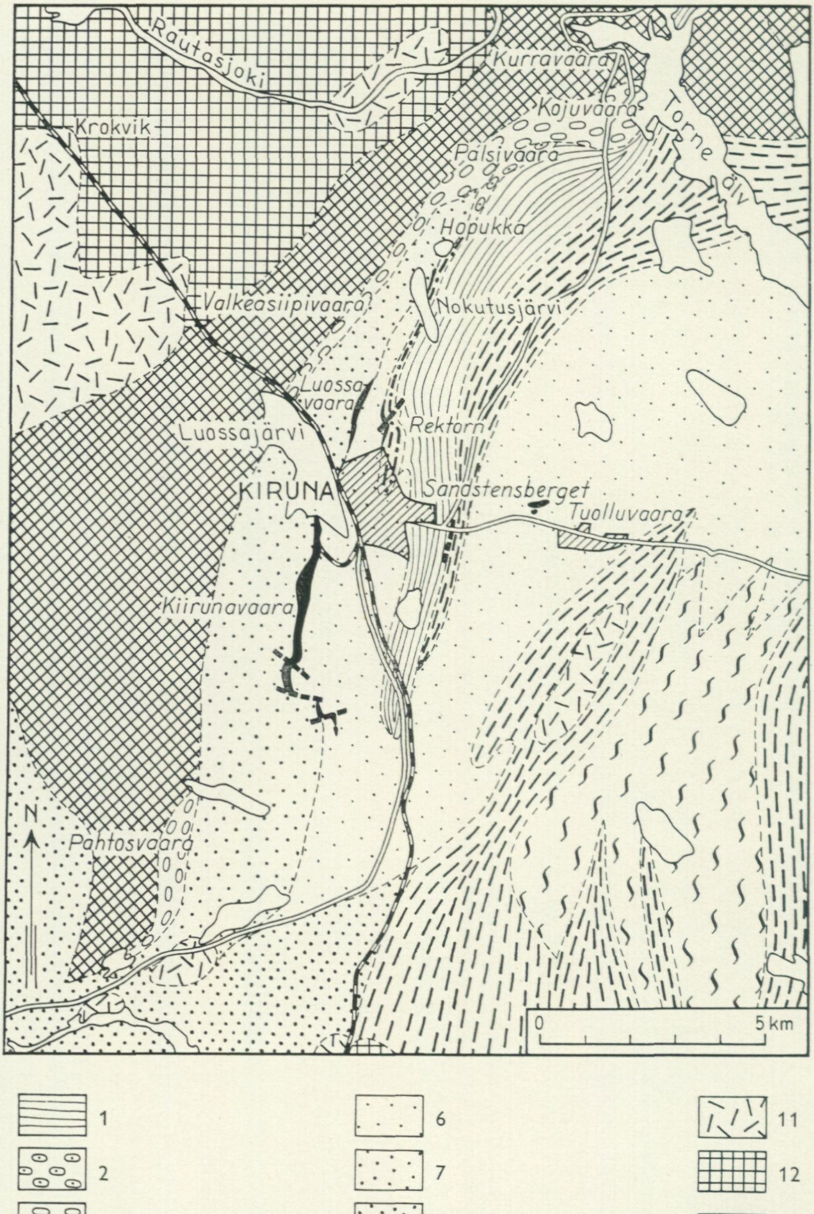
The Pre-Cambrian of the county of Norrbotten in northernmost Sweden is divided into two major cycles, an older, Svionian cycle and a younger, Karelian cycle. In both, two series of supracrustal rocks and two series of intrusive rocks occur according to the most recent interpretation (Ödman 1957).

Rocks of post-Pre-Cambrian age occur in the west and belong to the Caledonian mountain chain. They have Eocambrian, Cambrian and Silurian representatives. WSW of Kiruna a small area of tillite occurs which is probably Eocambrian in age, whilst in the Kalix and Luleå archipelago kimberlite dykes of post-Archaean age occur.

The table below gives in schematic form the geological history of Norrbotten:

<table>
<tr><td rowspan="4">KARELIAN CYCLE</td><td>Migmatite granite (Lina granite):
Simple granite with pegmatite and aplite

Folding and migmatisation</td><td>Syenite
Perthite granite
Sorsele granite
Edefors granite
Gabbro</td><td>transitions between more basic and acid types, are not accompanied by pegmatite and aplite</td></tr>
<tr><td>Bälinge Conglomerate</td><td colspan="2">Porphyrite</td></tr>
<tr><td colspan="3">Haparanda granite: a differentiated series gabbro-diorite-granodiorite-granite
Folding and intrusion</td></tr>
<tr><td>Vakko Series: conglomerate, quartzitic sandstones, phyllites</td><td colspan="2">Pajala-Kalix Series: basic volcanics, grey or black schists, limestones, jasper quartzites, sedimentary iron ores, quartzites, conglomerate</td></tr>
<tr><td></td><td colspan="3">Hiatus</td></tr>
<tr><td rowspan="4">SVIONIAN CYCLE</td><td colspan="3">Revsund granite: simple granite with pegmatite and aplite
Folding and migmatisation</td></tr>
<tr><td colspan="3">Pite Conglomerate</td></tr>
<tr><td colspan="3">Arvidsjaur granite: a differentiated series gabbro-diorite-granodiorite-granite
Granite N of Kiruna
Quartz-diorite at Ultevis
Folding and intrusion</td></tr>
<tr><td colspan="3">Porphyry-leptite formation: basic-acid lavas
pyroclastic rocks
schists in the south
quartzitic sediments at Ultevis</td></tr>
</table>



Rautasjoki
Kurravaara
Kojuvaara
Torne älv
Krokvik
Pålsivaara
Hopukka
Valkeasiipivaara
Nokutusjärvi
Luossa vaara
Rektorn
Luossajärvi
KIRUNA
Sandstensberget
Tuolluvaara
Kiirunavaara
N
Pahtosvaara
0
5 km
1
2
3
4
5
6
7
8
9
10
11
12
13
14

The oldest member of the Svionian cycle is the **porphyry-leptite formation**, which consists for the most part of volcanic rocks. Besides porphyry and leptite[1] occur pyroclastic rocks of different types, sediments and limestone. Certain pelitic schists in the southern part of Norrbotten are also included in the Svionian and represent a direct continuation with the Skellefte field.

This member has its distribution in the southern part of Norrbotten in the Arvidsjaur region from where it extends northwards in a disconnected fashion towards Gällivare and Kiruna.

In the Arvidsjaur field occurs a richly differentiated series of lavas whose oldest member consists of basic lava and the youngest of more acid types. The lavas are succeeded by tuffs which are quantitatively subordinate.

In the Ultevis area W of Jokkmokk the supracrustal series is divided into 3 parts. The lowest of these consists of acid lavas with intercalations of basic lava. These are overlain by a thick series of quartzitic sediments and basic lava. Uppermost occurs a series of acid lavas.

In the area around Gällivare and Kiruna on the other hand rapid alteration occurs between basic and acid members. The volcanics here display throughout a higher grade of alteration and are now developed as leptites or leptitic gneisses. For the Kiruna area itself (Fig. 9) the following stratigraphy can be distinguished: further west occur effusive greenstones of spilitic composition and often with pillow structures. These are the so-called Kiruna greenstones. The greenstones are succeeded by the Kurravaara conglomerate which is a clastic sediment consisting for the most part of conglomerate but with some pebble-free, greywacke-like layers. The pebble material consists exclusively of acid extrusive rocks, particularly albitophyres and syenite porphyries. East of these rocks appears a thick series of lava rocks in which the iron-ores of Kiirunavaara and Luossavaara occur. The ores are underlain by a thick bed of syenite porphyry which passes into a fine-grained syenite downwards. The hanging wall of the ore bodies is formed by quartz-bearing porphyry which may even be interpreted as an effusive rock formed of several lava flows. East of these porphyries occur strongly schistose and sericite altered lava rocks known collectively as the Lower Hauki Series.

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[1] Leptite is a fine-grained, recrystallized, equigranular, metamorphic rock consisting for the most part of quartz and feldspar together with minor amounts of dark minerals. When the grain size is medium to coarse the rock is termed leptitic gneiss. The term was originally used for acid, volcanic rocks in the iron-bearing formation of Central Sweden but the term is now often used for intermediate to basic lavas and tuffs.

Fig. 9. Geological map of the Kiruna region.

1. Vakko series
2. Palsivaara conglomerate
3. Kurravaara conglomerate
4. Basic volcanics
5. Lower Hauki series
6. Quartz-bearing porphyry
7. Syenite-porphyry and syenite
8. Intermediate-basic lavas
9. Gneissose acid lavas
10. Gneissose basic volcanics
11. Lina granite and syenite
12. Gabbro
13. Iron ore
14. Fault

According to older interpretations (Geijer 1910, Sundius 1915) a monocline occurs in the Kiruna area, its limb dipping steeply eastwards and younger beds occurring in that direction. The whole series of rocks mentioned above were included in the porphyry-leptite formation. New investigations (Ödman 1957) suggest that the Kiruna greenstones and Kurravaara conglomerate belong to the younger Karelian cycle. The reassignment is based on the rock association in the greenstones and the composition of the pebbles of the Kurravaara conglomerate.

The Svecofennian folding which strongly affects the Skellefte area has only left weak traces of its first phase in the southern parts of the Arvidsjaur field. Over large areas, however, the Svionian rocks have been strongly affected by the later Karelian folding and in the process have been strongly metamorphosed.

In connection with the first Svecofennian folding appeared the A r v i d s j a u r g r a n i t e s. These consist of a well differentiated series ranging from gabbro-diorite-granodiorite to acid quartz-plagioclase microcline granites in the Arvidsjaur area. Within this area the distribution of the granite coincides in general with the volcanics and the granite differentiates seem to have chemical and petrographic equivalents amongst the different lavas. The Arvidsjaur granite is red and medium-grained consisting of quartz, albite, microcline, or microcline perthite together with less amounts of hornblende and biotite.

To the above-mentioned group can even the quartz diorite at Ultevis be assigned as well as the granites north of Kiruna. The latter are dominated by a grey porphyritic type which is made up of oligoclase, microcline, quartz and biotite.

Common for all the granites in this group is that none are accompanied by pegmatite or aplite.

Scattered over the southern and central parts of the county occur Svionian sediments younger than the above mentioned granites. To these belong the polymict P i t e c o n g l o m e r a t e which contains pebbles of basic and acid volcanics together with a grey granite most probably belonging to the Arvidsjaur suite. On the other hand pebbles of the Revsund granite and its migmatitic representatives are lacking. The conglomerate is intruded by the early Karelian Haparanda granite.

The last episode in the Svionian cycle is indicated by a strong folding during which the R e v s u n d g r a n i t e and its m i g m a t i c r e p r e s e n t a t i v e s were formed. These rocks are confined to the southern part of Norrbotten. Rocks affected by the late Svionian migmatisation are for the most part pelitic schists of the Skellefte type. All transitions from well preserved schists through gneissic schists to migmatites occur. The Revsund granite is confined to these rocks in which it can sometimes be seen how the gneissic schists pass into coarse grained Revsund granite by the growth of microcline augen. The Revsund granite originating by this process of granitisation is composed of microcline perthite, oligoclase and quartz. Minor amounts of biotite and hornblende occur. Both pegmatites and aplites are also found.

North of Kiruna occur small areas of late Svionian gneiss in which both sediments and volcanics have become involved in the migmatisation.

The oldest member of the Karelian cycle consists of a supracrustal group which includes the V a k k o- and P a j a l a - K a l i x Series. The Vakko Series is largely made up of sediments dominated by coarse conglomerate, quartzite sandstone and phyllite. Rocks of this series often rest on older rocks as is the case east of the porphyry-leptite formation near Kiruna. Here the Vakko Series begins with a basal conglomerate containing pebbles of quartz-bearing porphyry, apatitic iron-ore and rocks belonging to the Lower Hauki Series. In the area north of Kiruna, in the Vakkojärvi and Kovo zones, the series is made up of a basal conglomerate with pebbles of the underlying granite, succeeded by sandstone, phyllite and quartzitic sandstone.

The Pajala-Kalix Series is found at scattered localities from the Finnish border in the east where it is directly continuous with the Karelian rocks of Finland, to the Kiruna area in the west. It is also known from the southern part of Norrbotten along the coast of the Bothnian Gulf. No uniform stratigraphy for this series can be discerned but it shows a special association of rocks and correlation between different areas rests for the most part on this fact. The series is composed mainly of basic volcanics which often are in the form of pillow lavas and amygdaloidal; grey and black schists, carbonate rocks, jasper quartzites, conglomerate and quartzite. Together with the jasper quartzites occur bedded iron-ores of undisputed sedimentary origin. Even skarn iron-ores are present in this series. At some localities the series rests on a basement of porphyry-leptite.

The stratigraphic status of the Vakko Series is still not clear. In a number of places it lies directly upon Svionian rocks, at others, where the contact relationship to surrounding rocks is unknown, it contains pebbles of the porphyry-leptite formation. At several places it is overlain by volcanics belonging to the Pajala-Kalix Series. At others basic volcanics are found low down in the Vakko Series. Its relation to the youngest granite in the county, the Lina granite, is only known at Hippainen, SW of Svappavaara. Here the Vakko sediments are intruded and metamorphosed by the granite.

The Haparanda granite was intruded during the first phase of Karelian folding. It is represented by a richly differentiated suite of intrusives. These granites are identical in petrographic aspects with the basic and intermediate members of the Arvidsjaur granite series which is early Svionian in age. The Haparanda granites are limited mainly to areas with rocks belonging to the Pajala-Kalix Series. At a few localities it can be determined that the Haparanda granites post-date the supracrustal rocks belonging to the Pajala-Kalix Series. In general the granite is well preserved with a massive structure. Locally, however, it is gneissose in varying degree and affected by the younger late-Karelian granite. The most common type of the Haparanda granite Series is a granodiorite containing oligoclase-andesine, quartz, microcline, biotite and hornblende. The Haparanda granite is not accompanied by pegmatite or aplite.

The intrusion of the Haparanda granite Series was followed by a period of erosion involving the early Karelian mountain chain. Even the Haparanda granite was exposed and now occurs as pebbles along with Svionian and Karelian supracrustal rocks in the so-called Bälinge conglomerate. This conglomerate occurs at a number of small scattered localities in the southern part of Norrbotten. North of Boden near the Råneå river a porphyrite with quite a wide distribution seems to be about the same age.

Towards the end of the Karelian cycle strong folding and depression affected almost the whole of Norrbotten. Only certain areas farthest south remained unaffected by these processes. Both Svionian and Karelian rocks were involved. In connection with the folding migmatisation and granite intrusion took place. The late-Karelian deep-seated rocks are from the point of view of area most important in Norrbotten occurring almost everywhere.

Following the latest interpretation (Ödman 1957) the deep-seated Karelian intrusives can be divided into two groups, namely the migmatite granites to which the Lina granite, among others, belongs and the syenite series of rocks including syenite, perthite granite, Sorsele granite and Edefors granite.

The migmatite granite series is mainly found in connection with the veined gneiss areas and is made up of acid, quartz-alkali feldspar rich and undifferentiated granites, which are accompanied by pegmatites and aplites. This series includes several types of which the Lina granite has the widest distribution. The granites are red, medium to coarse grained and made up of albite-oligoclase, microcline and quartz. Dark minerals are subordinate. These granites show intrusive contacts at many places but in other cases the granites are developed from gneisses by granitisation in situ. These granites are clearly the youngest intrusives in the Pre-Cambrian of Norrbotten.

The syenite series constitutes a well defined province whose different members are connected by transitional types. This series which includes perthitic syenites, quartz-perthite syenites and perthite granite is not related to any migmatisation and is unaccompanied by pegmatite or aplite suites. It occurs outside the highly orogenic Karelian zones. The rocks are massive and lack any directional feature. Rapid alternations in mineralogical composition are the main features of this series. Transitional forms from a quartz-free plagioclase-perthite syenite through a quartz-syenite member to a true granite occur. Closely associated with the syenites are found gabbros, sometimes penetrated by syenitic dykes, sometimes gradual transitions between the rocks are seen. To the syenite series may be included the Sorsele granite in the SW part of Norrbotten. This shows a significant variation including quartz-syenite, syenite and gabbro besides normal granite. Also included in this series is the Edefors granite which is hornblende- and occasionally pyroxene-bearing but passes into quartz-syenitic and syenitic forms.

The perthite granite is a red, medium-grained rock whose main components are perthite consisting of microcline and albite in about equal amounts, and quartz. Dark minerals are virtually absent.

The syenites consist of brown or reddish-brown medium-grained rocks which are composed of albite-oligoclase, microcline, biotite and hornblende: sometimes pyroxene also occurs. The plagioclase rarely occurs as separate grains but is commonly associated with microcline as a perthite.

According to Geijer's (1931) interpretation the syenite series belongs to the older pre-Karelian sequence in the Pre-Cambrian. Geijer bases his argument on the fact that a clear relationship is evident between the Svionian volcanics and the rocks of the syenite series. This concerns the chemical composition as well as certain characteristic details. Ödman's arguments for assigning the series to the Karelian are that both the syenites as well as the perthitic granites cut early Karelian supracrustal rocks, and, furthermore, that all transitions between syenite, perthite granite and Lina granite occur. The petrographic and spatial relationship of the syenite series and the Svionian volcanics is explained by

Ödman by saying that the latter subsided as rigid blocks and the rocks of the syenite series were formed by palingenic processes.

In the area along the Finnish border from the Bothnian Gulf northwards, an ill-defined belt of late Karelian migmatites occurs. The primary material was for the most part Karelian rocks of supracrustal and intrusive type. Occasionally a gradual increase in the grade of metamorphism can be traced in the field from fresh rocks to strongly migmatized types. Within some areas amphibolites dominate and these have been interpreted as originally basic volcanics of the Pajala-Kalix Series.

As a rule these rocks developed as migmatites with veins of quartz and feldspar (microcline and albite-oligoclase) containing also biotite and muscovite together with amphibole and pyroxene in basic members. In certain areas no quartz-feldspar additions have taken place and the Karelian supracrustal rocks are preserved as gneisses.

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The Kiruna iron ores

by

Per Geijer

General geological setting

The iron ore deposits at Kiruna, like those at Gällivare, Tuolluvaara, and a number of other places in the same region, occur in a supracrustal formation, almost entirely made up of volcanics, which forms the oldest section of the Precambrian in these parts and probably is to be correlated with the Svecofennian (Svionian) of Central Sweden.

The huge ore body of Kiirunavaara and the much smaller "twin deposit" of Luossavaara form sheet-like bodies between a foot-wall unit of syenite-porphyry and a hanging-wall of a quartz-bearing porphyry. North of Luossavaara the foot-wall unit is found to rest upon a sequence of spilitic extrusives ("Kiruna greenstones"), conformably capped by the Kurravaara conglomerate, whose pebbles are predominantly of volcanic rocks. Earlier studies (Lundbohm 1910, Sundius 1915) resulted in the view that there was present here the primary substratum of the ore-bearing porphyries, these forming with the Kiruna greenstones a co-magmatic volcanic sequence. But recent regional work (Ödman 1957) has given strong reasons for correlating the greenstones and the conglomerate with the Pajala series, wide-spread in the surrounding country, which is referred to a later Precambrian cycle, the Karelian. The present relative position of the rock units, therefore, should be due to structural disturbances. Scarcity of exposures makes it impossible to obtain definite proofs for this correlation. But, in any case, no conclusions as to the magmatic development of the ore-bearing rocks can now be based on the assumption that the Kiruna greenstones formed an earlier phase of the same volcanic activity.

On top of the hanging-wall unit follows the Lower Hauki complex, a series of rather highly altered flows and silicified rocks, most of the latter probably being altered tuffs. The hydrothermal action that has befallen this unit has also produced in it a great number of small deposits of siliceous hematite ore. On very long stretches of the contact between the hanging-wall unit and the Lower Hauki there is a body of iron ore very rich in apatite, mostly narrow but expanding to greater width e.g. as the Rektor ore body on the slope of Luossavaara.

Above the Lower Hauki, again, there follow the sediments of the Vakko series (earlier known as "the Upper Hauki complex"), in part resting normally upon the older rocks with a moderate angular unconformity and a basal conglomerate of local material, but in part thrust over them along flatly eastward-dipping slip planes. The Vakko series is referred to the Karelian cycle.

The general strike direction in the district is slightly E. of N., turning more to the N. E. north of the ore mountains. The dip of all units is eastwards, about 50°—60° in the southern part (Kiirunavaara), steeper in the north and northeast.

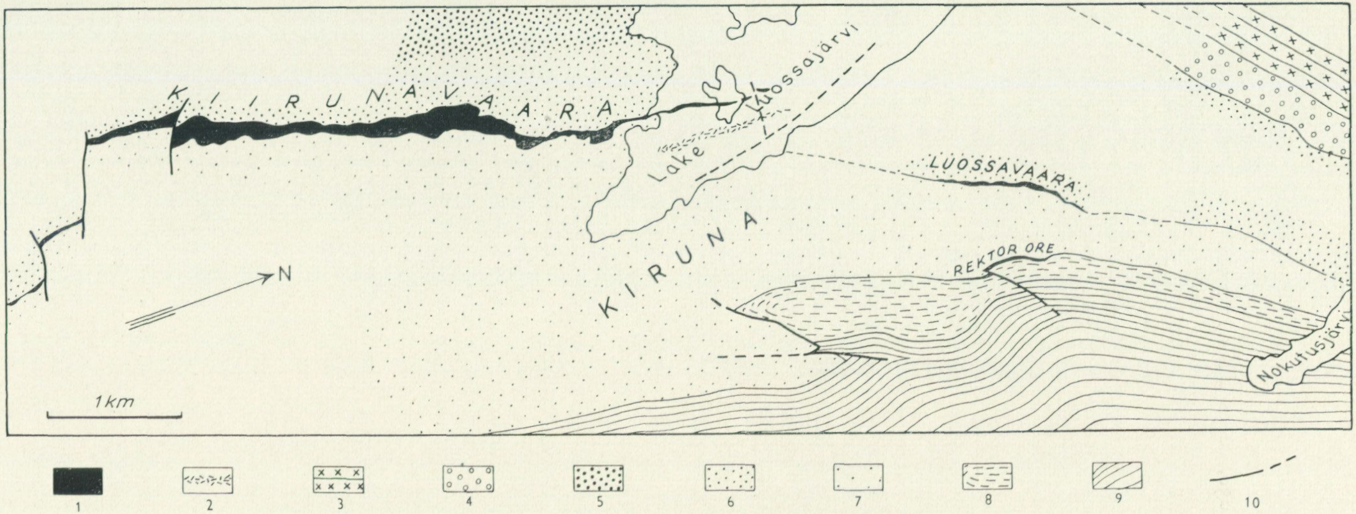


Fig. 10. Sketch map of the surroundings of the iron-ore deposits at Kiruna.

1. Iron ore
2. Zone with ore veins ("ore breccia")
3. "Kiruna greenstones"
4. Kurravaara conglomerate
5. Syenite
6. Syenite-porphyry
7. Quartz-bearing porphyry
8. Lower Hauki complex
9. Vakko sedimentary series
10. Fault

Conditions of field study

Before mining started (in 1903) the ore mountains illustrated very clearly the resistance that the hard ore had offered to erosion. The Kiirunavaara ore body formed a mostly bare ridge, culminating in a top 248 m above the level of Lake Luossajärvi, with the wall rocks sloping away on either side. The slight Post-Glacial weathering had brought out, in the ore outcrop, almost every detail in the relative distribution of magnetite and apatite. The much narrower Luossavaara ore was little exposed, and the ore mountain is roughly circular in outline, but its maximum height was only 20 m less than that of Kiirunavaara. The foot-wall unit was well exposed in outcrops on the northern part of Kiirunavaara, less so on the sister mountain, but again better N. E. of it. On the hanging-wall, outcrops were rather common, except on Kiirunavaara at greater distances from the ore body. Stripping of ore boundaries, etc., furnished new exposures. This was the general situation during the first decade of the present century, when most of the geological work was done on which present knowledge of the district rests, and still at the time of the visit by the international geological congress in 1910. The great progress of mining since that time, and the deep diamond drilling that was carried out in 1914—1923, have given much additional information. On the other hand, outcrops have largely become covered by dumps, and the instructive weathered ore surface has completely disappeared, the only rests being found in collections.

The foot-wall unit

On Kiirunavaara, this unit is known from the ore contact westwards for a distance corresponding to a thickness of about 700 m. Further W., beyond the foot of the mountain, extends a vast area of boggy ground with no exposures whatever. The lower part of the unit is developed as a fine- to medium-grained syenite with feldspars about 5 mm in length in the coarsest variety. The feldspar is a microperthite with the albite component predominating. Further there generally are diopside, magnetite, titanite, zircon. A remarkable textural feature is that the titanite has been the last mineral to form, in part through reactions with apatite. The chemical composition may be summarily illustrated by giving normative figures from two analyses:

	I	II
Q	0.42	2.77
Or	12.86	19.57
Ab	53.21	52.15
An	4.18	3.90
P	11.10	11.63
M	17.04	9.52
A	0.93	?

Upwards the syenite changes into forms in which feldspars a few mm in length stand out as phenocrysts against a more fine-grained groundmass, and these in turn grade into the porphyries that make up the upper part of the unit, a thickness of about 350 to 470 m. All transitions are gradual, but there is no regular gradient in the change in grain size.

Of porphyries there are two main types. One is a grey rock with tabular feldspar phenocrysts, generally not numerous. Its groundmass is made up chiefly of feldspars in broad laths mostly about 0.1 mm in length and arranged at random; also its other constituents are the same as in the syenite, and the bulk composition is like that of the latter. It may be noted that texture and grain size are comparable to those of proved extrusives of a syenitic composition, as the rhomben porphyries of the Oslo region. Sometimes there appear in this porphyry vesicle fillings of one or several of the minerals actinolitic hornblende, magnetite, apatite, titanite. These nodules are surrounded by a narrow, light-coloured halo. Through increasing frequence of such bodies a transition is effected to a rock in which they may make up even half the volume; then the haloes have coalesced and the rock mass, apart from the nodules, consists only of feldspars and is pink-coloured throughout. While the nodules often have the character of typical vesicle fillings, in other cases they are less distinctly set off from the groundmass ("embryonal nodules"). In bulk composition there is no general difference between rocks with or without nodules, showing that the latter have been formed as local concentrations in the crystallizing eruptive, but in varieties very rich in nodules there must have been at one stage an excess of the nodule-forming substances.

The scant exposures on Luossavaara indicate the same general characters of the porphyries. The deeper portions of the unit are concealed by drift, and it is therefore uncertain whether any more coarse-grained, syenitic phase occurs there. More numerous outcrops further N. E. show similar porphyries but also a peculiar variety that has been called magnetite-syenite-porphyry. It consists of albite and about 30 percent magnetite, in a fine-grained texture, the magnetite occupying the interstices between laths of albite. Nodules occur here, too, but consist of albite. In this part of the district, the foot-wall unit is exposed to a (calculated) depth of about 200 m from the contact with the hanging-wall unit. Further W. N. W. there is a covered gap, about 400 m wide, and then, along the contact with the Kurravaara conglomerate, a narrow belt with outcrops of porphyritic rocks conforming in a general way to types of the foot-wall unit.

The characters of the foot-wall unit on Kiirunavaara, as here described, show that, in this part at least, it is a continuous igneous body. It is unlikely that it ever formed a surface flow of anything approaching ordinary character. Probably it represents an outflow where the roof had collapsed over a comparatively wide area, rather than one from a fissure or a crater vent. Its extrusive nature is, in any case, evident from the general rock relations in the district, and from the depth to which surface textures go down in it. For reasons already given it cannot be ascertained whether the more northern parts of the unit are similarly built.

The hanging-wall unit

The thickness of this unit is greatest in the south, on Kiirunavaara and eastwards, where it may perhaps surpass 1 200 m. The probability of some amount of faulting, and uncertainty about the actual dip in the eastern part, preclude a more precise estimate. On Luossavaara, again, it is about 400 m, and northeastwards from there it gradually decreases further. The whole of this unit is, in spite of local variations, homogeneous with regard to the general nature of the rock. This is a porphyry with feldspar phenocrysts, mostly isometric and red-coloured, in a dense groundmass generally red, or dark from finely distributed magnetite. The phenocrysts are perthitic, with the albite component predominant, and the groundmass is made up of alkali feldspar and quartz, in rhyolitic proportions. Among other constituents, magnetite is the most common one. In texture the groundmass is very often poikilitic, occasionally spherulitic, and else presents a very fine-grained aggregate with irregular grain boundaries, probably a slightly coarsened devitrification texture. Fluidal banding occurs, and "buttonholes" chiefly filled with quartz.

The megascopically visible variations mainly concern the frequency, shape, and size of the phenocrysts, which are often compound, and the colour of the groundmass. Locally on Kiirunavaara, near the ore, there is a greyish variety with white phenocrysts.

The chemical composition of the more common types may be illustrated by the following normative figures:

	III	IV	V	VI
Q	27.91	23.56	23.38	14.68
Or	26.27	17.89	12.86	16.21
Ab	33.19	48.99	52.68	54.25
An	1.39	1.95	4.26	4.46
C (Al_2O_3)	1.02	—	0.20	—
P	1.21	2.82	1.70	3.56
M	8.31	4.39	3.18	4.99

Eutaxitic flow structures are found in many places, as in the southern part of Kiruna town where lumps of porphyry with a bluish groundmass are enclosed in a matrix that is reddish throughout. More remarkable is a belt on Luossavaara, about 100 m wide and with vaguely defined boundaries, which has been described as an agglomerate. It consists of fragments and a subordinate matrix that is mostly ordinary porphyry but partly considerably altered. The fragments, which occasionally surpass 1 m in size, generally are rounded but sometimes angular. Most of them represent types of the foot-wall unit but there are also many varieties of the hanging-wall unit. Fragments of iron ore also occur.

Isolated fragments of the foot-wall porphyries are sometimes encountered elsewhere as inclusions in the hanging-wall unit. More remarkable, both quantitatively and because of its geological significance, is the occurrence of inclusions of ore. These vary in size, generally between a few cm and some dm, and mostly — at least the larger ones — are angular in shape. They represent a number of varieties of ore, such as make up the main ore bodies of Kiirunavaara and Luossavaara, ranging from the richest magnetite even to pure apatite rock. The distribution of these fragments is noteworthy, as they are lacking near the ore body of Kiirunavaara, occurring there only some distance up in the unit, but plentiful just above this contact on Luossavaara, where they quite locally may even make up about half the volume of the rock. When first noted, these inclusions were regarded as proofs that the hanging-wall unit was younger than the ores. Later, however, it became quite clear that the latter are intrusive into the adjacent hanging-wall unit, and the conclusion became inevitable that the fragments must be derived from some older ore body of the same nature, otherwise unknown. It was once suggested (Stutzer 1907), apparently on ground of the distribution of the inclusions on Kiirunavaara, that the ores were later than the bottom flow of the hanging-wall unit but earlier than subsequent members of it. This possibility, however, is ruled out by the relations on Luossavaara, as described above.

It would be against all geological experience to interpret the hanging-wall unit as one undivided magmatic body, as is the conclusion with regard to the foot-wall. With its thickness, such an origin would have manifested itself in textural variations. But it has not been possible, so far, to trace within it any separate flows. However, practically no study has been devoted to this unit after 1910. Certain features, as the Luossavaara agglomerate, may suggest to a geologist today the presence of "pyroclastic flows". Such an origin would be difficult to prove — or disprove — in the present state of the rocks. But most of the hanging-wall unit is texturally like the dike porphyries (compare the following), indicating that probably ordinary flows at least are the rule within it.

The main ore bodies of Kiirunavaara and Luossavaara

In size, the deposits of these "twin ore mountains" are very different. That of Kiirunavaara probably is the largest continuous body of high-grade iron ore known anywhere, while Luossavaara is incomparably smaller and is surpassed also by several other deposits in the same region.

The Kiirunavaara ore body is a sheet with a strike length, on land, of about 4 400 m (incl. the faulted southern tip); a further continuation northwards, below Lake Luossajärvi, is narrow and of no economic interest at present, its length is about 1 000 m. The ore body follows the rather straight contact between the foot-wall and hanging-wall rock units.[1] A bend visible in fig. 10 is due to interference of dip and mountain slope. The dip is easterly, generally between 50° and 60°, the horizontal width varies somewhat and averages about 90 m. The deepest drill hole so far put down at Kiruna, "Zenobia II" E. of the northern end of the mountain, entered the ore body at 549 m below the level of the lake, and passed out of it into the foot-wall porphyry at 723 m. From the geological relations, including what has been brought out by deep drilling, and the carefully mapped magnetic anomaly, the probable now remaining ore quantity has been estimated at about 1 600 million metr. tons, possibly a good deal more. From the start of mining in 1903 through 1959, production has totaled 235 million tons (production from Luossavaara has been additional 13 million tons).

The ore mineral is magnetite. Hematite occurs as a primary mineral in very small amounts, as crystalline lumps enclosed in magnetite and as thin veinlets. Secondary (martitic) hematite is important within a portion in the southern part. The chief non-iron mineral is apatite, which is very unevenly distributed. It is a fluorine apatite with very little chlorine and carries about 0.9 percent oxides of the cerium metals. Of other constituents, diopside and actinolitic hornblende (in part uralitic) are found in some quantity within a few limited areas. Finally may be mentioned the regular presence of microscopical grains of zircon in the segregations of apatite rock.

[1] The southernmost part of the deposit, however, shifted eastwards along a fault, does not consist of a continuous ore body along the contact but of a chain of intrusions either at it, or close to it in the porphyries on both sides.

Magnetite and apatite, then, can be said to constitute the ore, in any case from the point of view of commercial exploitation. To suit the requirements of the market, the ore as shipped is graded into several "phosphorus classes". At present these are:

B	about	66	percent	Fe, <	0.1	percent P
C_1	»	65	»	»	0.1—0.4	» »
C_2	»	63	»	»	0.4—0.8	» »
D	»	58	»	»	1.75	» »

Because of the great and often sudden variations in phosphorus content, mining is directed with the aid of "phosphorus maps" showing the results of sampling.

In the upper portions of the ore body, ore very low in phosphorus occurred, in minable units, only within a few rather small areas. Mining and deep drilling have disclosed a great increase in this quality when going down the dip. It must be remembered that this direction, in the ore body as it was formed, probably was almost horizontal.

The ore always is fine-grained and when low in apatite appears dense, steely. For the individual magnetite grains, 0.03 mm is a normal size. As in the associated rocks, there is no sign of any textural metamorphism, in strong contrast to the situation in the Gällivare deposits, originally similar in nature. The apatite mostly occurs as stout prisms, varying about 0.1 mm in length in the pure apatite rock. In ore varieties containing magnetite aggregates and such of pure apatite, the latter occasionally exhibit a beautiful trachytoidal arrangement of the prismatic grains.

Ore rich in apatite presents great and interesting variations in the relations between magnetite and apatite. These came out especially well in the weathered ore outcrops.

Sometimes the mixture is quite homogeneous, even when the apatite makes up about half the volume. But generally, when there is much apatite, one finds a streaky alternation of different varieties, ranging from aggregates or lumps of pure magnetite to pure apatite rock. A detail of great interest was first noted by Stutzer (1907): in ore with evenly distributed apatite there occur lumps of the latter, a few centimeters in size, which are surrounded by a mantle of pure magnetite. Where a sequence between different varieties can be discerned, as a rule the one richer in apatite is the later. This relation is especially well brought by bodies of pure apatite rock where in contact with high-grade magnetite, which they split up into angular fragments. Such apatite segregations are common in some parts and take various shapes: from irregular bodies that may reach meters in diameter, to tabular ones that combine a thickness of a few decimeters with a strike length of a score of meters. All units show in their shape a general conforming to the strike and dip of the ore body as such, although with local irregularities.

An especially remarkable ore variety is the "stratified" one that could be studied in the outcrop, locally near the foot-wall on northern Kiirunavaara. It shows a regular lamination of ore (with some apatite) in seams about 1 mm thick, and thinner ones of pure apatite. By more streaky forms it grades into the normal types of magnetite-apatite mixture. It may be noted that similar laminated forms are found also in deposits where the ore bodies form fissure-filling dikes, as at Tuolluvaara, 4 km E. of Kiruna.

Another peculiar form is the "skeleton ore", with an apatite matrix containing arborescent growths of magnetite, similar to such of microscopic dimensions found in some porphyries of the foot-wall unit, but here reaching up to about 5 cm in size.

Sulfides are very rare in the Kiirunavaara deposit. Probably none belong to its original constituents. Pyrite is occasionally found on joints and in the filling of fault fissures. A few small copper veins offer a certain scientific interest. They include one in the immediate foot-wall, which has bornite and chalcopyrite in a gangue chiefly of quartz and tourmaline, and one, possibly in the ore body itself, consisting of bornite and "high" chalcocite ("digenite") enclosing stalks of hornblende. Probably these copper veinlets are genetically connected with the iron ore deposit.

The first-mentioned vein also contributes information on the Pre-Glacial weathering of the Kiirunavaara deposit (Geijer, 1924 a). Only in the southern part of this deposit, but there within a wide area, such weathered ore has been found. The magnetite is largely oxidized to hematite, in the common martite pattern, apatite is generally removed (secondary iron phosphates have been identified in an ore shipment), and some quartz introduced into the pores thus formed. This weathering goes deep down but appears to end about 200 m below the outcrop. The copper vein shows secondary sulfide enrichment, with "low" chalcocite and covellite, and, as a later product, chrysocolla.

The contact relations of the ore body are, in principle, similar on both sides. At the foot-wall contact the ore often contains small inclusions of porphyry. A band, generally a few decimeters in width, of actinolitic hornblende skarn commonly occurs on the contact, sometimes with titanite. At a few places at or slightly above the contact there is found some tourmaline, otherwise foreign to the deposit. The boundary of the ore body is, from the mining point of view, very well defined, but very frequently there are numerous ore veins in the foot-wall rock, in part clearly seen to branch out from the ore body. In the southern part of the mountain, drilling has proved the occurrence of a network of such veins also deeper down in the foot-wall unit. Such systems are known as "ore breccia". They form a characteristic feature of many deposits of the Kiruna type, in different countries.

The foot-wall contact on northern Kiirunavaara, once very well exposed, has proved especially important for the understanding of the ore body's place in the sequence of geological events (fig. 11). Beside the foot-wall unit and the ore there occurs, in this part, a system of porphyry dikes in the foot-wall. This porphyry is similar to the other units in the character of its feldspar, intermediate in quartz content between the foot-wall and hanging-wall units, carries diopside like the former and is texturally similar, also in the shape and size of the feldspar phenocrysts, to the latter. About 10 such dikes are known. None have been found to cut the hanging-wall rock. But one has apparently, when reaching the contact with the latter, spread out as an intrusive sheet along this contact. This body has later been broken up by the ore body, large slabs of porphyry being enclosed in the latter and further penetrated by veinlets of ore rich in apatite and hornblende. Northwards the ore injects a spur, in part showing "stratified" ore, obliquely into the foot-wall. This spur grades into a system of ore veins in the contact zone between the foot-wall unit and the overlying dike porphyry, running for a distance of about 500 m and then

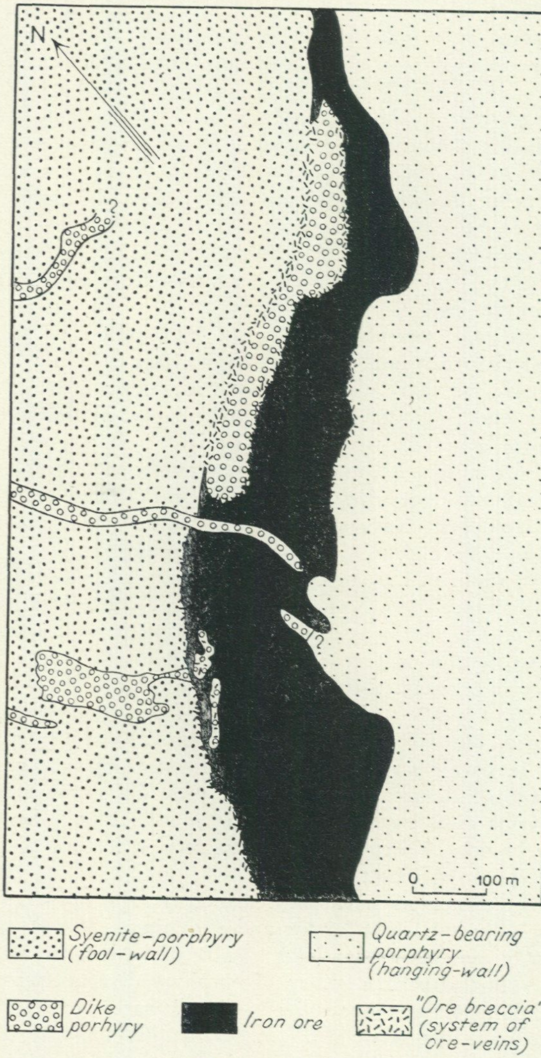
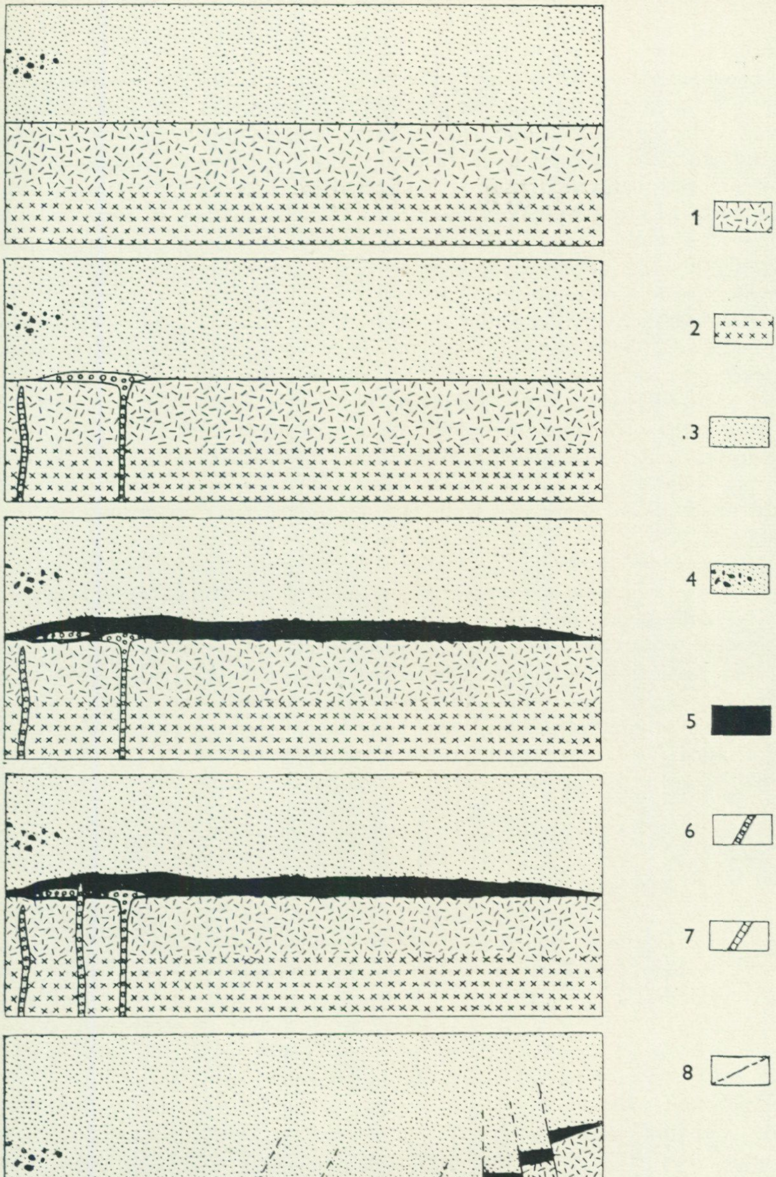


Fig. 11. Northern end of Kiirunavaara. Adapted from Geijer 1910.

uniting again with the ore body. The sharpest contrast to these relations is shown by another dike of the same kind of porphyry, about 15—20 m wide, which cuts across also the ore body with straight and clean-cut boundaries. These relations make it clear that the intrusion of the ore body took place when some of the porphyry dikes already were in existence, but before the last dike of this very characteristic set was intruded.

Beside the inclusions of dike porphyry just mentioned, the ore body contains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a couple of "horses" of albite rock that appear to represent altered inclusions of porphyry.

The hanging-wall contact in many places shows characteristic relations that prove the ore to be later than the adjacent porphyry. The ore, which then contains hornblende next to the contact, outwards begins to enclose fragments of porphyry, apparently in part replaced by hornblende. These fragments increase in frequency and size so that a transition is effected to porphyry with veins of ore, passing further into porphyry without such foreign matter. A zone of this nature reaches only a couple of meters in width. Drilling has shown that, at greater depth, veins of ore occur even some distance out in the hanging-wall, on a scale not seen at the surface.

The northern continuation of the ore body, below Lake Luossajärvi, is known only from two drill holes placed "in tandem". They show, along the contact between the porphyries, ore only a little over 2 m in thickness, and above it, in the hanging-wall unit, some meters' thickness of "ore breccia". The magnetically located "parallel ore" in the hanging-wall unit below the lake, is known only from one drill hole which shows a rather rich "ore breccia".

The ore body of Luossavaara exhibits nothing that requires a special description. In the foot-wall there is a wide zone of rather rich "ore breccia" below the ore body.

The latest events in the geological history of the ore mountains, before the weathering, were faulting and apparently accompanying granophyre intrusions. These are known only on Kiirunavaara. Its ore body is cut by a number of faults, generally striking about N. W. and probably always with a greater horizontal than vertical displacement. The largest granophyre dike runs in a N.—S. direction in the foot-wall unit. Other dikes of the same composition, in part with a felsitic groundmass, cut the ore body in its southern part. These dikes show no apparent affinity to the ore-bearing porphyries. In fig. 5 the most important stages in the geological evolution of the deposit are diagrammatically illustrated.

Rektor and Hauki ores

The Rektor ore body, on the southeastern slope of Luossavaara, is very rich in apatite. About 2.5 million tons of ore have been taken out there, most of it during World War II in order to supply the superphosphate industry with raw material.

The ore occurs on the contact between what is here called the hanging-wall unit, and the overlying pile of Lower Hauki volcanics. Its width is about 30 m. In composition it differs, in several respects, from the main ore bodies. The content of apatite averages above 20 percent. As ore mineral, hematite occurs in amounts comparable to those of magnetite. Small interstitial patches of

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Fig. 12. Diagrammatic section through Kiirunavaara, illustrating stages of its early geological history. From Geijer 1919.

1. Syenite-porphyry
2. Syenite
3. Quartz-porphyry ("hanging-wall porphyry")
4. Quartz-porphyry with inclusions of ore
5. Iron ore
6. Dike of porphyry
7. Dike of granophyre
8. Fault

quartz are rather common, as is also ankeritic carbonate. The apatite is, in part, rather evenly distributed but often forms a regular and fine banding with the iron minerals. A great portion occurs as segregations of pure apatite rock. Sometimes these show transitions to ore, in other cases they form distinct veins brecciating it, or bed-like bodies conforming roughly to the strike and dip of the ore body.

At the lower contact of this deposit, the quartz-bearing porphyry of the hanging-wall unit generally is altered to some meters' width, with new-formed sericite, ankerite, and biotite. It is also frequently intruded by veins of apatite, with or without iron minerals. Above the ore body, the bottom member of the Lower Hauki complex is the Rektor porphyry bed. This peculiar rock consists of a dominantly potassic feldspar, and quartz. Much of it has some small quartz phenocrysts and a granular aggregate of rounded feldspars, 0.2—0.3 mm in diameter. It has been suggested that these may represent recrystallized spherulites. For the rest — the upper portion of the bed at the mine workings, and its whole thickness northeastwards from there — the Rektor porphyry has spherulites and spherulite-fringed tabular feldspar phenocrysts in a dense, flinty quartz matrix. The latter clearly is a product of hydrothermal alteration and in places contains a great amount of iron ore minerals. Probably it has replaced a volcanic glass groundmass. Patches of sericite with tourmaline also occur in it.

At the upper contact, the ore body contains numerous and large inclusions of this porphyry, and also of a type that occurs on top of the Rektor porphyry bed. These fragments are in part silicified. A comparison suggests itself with the upper contact of the Kiirunavaara ore body, where instead replacement by hornblende has occurred in enclosed fragments.

The few exposures of the lower boundary of the Lower Hauki complex S. of the Rektor workings indicate that probably a narrow band, consisting chiefly of apatite, extends along it from the ore body for a length of about 1 400 m, dwindling to only about 1 m in width. In the northeastern direction, again, a similar body possibly extends all the way to Lake Nokutusjärvi (fig. 10), to expand, E. of the lake, as the Nokutusvaara ore body.

The silicified and ore-rich portions of the Rektor porphyry typically illustrate the development of the hematite ores of the Lower Hauki. This volcanic pile is made up of flows — syenite-porphyries or trachytes, much sericitized, and porphyry related to the Rektor type — and of very strongly altered forms interpreted as originally tuffs. Minerals characteristic of this alteration, whose hydrothermal nature is evident, are quartz, hematite, sericite, barite, tourmaline and orthite. A trait that is remarkable from a geochemical point of view is the extreme scarcity of sulfides. Pyrite is totally lacking. Copper stains are not rare, and are derived from a very wide-spread but quantitatively most insignificant mineralization with chalcocite and bornite. The analogy with the copper occurrences in the huge magnetite bodies may be noted.

Origin of the ores

As aptly formulated by Stutzer (1907), "all earnest observers" have reckoned with a close genetic connection between the ores and the associated porphyries. The first important contribution was by Bäckström (1898, 1904), who emphasized the evidence of the vesicle-fillings in the foot-wall porphyry, which show that minerals that normally are the first to crystallize in an igneous rock, here occur as the latest element. Their deposition was thought to be due to volcanic after-action, the material having been transported as gaseous compounds, chiefly chlorides and fluorides, and a similar origin was, in general terms, attributed also to the ore bodies. A somewhat more precise variation of this interpretation is represented by De Launay's pneumatolytic-sedimentary hypothesis (1903), rather ingenious with regard to the facts then known, but soon, by better exposures, proved inapplicable. Already in 1898, another hypothesis had been presented by Högbom, who drew attention to certain analogies with iron ores associated with syenitic rocks in the Urals, and concluded that there exists a group of magmatic non-titaniferous iron ores, analogous in origin to the titaniferous ones but connected with rocks of syenitic nature instead of with gabbroic types. Högbom clearly reckons with differentiation *in situ*. Stutzer (1907), who produced strong evidence for a magmatic origin of the ores, especially by noting illuminating details in the distribution of magnetite and apatite (compare above), regarded the ore as "eine gewanderte magmatische Ausscheidung", a conclusion confirmed by later investigations. Stutzer's characteristic of the ore body as a dike is less fortunate, as the rock series most probably occupied an approximately horizontal position at the time of the ore intrusion; an intrusive sheet or a sill would seem a more appropriate designation.

In 1905—1909, on the initiative of Hjalmar Lundbohm, then manager of the mines, a detailed geological investigation of the ores and associated rocks was carried out for the Luossavaara-Kiirunavaara mining company (Geijer 1910). The following views on the origin of the ores are those then arrived at, on some points modified or elaborated on the basis of new evidence obtained from these and related deposits (Geijer 1919, 1924 a, 1924 b, 1931, 1935, 1950). Data collected during these studies have also furnished most of the material for the above descriptions.

The ore bodies are intrusive, as shown by their contact relations, including the "ore breccias". Since the latter are offshoots from the main ore bodies, they cannot represent any later "mobilization" of material. Metasomatic action has been practically restricted to the development of hornblende in the contact zones. Similar relations are characteristic also of Precambrian, Mesozoic, and Tertiary deposists of the same nature elsewhere. The "ore magma" must have been characterized by a high mobility.

The magmatic origin of the main ore bodies is indicated by the following facts. All minerals are such as are also found in the associated igneous rocks. The texture is fully compatible with a magmatic formation, and some details, as the trachytoidal arrangement of apatite prisms, can hardly be explained in any other way. The relations of magnetite and apatite bear witness to differentiation processes within the ore intrusions. But they also show, on the other hand, a difference in age between certain phases. These variations indicate a solidification in stages, in a way hardly paralleled in a "normal" igneous rock.

The Rektor ore and related occurrences, as the dikes of apatite that at some places, particularly between Luossavaara and Lake Nokutusjärvi, split up porphyry of the hanging-wall unit, have so much in common with the main ore bodies that their formation must have been closely related to that of the latter.

But their composition, with quartz and carbonate (and tourmaline in the apatite dikes), suggests formation at a lower temperature. This is also apparent from the associated wall-rock alteration, as described above, in contrast to the development of hornblende at the main ore bodies.

The Hauki hematite ores, finally, are the products of a replacement process of hydrothermal nature. But they exhibit geochemical features that may be said, with come extension of the term, to show consanguinity with the Rektor ore and even with the main ore bodies.

When seeking the cause of this huge-scale fractionation of iron and associated compounds from a mother magma, the following facts are pertinent.

The relation of the magnetite ores to the porphyries always is that of a later intrusion, no original gradations between the two having been noted. The geological effects of the differentiation, therefore, have been such as would result from a limited miscibility.

The vesicle-fillings or nodules in the foot-wall unit show that factors have been at work that caused the substance of magnetite, apatite, hornblende, and titanite to be kept in solution until the final stages of the crystallization of the feldspar rock. Their relations to the feldspar rock, as reported above, show that they are not the products of later fumarolic action as imagined by Bäckström. While these bodies are not, in their nature, directly comparable to the ore bodies, there is so much of similar relations that it cannot be doubted that the physico-chemical conditions which, in these two types of concentration of magnetite etc. have caused the separation, must have been closely related. In the case of the vesicle-fillings, the action of volatile magma constituents is most clearly indicated.

The Rektor ore (and related forms), when compared with the main ore bodies, by its mineral composition indicates a lower temperature of formation and more influence of volatiles, while still presenting textural features that appear to be best interpreted as magmatic.

With the Hauki hematite ores, finally, one enters the realm of typical hydrothermal after-action, with water, carbon dioxide, etc.

From these facts one arrives at the interpretation that the substances that formed the main ore bodies were fractionated out, as a separate magma, from its mother magma under the influence of volatile constituents. This separation must have taken place somewhere in the volcanic sub-structure or even deeper down. In the case of the Rektor ore, volatiles have remained until a later stage. The vesicle-fillings may be regarded as *in situ* examples of a related although not quite identical form of fractionation.

An interesting support to this interpretation has been given by Fischer (1950), who melted sodium silicate, magnetite, and apatite, with fluorite, and obtained two separate melts, magnetite and apatite being concentrated in one of them. The results of Fischer's experiment thus point in the same direction as the accumulated field evidence: that the ore substances were concentrated through a process of magmatic differentiation in which volatiles were a deciding factor.

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Road-log

W e d n e s d a y 3 r d A u g u s t a n d F r i d a y 2 6 t h A u g u s t.
Departure with express train ("Nordpilen") from Stockholm to Bastuträsk.

T h u r s d a y 4 t h A u g u s t a n d S a t u r d a y 2 7 t h A u g u s t.
Arrival Bastuträsk in the morning. Bus Bastuträsk—Norsjö.

Bus to *Lillholmträsk*. In a road-cutting the Elvaberg phyllites will be seen. These are usually black and grey in colour, sulphide impregnated and rusted at the surface. Bus to *Ledfat*. Structurally well preserved and practically unmetamorphozed conglomerate and sandstone visible in several cuttings. Bus to *Adak* mine. Underground visit. Bus to *Kokträskvägen*. The Adak granite. To *Malåträsk*, overnight stop.

F r i d a y 5 t h A u g u s t a n d S u n d a y 2 8 t h A u g u s t.
Bus Malåträsk—*Rakkejaur* where the basal conglomerate of the Elvaberg Series with pebbles of the Jörn granite is invaded by sulphides related to the Rakkejaur ore-body. The geology and different ore types are demonstrated. Bus to *Högnäs*. Grey Sorsele granite with basic, partly ghost-like fragments. Bus to *Grundträsk*. The Vargfors andesite with porphyroblasts of augite. Bus via Nicknoret to *Granbergsforsen*. The stratigraphy of the Maurliden Series. Low metamorphic phyllites, greywackes and sandstones with graded bedding. Quartz-porphyry. Flat-bedding. Overlain discordantly by the basal marine facies of the Elvaberg Series which consists of lime-cemented sedimentary breccias and conglomerate. Bus to *Södra Mensträsk*. Profile through banded schists and quartz-porphyry + felsite (Maurliden volcanics) with extrusive structures of the Maurliden series. The marine facies of the basal members of the Elvaberg series (lime-cemented, sedimentary breccias and sandstone). Ore impregnations in the ancient weathering surface between the Maurliden and Elvaberg series. About a 2 km walk. Bus to *Norsjö*, overnight stay.

S a t u r d a y 6 t h A u g u s t a n d M o n d a y 2 9 t h A u g u s t.
Bus Norsjö—Svansele—*Vargforsbygget*. Abborrtjärn conglomerate with beds of Vargfors andesite. Fault tectonics. Bus to *Dömanberg*. Dömanberg conglomerate. Bus to *Svanfors*. Abborrtjärn conglomerate overlying deeply weathered porphyry belonging to the Maurliden series. Bus to *Kusfors*. The Jörn granite. Bus to *Petiknäs*. Quartz-porphyry of the Maurliden series. Bus to *Renström*. The Revsund granite. Bus to *Boliden*. A brief account of the Boliden mine given in the company's geological museum. The open-pit and ore types will be studied at the mine. Bus to *Nyholm*. Banded Elvaberg phyllites. Bus to *Skellefteå* for overnight stop. Excursion members are the guests of the Boliden Mining Company at dinner.

S u n d a y 7 t h A u g u s t a n d T u e s d a y 3 0 t h A u g u s t.
Bus Skellefteå—*Varuträsk*. Li pegmatite. Bus to Skellefteå. *Vitberget*. Schists of the Elvaberg series in higher grades of metamorphism than seen previously. Medium grained Revsund granite with inclusions of Elvaberg schist. Bus via Byske to *Åbyn*. Highly metamorphozed schists intruded by the Revsund granite = "Coast-gneiss". Bus to *Järvre*. Reddish grey coarsely porphyritic biotite granite with large microcline porphyroblasts of the Revsund granite type. Bus via Piteå

to *Öjeby* sandsilo. Haparanda granite cut by late-Karelian granite. Bus via Gäddvik to *Luleå* for overnight stop.

Monday 8th August and Wednesday 31st August

Bus Luleå—Kalix—*Storöhamn*. At the quay-side samples of the rocks of the region in low blocks. Boat from Storöhamn to *Västra Gräddmanhällan*. A dolomitic limestone with partly limy and partly quartzitic sandstone layers. In the dolomitic limestone occur abundant stromatolites (interpreted as cabbage-formed lime algae). The south-east cape consists of a dark dolomitic marly shale with limestone fragments and thin limestone layers near the contact. The rocks are cut by a number of kimberlite dykes with a N—S strike. The normal brown to dark brown kimberlite is for the most part altered and green or red in colour. This ultrabasic rock with low silica content displays pseudomorphs, often idiomorphic olivine. In the largest dyke, accumulation of hematite may be especially noted. On the westerly cape of the island occur numerous blocks of a breccia consisting of rocks of the Kalix series with a kimberlite matrix. This type probably originates under the surface of the sea NW of Gräddmanhällorna.

Boat to *Trutskäret*. Banded and unbanded tuffites, grey to greenish grey in colour. In these occur lens-shaped, partially cavernous slabs of limestone which were originally more continuous layers but are now boudined. As a result of later tectonic disturbances these boudins now have an imbrication structure. The rocks are cut by narrow dykes of kimberlite which sometimes occur "en échelon". Boat to *Lutskärshällan*. On the small island in the bay between Lutskäret and Vitgrundet, lava partly with pillow structure. This belongs to the centre of a synclinal trough. Here occurs also a tuffite. The "pillows" stand out on account of a more resistant outer layer. Boat to *Vitgrundet*. The largest continuous exposure of dolomitic limestone in the Kalix "skärgård" (= skerries). The pale grey to greyish yellow limestone is rich in stromatolites and on Vitgrundet the largest examples known occur in the purest limestone layers. A horizontal section through the smaller ones is almost circular but the larger ones are ellipsoidal. The very largest have a long diameter of several metres. In the limestone occur sandstone layers occasionally. The sandstone, which now and again may be quartzitic, often displays discordant layering (cross-bedding) and ripple-marks. Boat to Karlsborg. Bus to *Kalix* for overnight stay.

Tuesday 9th August and Thursday 1st September.

Bus Kalix—Sangis, en route the Haparanda granite will be examined. Bus to Hedenäset where the Torne river forming the border between Sweden and Finland, is reached. Bus to granite mountain of *Luppio* which rises high above the surrounding lowland terrain. Grey, fine-grained, very homogeneous late Karelian granite. Shows very regular and perfectly developed jointing caused by compressional forces related to tectonic movements. From the top of the mountain a fine view over the hills on the Finnish side may be obtained. The highest coastline is there well developed, the hills having a wooded summit and bare lower slopes. The latter were originally washed by the sea during the last glaciation and the soil removed. Bus to *Ruokojärvi*. In a road-cutting late-Karelian gneisses mainly of quartzitic composition, sometimes with thin schist layers. Immediately north of this locality the Arctic Circle is crossed. Bus to *Tärendö*. South of the village, gabbro is exposed in a roadside exposure. The rock is assigned to the

Syenite Series. Bus to *Isokursu* (Rautajoki canyon). Perthite granite. The canyon has granite walls 40 m high. In Norrbotten some canyons are called "kursu" by the finnish speaking people. Their size varies greatly, the depth being from a few metres to 60 m and the length from a few hundred metres to 20 km. They are unrelated to any special kind of rock and are interpreted as the result of glacifluvial erosion in the vicinity of or under a land-ice sheet. In certain cases they may have been formed in tectonic zones of weakness in the bed-rock excavated by glacial erosion. Bus to *Masugnsbyn*. Exposures of a carbonate rock consisting of calcite and dolomite and a skarn iron-ore forming the southernmost part of an iron-ore belt 8 km long. This part of the belt was discovered in 1644 and is the earliest known iron-ore in Norrbotten. In 1646 a blast furnace was set up and was the northernmost ever worked in the world. The iron-ore consists of magnetite and occurs along the notherly and easterly edge of a narrow belt of leptite which is enclosed on both sides by granite. The part we see lies between carbonate rock and perthite granite. The whole ore belt has abundant skarn and also inclusions of carbonate rock. The skarn minerals include diopside and tremolite, as well as chondrodite and phlogopitic mica. In small amounts occur layered, relatively silica-rich ores which are associated with iron-rich silicates such as pyroxene, cummingtonite and garnet. They have undoubtedly a sedimentary origin. Regarding the skarn ores Geijer (1929) considered them due to metasomatic replacement of the carbonate rock. Overnight stop at *Vittangi*.

Wednesday 10th August and Friday 2nd September.

Bus Vittangi—*Äijärova*. Altered greenstone and graphite-bearing schist belonging to the Pajala—Kalix series. Bus to Svappavaara and on to *Gruvberget*. Old copper mines in leptite worked from 1645 and in to the 18th century. In the northern part of the mine area magnetite ore passing southwards into a hematite ore devoid of magnetite. The ore also contains apatite, calcite and actinolite together with quartz, biotite, muscovite and pyroxene in minor amounts. The hematite ore is garnet-bearing occasionally. Both magnetite and hematite ore occur in the same steep, east-dipping sheet which is enclosed by leptitic rocks. In the southern part of the mine area kaolin clay and soft hematite ore may be seen. They are formed as a result of weathering phenomena, the former from the hanging-wall leptite, the latter from hematite ore. Bus to *Kiruna,* en route the iron-ores of Mertainen and Tuolluvaara will be passed. They are both phoshorus-poor magnetite ores in the form of irregular vein-like bodies brecciating porphyric rocks. In Kiruna evening free and overnight stop.

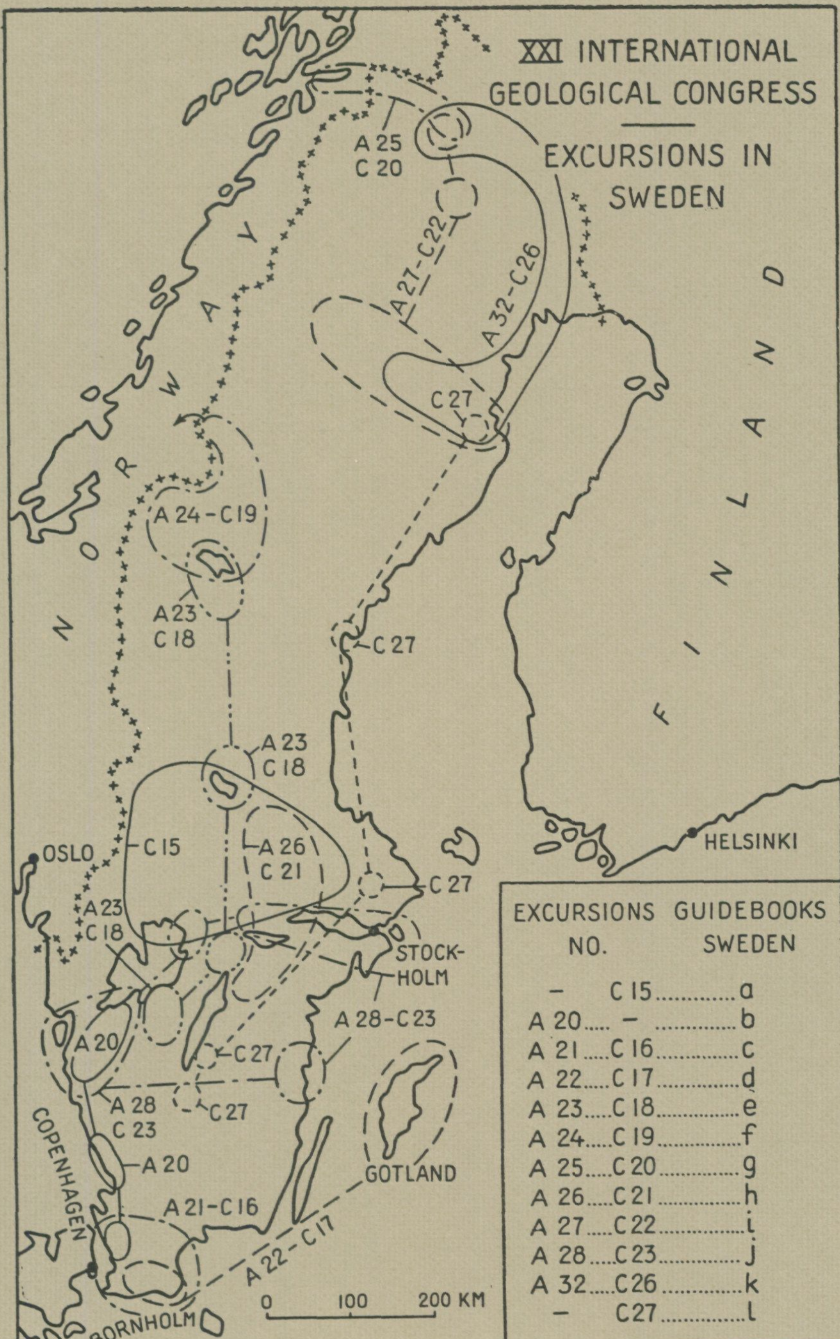
Thursday 11th August and Saturday 3rd September.

Bus to *Luossavaara* summit. Panoramic view of Swedish Lappland. Exposures of syenite porphyry and ore breccia. Bus to *Kiirunavaara*. Examination of open-pit under guidance of the mine management. Bus to *Kojuvaara*. Transition Kiruna greenstone—Kurravaara conglomerate. Pillow structures in the greenstone. In the conglomerate, pebbles mainly of grey syenite porphyry with smaller number of epidote altered porphyries, jaspilitic quartzites, greenstones, tuffites and iron-ore. Layers poor in pebbles but sometimes with cross-bedding. Bus to *Sandstensberget*. Quartzitic sandstone belonging to the Vakko series. Conglomeratic layers with pebbles of quartz-bearing porphyry and dark phyllites. Bus to

Doktorns kulle. Transition Lower Hauki series—Vakko series. Light sericite quartzite of the former in contact with a basal conglomerate of the latter. Both rocks vertical and strongly schistose. Pebbles of hematite and quartz-bearing porphyry. The basal conglomerate passes eastwards into a greywacke with conglomeratic layers with pebbles of quartz-bearing porphyry, iron-ore, phyllites and rocks of the Lower Hauki series. Above the greywacke a phyllite and a quartzitic sandstone with conglomeratic layers similar to that on Sandstensberget. *Open-pit of Rektorn.* Ore and associated rocks demonstrated by the mine management.

Friday 12th August and Sunday 4th September.

Bus to *Holmajärvi.* Eocambrian tillite with fragments of Kiruna volcanics, limestone, schist and red perthite syenite. The tillite is 14 m thick and is underlain by the perthite syenite which also may be seen in exposures to the SE. The rock is similar to the Eocambrian tillites of the Caledonian mountain chain, which lie 30—40 km further west. Return to Kiruna. Train departs 13.20 hrs.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