SVERIGES GEOLOGISKA UNDERSÖKNING

SER. C Avhandlingar och uppsatser N:o 548

ÅRSBOK 50 (1956) N:o 4

A PETROLOGICAL INVESTIGATION IN LAKE NORRA DELLEN BY MEANS OF FROG-MAN EQUIPMENT

BY

LEONARDO L. REDAELLI

Pris 2 kronor

STOCKHOLM 1957
KUNGL. BOKTRYCKERIET. P. A. NORSTEDT & SÖNER
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Preface

This investigation was originally carried out as an examination work for the mining engineer's degree at the Royal Institute of Technology, Geological Section, head Prof. O. H. Ödman. The practical purpose of my work has been a petrological mapping of the bottom of Lake Norra Dellen for the Geological Survey of Sweden, director Prof. N. H. Magnusson, on the proposal of Dr P. H. Lundegårdh, who has mapped the surrounding Archean bed-rock. I should like to express my gratitude to these three persons, who have been lively interested in my work. Further, I have to direct my deep thanks to Disponent G. Sundblad of the Iggesunds Bruks Ltd, who has provided me with raft, compressor, tug, and necessary workers. The Royal Swedish Navy has put at my disposal a complete diver's equipment. My gratitude is here especially directed to Lieutenant B. Cassel and Eng. B. Östergren.

Finally, I will call into remembrance the good job of my co-workers during the field investigation.

Contents

Introduction

This paper is concerned with an attempt to apply geologic research methods (surveying and taking of specimens) to an underwater region — in this case the well-known Dellen andesite. The work was carried out in Lake Norra Dellen and formed part of a new survey of Gävleborg province by the Swedish Geologic Survey. The investigation was concentrated mainly to the lake bed, but four previously known outcrops on land were also examined. The diver used the following equipment for the underwater investigation:

1) Rubber dress, belt with lead weights, and fins.
2) Aga-Divator compressed-air unit (Fig. 1).
3) Specially designed harness for towing (Fig. 3).
4) Tow and life-line.
5) Sextant (Fig. 5).

Fig. 1. Installation of air cylinders. Photo P. H. Lundegårdh 1955.

This equipment and various other items were borrowed from the Royal Swedish Navy. AB Iggesunds Bruk kindly lent the tug "Dellen", a raft, an air compressor personnel.

The diver descended from the raft (11 × 6 m. with cabin, Fig. 2), on which the equipment could be stored during the night. The compressor (Atlas Diesel rock-drilling compressor, 7 kg/sq.cm.) was mounted on the stern of the raft. The exhaust gases were led away through a 3-m. long pipe in order to prevent carbon monoxide from mixing with the intake air and being breathed by the diver. The raft was chained to the side of the "Dellen" and thus the tug could rapidly slow down and reverse the raft. However, the raft and tug tended to rotate, which made it difficult to use the sextant, as described below.

The Physiological Aspects of Diving

The procedure followed consists of two distinct methods which are dependent on the physiological effects of diving.

a) From the surface down to a depth of about 10 m. a diver can operate freely for an unlimited length of time and perform light to medium-heavy work; at a depth of 10 m. the pressure exceeds that at the surface by 1 atmosphere. Even though a certain amount of nitrogen dissolves in blood plasma at this pressure it is so small that rapid ascent after a long period under water produces no ill effects.

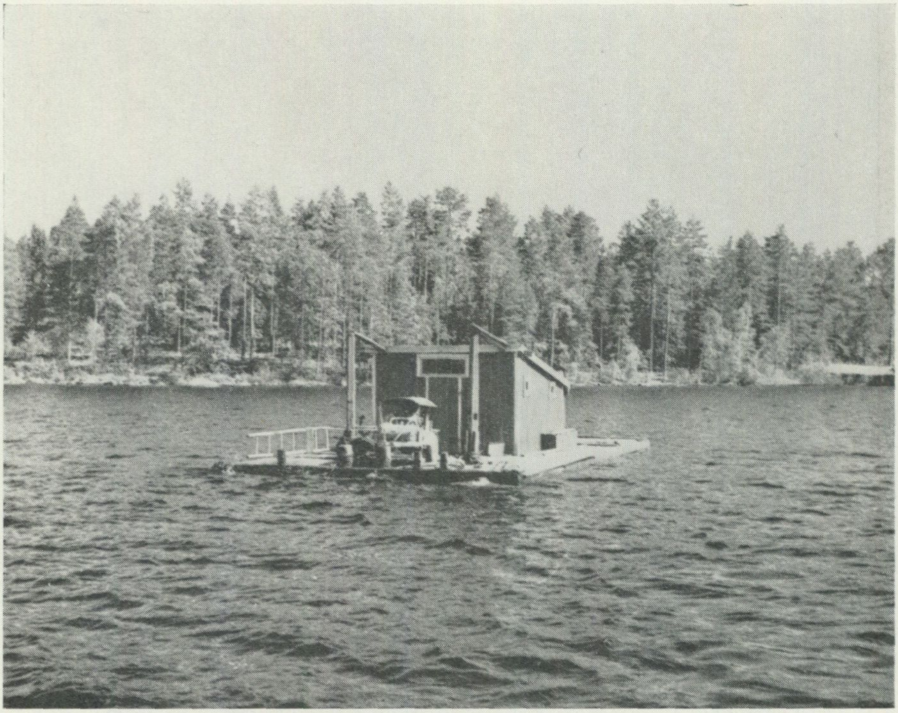

Fig. 2. The raft. Photo P. H. Lundegårdh 1955.

b) From 10 m. to 40—50 m. great care must be taken during the ascent. At over-pressures in excess of 1 atm., nitrogen begins to dissolve in the blood in large quantities. If the diver ascends rapidly from such depths he is liable to get decompression sickness ("the bends"), for the dissolved nitrogen then returns to the gaseous state and forms a large number of gas bubbles in the blood, possibly with serious results. This can easily be avoided if the diver makes the ascent in stages, pausing for various lengths of time at various depths for "airing". Tables are available giving the lengths of time for which the diver should pause at specified depths for decompression, that is, in order to get rid of the nitrogen dissolved in the blood without the formation of bubbles by means of breathing at a lower pressure. The table must be strictly followed under all circumstances in order to prevent discomfort or accidents. It is therefore essential to have accurate information on the depth to which the diver has descended and the length of time for which he has remained at the depth. At depths greater than 30 to 50 m., "nitrogen narcosis" starts to occur. This is caused by an excess of nitrogen dissolved in the blood, producing an intoxicating narcotic effect which varies greatly from one person to another. The air feels thick and has a metallic taste, the voice becomes shrill and unrecognizable, ability to work is reduced and power of judgement becomes less keen. These effects can be avoided by using other mixtures of gases instead of air, e. g., oxygen and helium.

The depths attained during the Dellen investigation did not exceed 35 m. Moreover, the author has not so far been subject to nitrogen narcosis. In view of this, there was no need to take any special precautions in this respect.

Reference: Naval Diving Instructions (Swedish), Part II.

Procedure

a) From the surface to a depth of 10 m.

The diver was towed by the tug. The equipment included a harness consisting of a bent iron bar which was fitted into special rings on the belt during towing. After towing, the line could easily be disconnected from the rings. The simple construction of the harness is shown in Fig. 3. The long sides of the triangle consisted of steel cables with a diameter of 0.5 cm., meeting in an iron ring.

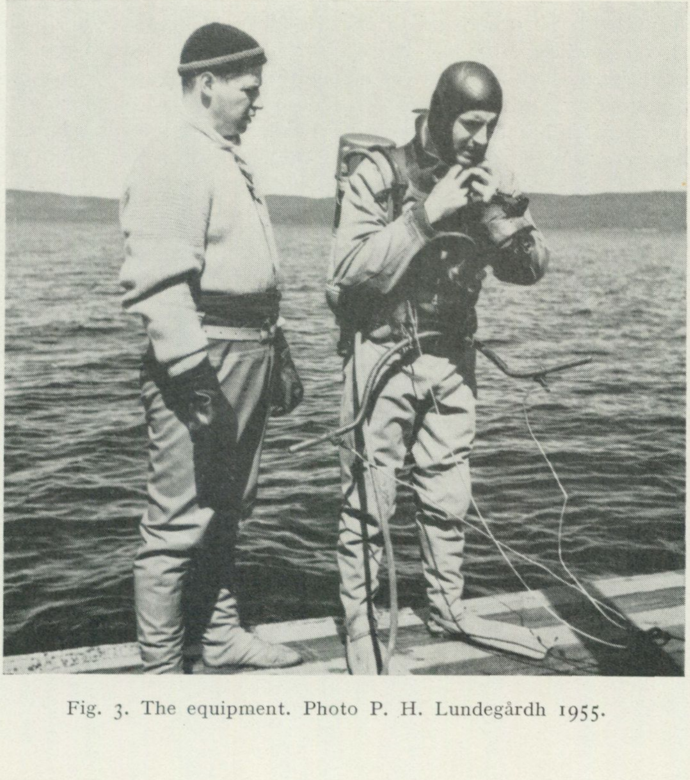

Fig. 3. The equipment. Photo P. H. Lundegårdh 1955.

The steel cables had, however, a tendency to become entangled with the life- and tow-line, especially during ascent and descent at the surface when the line was not taut. For this reason it would certainly be better to make the harness as a rigid triangle of iron bars. The life-line, which was also used for towing, was a 35-m. long nylon rope guaranteed for a load of 500 kg. It was wound on a reel with a handle (naval model). The line was attached to the diver's belt in accordance with regulations. About 3.5 m. from the end attached to the diver's belt the rope carried a hook which was fitted into the ring on the harness during towing. The rope thus served as both a life-line and a tow-line. The diver used the slack part of the rope between ring and belt for signalling. In view of the special nature of the work, a system of signals was devised which differs to some extent from that used by the Navy.

Table 1. Signals

Signal	given	
on signal rope	to diver	by diver
1 jerk	"Are you all right?"	"Lower away" as answer: "All well"
2 jerks	—	"Stop and reverse"
3 jerks	"Come up"	"Pull me up"
4 jerks	—	Emergency signal
shaking	"Repeat signal"	Go ahead
shaking and 1 jerk: Slower		
» » 2 jerks: Faster		

The assistant held the other end of the life-line, acting as a shock absorber to some extent, received signals from the diver and passed them to the engineer on the tug. The diver had also a sheet of masonite measuring 50 × 35 cm. which he could use for steering and for varying his depth in the water during towing by holding it between his hands just above his head, resting his arms on the harness, and breathing in or out particularly hard at the right moment.

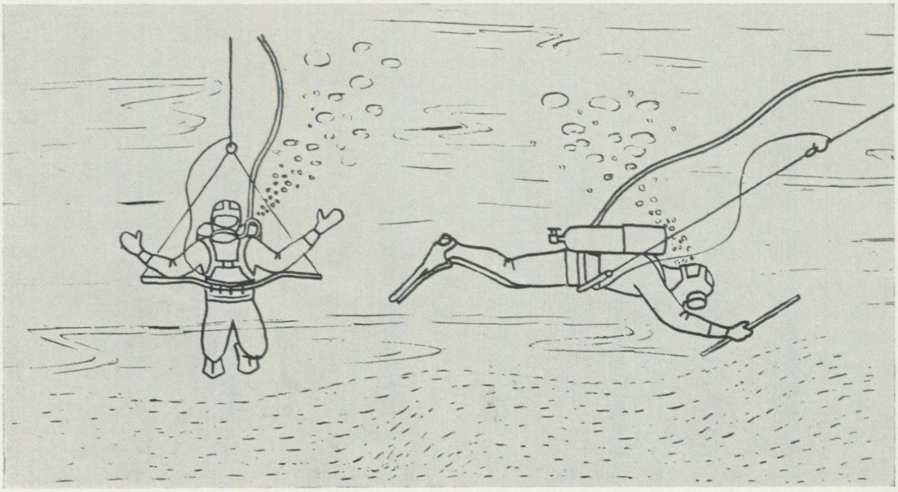

Fig. 4. Operations in water. L. Redaelli del. 1955.

The procedure was as follows: The tug collected the raft, which was anchored where work had finished the previous day. The skipper and engineer lashed the raft to the tug. The assistant helped the diver to dress, and the compressor operator started the compressor. The anchor was raised, and the diver, equipped with harness and sheet of masonite, went into the water, swam to the bottom, and gave the starting signal (shaking). The tug started to move, the engineer held the predetermined course, the compressor operator minded the compressor and payed out or pulled in the air-line, and the assistant let out 10 to 20 m. of rope, depending on the depth. The diver kept about 1 m. from the bottom all the time, and steered with the sheet of masonite (Fig. 4). The rate of towing was slightly greater than the cruising speed, about 8 to 10 km/h. If the diver saw rock, or something resembling rock, he gave the signal "lower away" with one jerk, and the assistant payed out more rope without stopping the tug. This gave the diver time to make sure whether it really was rock he saw. If not, he signalled "go ahead" by shaking the life-line, the assistant pulled about 10 m. of rope back onto the raft, and towing continued. But if it was rock, the diver had time to make sure of this before the slack was taken up and he then signalled "stop and reverse" with two jerks. The tug stopped, went astern, stopped again directly above the diver and dropped anchor. The air bubbled rising to the surface clearly marked the position. The diver observed the arrival of the tug as a dark shadow on the bottom. He then swam to the surface, discarded the harness, collected a sledge-hammer and, with the aid of its weight, sank rapidly to the bottom. After taking a specimen he signalled "pull me up" with three jerks. The diver climbed up onto the raft, handed over the specimens after marking them, and took off the heavy equipment, and took a fix by means of the sextant, Fig. 5. The

Fig. 5. The sextant. Photo M. Englund 1955.

sextant (see fig. 5) consisted of a telescope which was mounted on a scale and could be rotated round a circular plate. After levelling the instrument and taking sights on three objects on the shore which could easily be recognized on the map (the tip of a promontory, a small island, or the like), three lines were drawn on the plate. The angles between the lines fixed the position of the raft on the map. Using this method, levelling and sighting were not easy, as the raft seldom lay absolutely still. The accuracy was estimate as 20 m. on a 1 : 1,000 map. When greater accuracy was desired, the raft was anchored fore and aft and sights taken after it had stabilized, which took quite a long time.

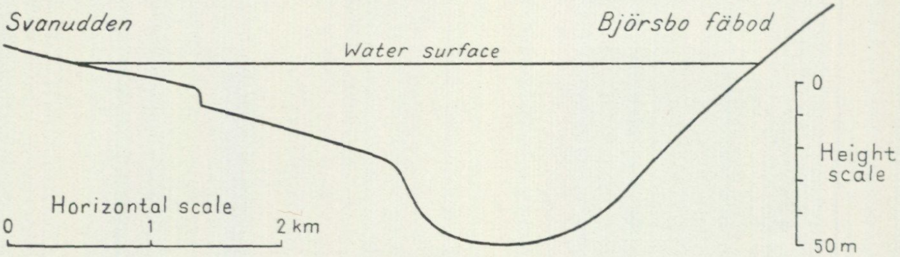

Fig. 6. Section through Lake Norra Dellen. M. Ekman del. 1956.

The towing method described above proved to be very rapid and efficient. 10 to 15 km. a day could easily be surveyed, 1 to 2 km. at a time if no rock was sighted. It was necessary, however, for the diver to rest and warm himself after every rock, or after a couple of kilometres' towing in order to avoid fatigue after a long spell under water.

If there are many blocks of stone on the bottom, great care must be taken, and the towing speed must be reduced considerably so as to avoid colliding with rocks. Care must also be taken not to exceed a depth of about 10 m. If this is to be done it is essential to have exact information on the maximum depth and time of exposure (for later ascent in stages), and this is virtually impossible when the diver is being towed over an undulating lake bed.

Taking account of the above-mentioned precautions, the method is rapid, very efficient because of the long strip that can be surveyed in a day, completely safe, and easy to use after only some ten hours' training.

b) Depths greater than 10 m.

The second method is used where the towing method can no longer be applied because of poor visibility and in particular, because of the risk of being affected by "the bends".

In order to gain a knowledge of the nature of the lake bed while keeping the number of descents to an absolute minimum, a sounding line was towed behind the raft. The lead consisted of an iron bar 3 m. long and 1.2 cm in diameter with a 2 m. long iron pipe pushed on to the lower end and attached to the bar by a small shaft so that the pipe was free to move to a certain extent. (See sketch.) The lead was towed behind the raft on a steel cable with a small washer every five metres to mark the depth. The nature of the lake bed could be judged by holding the cable in the hand. It was possible to distinguish by ear between sludge, sand, pebbles and solid rock. As soon as solid rock was reached, the tug was stopped and the diver descended along the sounding line to the lead. This enabled the depth and time of exposure to be accurately checked, and thus the diver was not subjected to any risk whatsoever. With the aid of this method, which was used during the last few days of the investigation, two ledges were located and charted. The first of these (No. 14) was at a depth of 21 m., where it was so dark that the diver had to feel his way; the other (No. 15) was at a depth of 14 m. This method, too, has been found excellent, but runs must be made closer together than usual as the strip investigated is really no wider than the lead. In cases like this, echo sounding equipment would be of great service to the geologist; it would enable large underwater areas to be investigated at a time and all marked differences in level to be pinpointed so that detailed examination could be restricted to these regions.

Conclusions Regarding Procedure

The two methods can certainly be used wherever there is water. Method a) might be rendered impracticable by excessive vegetation which would make towing difficult. But vegetation occurs where the bottom is muddy and not where it is stony or rocky: only the latter is generally of interest to the petrologist. Method b) requires the use of a searchlight. In the course of the Dellen investigation, several unsuccessful trials were made with an Atlas Diesel compressed-air searchlight. Failure was due to excessive bubbling from the lamp on a number of occasions. In addition, the lamp swung violently and was difficult to steer. A battery-driven searchlight would certainly be preferable. The experience gained thanks to the generosity of AB Iggesunds Bruk enable the following conclusions to be drawn: An ordinary motorboat would be quite sufficient for future work, with two provisions; first, there must be a cabin where the diver can change, warm himself and rest, secondly, a guard (net or grille) must be fitted round the propeller to protect the diver. Further, there is no need for a compressor. Three large air cylinders (those available commercially are excellent for the purpose) hold enough air for one working day. The team can then be reduced to three people: helmsman, assistant and diver. This method would enable survey work to be carried out more conveniently, more rapidly and, in particular, much more cheaply.

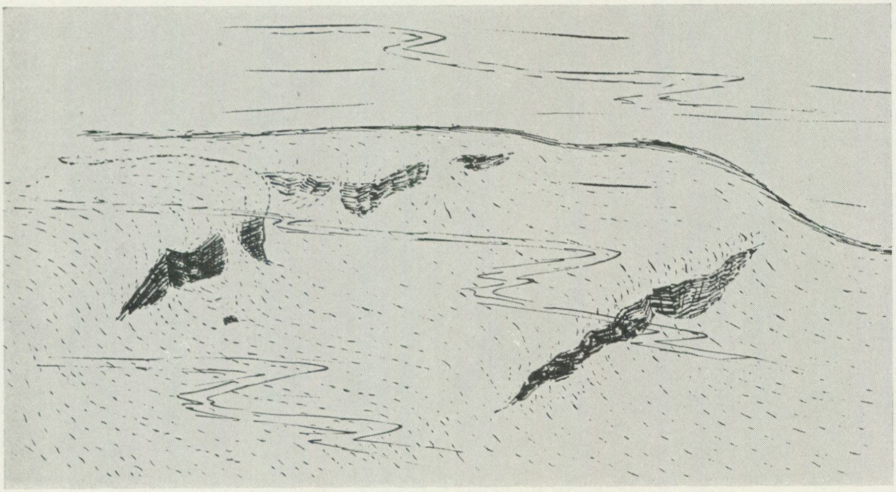

Fig. 7. Outcrops under water, type 1. L. Redaelli del. 1955.

General Remarks on Lake Norra Dellen

The water in Lake Norra Dellen is dark brown in colour and is rich in humus acids. At certain points, especially in the middle of the lake, the water is heavily contaminated by some organic substance which forms yellow particles with a size of 1 to 2 mm. and reduces visibility still further. There are no appreciable currents in the region covered, with the exception of a slight westerly current on the south side. From the surface, the bottom can be seen to a depth of about 1.5 m. if the bottom is sandy or muddy and to a slightly smaller depth where the bottom is stony, owing to the dark colour of the rock. Under water, the lateral visibility is 6 to 8 m. at a depth of 5 m., 1 to 1.5 m. at a depth of 10 m., and at a depth of 15 m. white objects become yellowish-brown and can only be seen in the immediate vicinity of the diver's mask. All other colours vanish at this depth. Complete darkness prevails at a depth of 20 m. The vegetation is extremely sparse; a grass-like growth sometimes occurs down to a depth of as much as 2 m., never lower. When the temperature at the surface was 18° C it was only 10° C at a depth of 4 to 6 m. The boundary between warm and cold water was sometimes so well defined that the diver could hold half his hand in the warm water and the other half in the cold water. At a depth of 15 m. the water temperature was 7° C. At greater depths the thermometer could not be read because of the poor visibility, but the temperature was estimated at 4° C and remained constant down to the bottom.

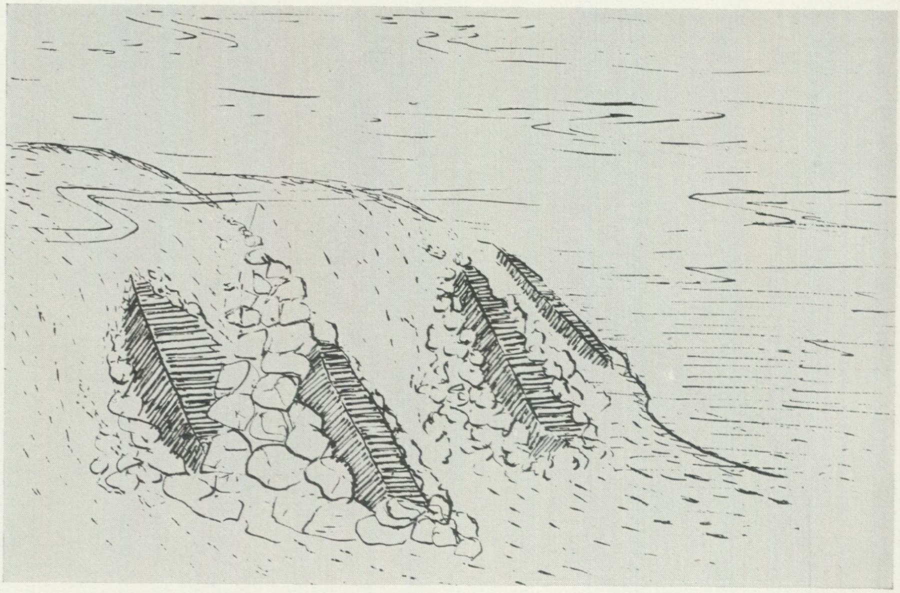

Fig. 8. Outcrops under water, type 2. L. Redaelli del. 1955.

The bottom is almost entirely covered by a thick layer of extremely fine-grained yellowish-white mud, somewhat coarser in consistency where currents occurred. At some places the mud layer is more than 2 m. thick.

The western part of Lake Norra Dellen has an average depth of 8 to 10 m., but is crossed by several ridges running North—South. These ridges rise almost to the surface, forming shoals. The uppermost parts of the shoals consist of boulders (gneiss exclusively), the slopes of gravel and sand. The bottom between the shoals is muddy. The mud is jelly-like in the uppermost layer, a couple of centimetres in thickness) and harder below. Two blocks are visible at the surface. The more southerly of them (the smaller one) lies on a ridge and rises from a depth of 1 m. to 1 m. above the surface. The more northerly block lies on a flat muddy bottom and rises from a depth of 5 m. to 3.5 m. above the surface. Both blocks consist of gneiss and are presumably debris from icebergs. Two heavily weathered gneiss shelves were found on the slopes of the above-mentioned ridges. To the east of Orrön the lake bed consists of 3 distinct plateaus, see Fig. 6. The first and most southerly of these is the continuation of Norrbolandet under water. Its central width is about 200 m and it extends through, and is bounded by, the andesite region. Its north edge lies at a depth of 5 to 8 m. Most of the rock ledges (15) were found on this edge. The second plateau, working towards the North, probably forms the northern limit of the andesite. It begins in the South at a depth of 10—12 m. and ends in the North at a depth of 25 m., whence it slopes steeply down to the deepest part of the lake, which lies about 50 m. under the surface. This third plateau is only 50—70 m. wide and slopes steeply up at the north shore. All three plateaus are covered by thick layers of mud. Only at their edges does rock protrude here and there. The edges consist for the most part of scree which though covered in places by sediment, is always sharp and clearly defined. This fortunate state of affairs permitted examination of the lake bed to be confined to these edges.

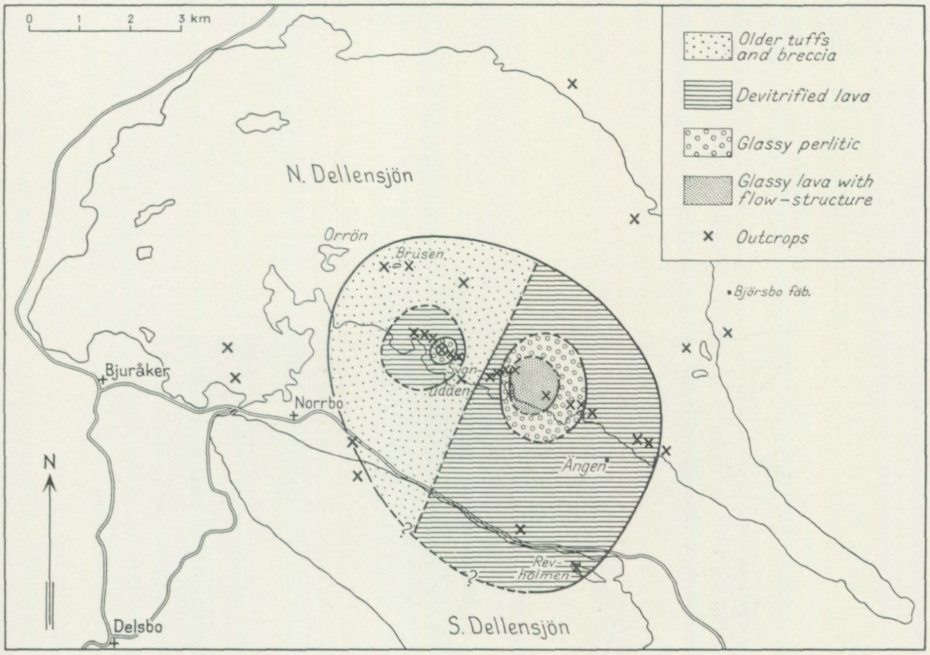

Fig. 9. Petrological map of parish of Norrbo, Hälsingland. M. Ekman del. 1956.

The appearance of most of the ledges is best illustrated by Fig. 7. The rock was often invisible, but its position under the mud could easily be guessed. In such cases it was found impossible to get at the rock, for the disturbed mud reduced visibility to zero. A sludge pump on the raft would be needed in order to pump away the mud.

There are wide belts of scree along the edges of the plateaus. They consist of pieces of rock formed by irregular cleavage. Their length seldom exceeds 0.5 m.; usually they are smaller. In several cases there was no doubt that the solid rock was in the immediate vicinity, although not exposed. Another type of rocks (Nos. 16 and 14) consists of slabs up to 3 m. in length and oriented S—N, their edges projecting a decimetre or two from a steep, stony bottom (Fig. 8).

It proved easier than expected to take up specimens. An ordinary geologist's hammer was too small; a sledgehammer was found to be excellent. The water acted as a cushion round the rock, the hammer never rebounded and hit particularly when the diver could follow through with his full weight. When taking specimens, the diver must be very careful not to cut himself on sharp edges of rock, as cuts do not heal under water.

Topographical Description

Topographically, the region is remarkable and is reminiscent of the volcanic depressions known as calderas found in the Bay of Naples, on Java, in Mexico and other places. The two Lakes Dellen and Norrbolandet form a round depressed region which does not rise far above the water level of the lakes (42 m. a. s. l.). On all sides there are mountain ridges of Archaean gneiss-granite and granite, which are 300 to 400 m. in height, with wide valleys in between. The deepest points in the Dellen depression lie 10 m. below sea level and are located in the narrow inlets running down towards the South-East in both lakes. The area of the depressed region is estimated to be about 310 sq.km.

Fig. 10. Crystal tuff. Thin section magnified 26 ×. Photo N. Sundberg 1955.

In round figures:	Lakes North and South Dellen	160 sq.km.
	Norrbolandet	150 sq.km.

In this region the volcanic mineral seems to occur almost in the middle of the depression and covers an area of about 44 sq.km. made up as follows:

in Lake Norra Dellen	18 sq.km.
in Norrbolandet	18 sq.km.
in Lake Södra Dellen	8 sq.km.

The boundaries of the region could be mapped with sufficient accuracy except for that lying in Lake Södra Dellen, which was not surveyed. In the West, the andesite extends no farther than to Norrbo church. Specimens taken in the crypt of the church seem to come from the actual boundary, where the primary rock has mixed with the andesite and been greatly enriched in ore minerals. To the west of Norrbo church, only gneiss-granite and gneiss were found, together with two gneiss ledges in the inlet which extends towards Lake Södra Dellen. In Lake Södra Dellen, a submerged gneiss ledge was found 650 m. south of Norrbo church. Andesite boulders were found on Brusen Island in Lake Norra Dellen. The northern dip starts immediately to the North of this island, and, as suggested above, seems to form the northern boundary of the andesite. The last andesite outcrop occurs off a promontory one km. east of Ängen, with a gneiss ledge 500 m. east of it. There is an outcrop on Svanudden on Lake Norra Dellen and another on Revholmen in Lake Södra Dellen. Andesite was found during well-digging by Lake Hålsjön. All other ledges were found along a dip 200—300 m. north of the south shore of Lake Norra Dellen.

Geological and Perrographic Description

The Dellen andesite consists of old tuffs, mainly in the western part of the field, together with lava of at least three generations. The oldest lava, the glass of which is almost completely devitrified, fills the eastern part of the field and a small region in the western part of the field and appears to have covered the older tuffs. In its turn, this devitrified lava has been partly covered, in both the western and the eastern part, by younger glassy lava with slight incipient devitrification. In the middle of this last-mentioned lava region there occurs, in both the western and the eastern part, the lava which appears to be youngest, a dark, mafic lava with well-defined fluidal structure. The following sketch shows how the lavas seem to occur. The points from which specimens were taken are marked by crosses.

The probable explanation for the development of the Dellen volcanic region seems to be as follows:

1st stage: Explosion through one or more fissures with a large number of tuffs over a wide region.

2nd stage: A quieter period with at least three lava eruptions from at least 2 craters. Both craters were situated in the northern part of Norrbolandet and some distance out into the lake, about 2 km. apart. They were probably located along the same explosion fissure, parallel with the East-West direction of Norrbolandet. The eastern crater seems to have been the larger and discharged more lava than the other. The lava from this crater has covered the older tuffs in the eastern part of the field, but the latter are certainly preserved in the depths. Apparently this crater was also connected to the western crater. The lavas discharged from the two craters are identical.

3rd stage: Caving in after emptying of magma reservoirs and formation of the Dellen depression. The volume of the Dellen depression (area of depression × mean height of the surrounding plateau mountains) is estimated to be 100—150 cu.km. Assuming that an approximately equal volume of magma has been

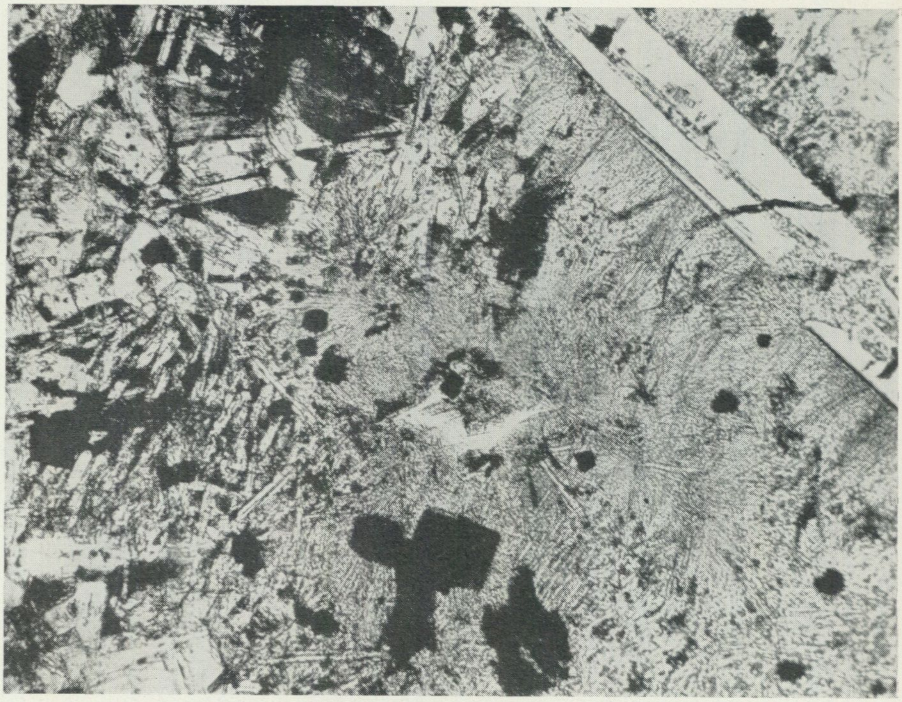

Fig. 11. Devitrified lava. Thin section magnified 110 ×. Photo N. Sundberg 1955.

erupted, the volcanic region must have been considerably larger than the present one, which has an area of only 44 sq.km. Thus the volcanic ejecta, and the lighter tuffs in particular, mud have been carried away. Similar reasoning leads to the assumption that the Dellen volcanoes must have been fairly high. This is confirmed by examination of the lava which constitutes Group II and seems to be the oldest of the lavas. This lava is completely devitrified and has apparently been buried under considerable quantities of younger material.

Description of Rocks

The andesite occurs mainly as tuffs and lavas, and can be classified in the following groups:

I Breccia and tuffs
II Devitrified andesite (lava)
III Glassy andesites (lava) {A. Glass rich in silica, with incipient devitrification
B. Glass rich in iron, without devitrification

GROUP I: BRECCIA AND TUFFS (Fig. 10.)

The rocks of the first group are usually yellowish-grey or greenish-grey in colour and contain large and small fragments of gneiss, which can attain a length of several decimetres at the outermost edges of the volcanic region. Under the microscope, the tuffs show crystalline fragments, probably from Archaean rocks. The microcline

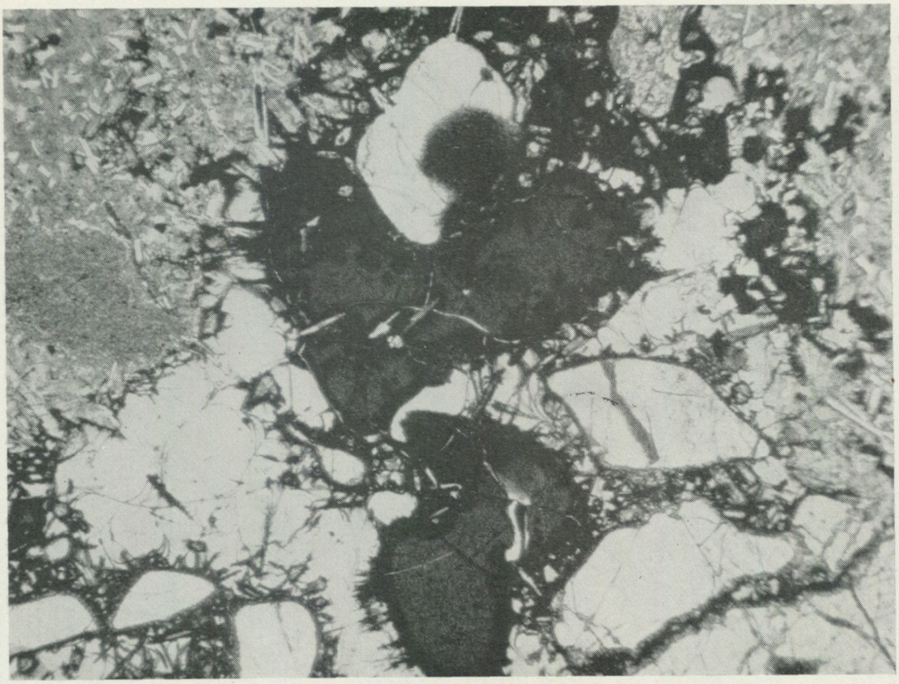

Fig. 12. Xenolith composed of secondary glass and serpentine in devitrified lava. Thin section magnified 24 ×. Photo N. Sundberg 1955.

in them has been wholly or partly converted into orthoclase, with all intermediate stages. The tuff matrix occurs in greatly varying quantities. Where it is present in generous quantities it is possible to see the fine, grey tuff matrix packed in thin layers round the fragments. On the other hand, the tuff matrix sometimes occurs so sparsely that it has only been able to cement the smaller fragments together. Some of the fragments have been remelted to form glass, especially along the edges. Long hair-thin glass needles occur generally in the tuff matrix. These needles embedded in the tuff material also occur in contemporary lavas and are presumed to originate from bombs and lapilli. Some of the quartz phenocrysts exhibit a structure clearly reminiscent of quartzite.

The rock penetrated by the volcanoes seems to have consisted in part of quartz sandstone or quartzite. P. H. Lundegårdh (personal communication) has also found quartzite in a sedimentary layer stretching from Hornslandet E. S. E. of the Dellen Lakes to Hassela N. of the Dellen lakes.

Such a rock has not, however, been found in the Dellen depression, but at Hogland, to the East of Lake Norra Dellen, there are many boulders of quartz sandstone, probably of local occurrence (A. Blomberg 1895, p. 39). Lundegårdh also states that there are quartzite fragments in a volcanic outcropping near Friggesund close to Lake Norra Dellen in the North-West.

GROUP II: DEVITRIFIED ANDESITE

Group II appears to be the oldest of the lavas in view of its complete devitrification. The colour of the specimens varies from light to dark green, and the fissile surface is dull in appearance. Under the microscope, without crossed nicols (Fig. 11),

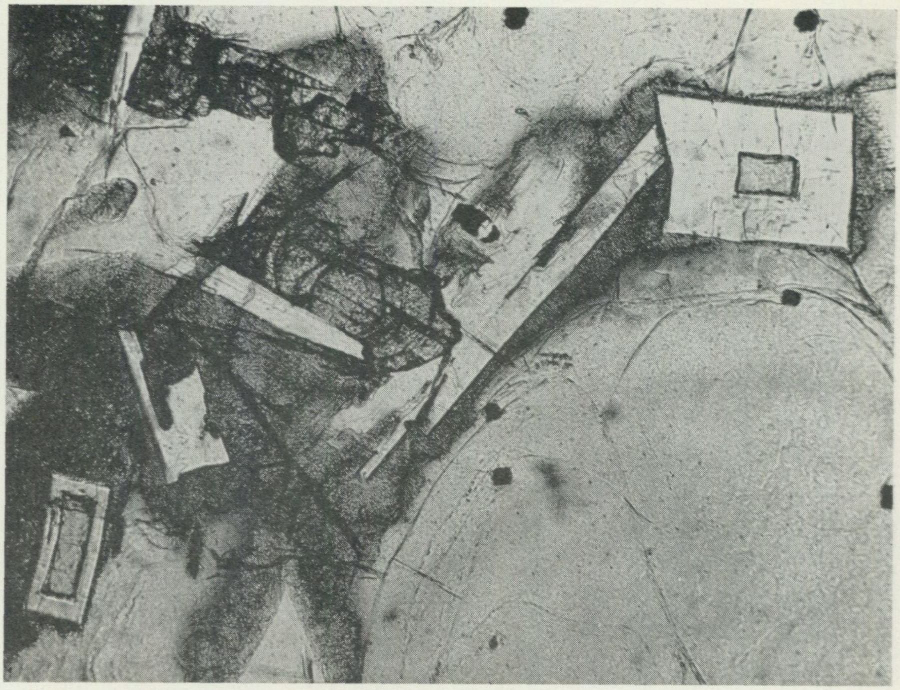

Fig. 13. Glassy lava with perlite texture and plagioclase frames. Thin section magnified 110 ×. Photo N. Sundberg 1955.

the specimen is found to consist of basic material and 20—25 % of phenocrysts, which have apparently congealed rapidly. The basic material is light yellow in colour, and often has a darker appearance owing to accumulations of magnetite microlites. It also exhibits a large number of irregular cracks, but no suggestion of perlitic structure. Under crossed nicols the basic material is found to be completely devitrified (Fig. 3). Glass residue amounting to 10 % was found in one specimen only. A network of extremely small needle-shaped particles of potassium feldspar, which are often ophitic and never have sharp boundaries. Quite large ablong cavities filled with a fibrous, zeolite-like mineral are often seen. The fibres are so arranged that the cavity resembles a kidney in cross-section. The phenocrysts consist mainly of plagioclase (= 20 % of the specimen) and pyroxene (= 5 %). The unusually light plagioclase occurs mainly as thin wide-zoned needles which are more basic internally and which have a length of up to 1 mm. It is very basic and, according to several analyses, almost a labradorite. More typical of the Dellen lavas is the occurrence of plagioclase in the form of picture-frames. These frames (Fig. 14) enclose a small quantity of undevitrified glass, which the frame has apparently protected from devitrification. In the obliquely cut frames the plagioclase has a fork-shaped appearance. It has not yet been found possible to explain this remarkable form of crystallization.

The pyroxene occurs mainly as long needles, longer and thinner than the plagioclase needles. They sometimes attain a length of 5 mm. The pyroxene consists of both hypersthene and augite and in this group of minerals it is often converted into a yellowish-brown serpentine mass. This mass forms pseudomorphs of the abovementioned minerals and often contains rounded pyroxene residue. Small to medium-

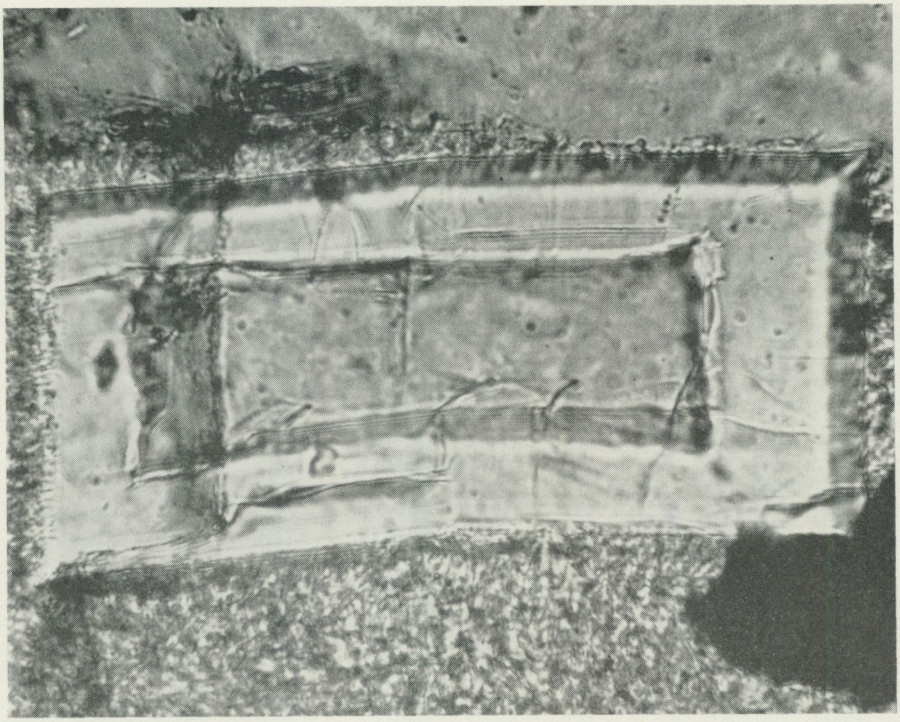

Fig. 14. Frame-shaped plagioclase phenocryst with glassy kernel. Thin section magnified 580 ×. Photo N. Sundberg 1955.

large magnetite particles, which are often idiomorphic, occur throughout, even in the plagioclase and pyroxene. They have apparently been the first to crystallize. A fragment which had been transported by one of the lavas in this group and which seems to originate either from the depths or from surrounding rocks is worthy of mention (Fig. 12). It consists of 9 fairly large quartz particles, which are heavily corroded and rounded, and several smaller crystals of microcline and orthoclase. Pure volcanic glass which exhibits a well-developed perlitic texture occurs between the above-mentioned recrystallized crystals. This glass is also partly devitrified, but only in contact with the lava which surrounds the fragment. Brownish-green serpentine aggregates which tend to become intensely brown near the margins and also locally in the centre, occur in those parts of the fragment that border upon the surrounding lava. Where the serpentine mass turns brown it shows a strikingly beautiful spherolitic effect in the form of light-yellow crosses when viewed under crossed nicols.

GROUP III: GLASSY ANDESITES

This group consists of two distinct lavas.

A. Siliceous Glass

This lava, which is the most distinct, is black, dense to glassily grainy, shiny when fractured, and blackish-grey on weathered surfaces. During solidification, a large proportion of its substance has formed a glass which is optically very similar

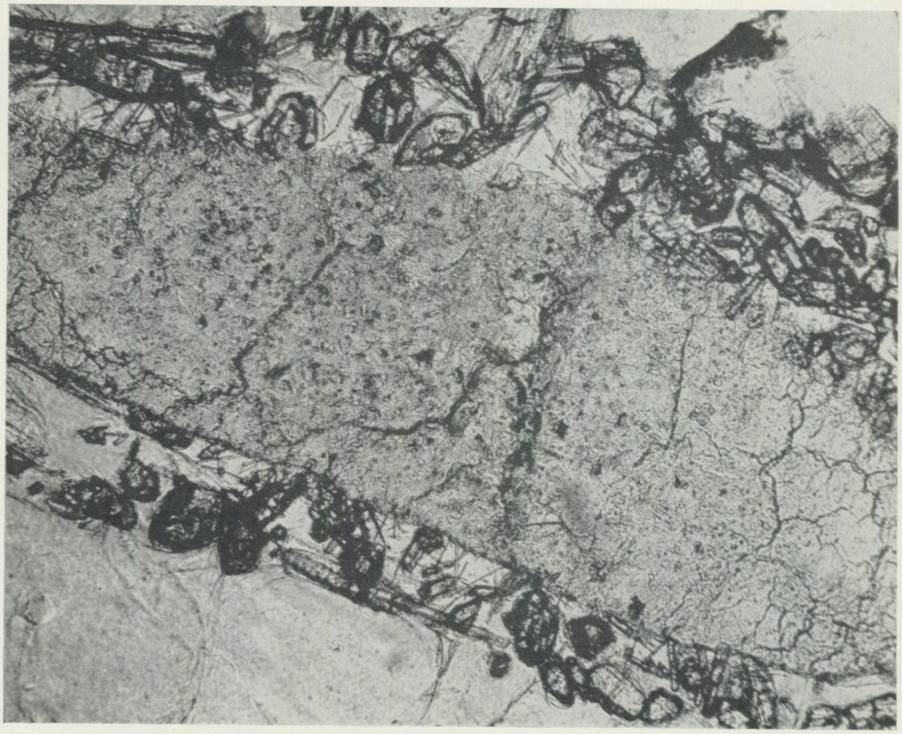

Fig. 15. Glassy lava with quartzite xenolith enclosed in a shell of pyroxene. Thin section magnified 125 ×. Photo N. Sundberg 1955.

to ordinary glass. The lava consists to 75—80 % of glass, about 10 % of spherolites. The remainder is plagioclase and pyroxene phenocrysts and grains of magnetite. The glass is yellowish and completely isotropic, and has a refractive index of about 1.50. It is thus very rich in silico and exhibits an unusually well developed perlitic texture. (Fig. 13.) The almost concentric rings often continue in the spherolites. These spherolites are yellowish-brown, apparently anisotropic, and composed of a feather-shaped arrangement of fibrous minerals, probably feldspar. They occur mainly in the ends of or around the plagioclase needles, and also directly in the basic material. They are always surrounded by a lighter border in the glass and suggest incipient devitrification of the glass. The plagioclase crystals normally consist of numerous needles of up to 1 mm. in length or of small "picture frames" (Fig. 14) like those described above. In this case, too, the plagioclase exhibits a beautiful zonal structure with wide twin lamina and consists of labradorite. The pyroxene occurs as thin needles of up to 5 mm. in length and as smaller grains, and consists of both hypersthene and augit with very marked transitions both laterally and longitudinally. Small magnetite grains are scattered liberally throughout. A xenolite has also been observed in this lava (Fig. 15). It consists of an oblong granulated lump of quartz and is presumably a quartzite fragment which can be compared with those occurring in Group I. It is barely 1 mm. long, rounded, and is surrounded by a large number of more or less attenuated pyroxene microlites.

B. Glass Rich in Iron

This appears to be the youngest lava, as it occurs in the middle of the surrounding lavas and because devitrification is absent. The lava is characterized by a dark-brown glass which is rich in iron and which often displays a beautiful fluidal structure but no perlitic texture. Certain small accumulations in the glass are considerably darker than the rest of the material. This phenomenon is common around or at the ends of the plagioclase crystals. Where this occurs the glass is slightly anisotropic, but not to an extent indicating incipient devitrification. The anisotropy is presumably due to strain during solidification. Magnetite grains occur in generous quantities, and the glass around them is decoloured and yellow. The variations in colour seem to be due to changes in the Fe^{II}/Fe^{III} ratio. Labradorite crystals occur as usual in the Dellen andesites, that is, as long needles and as "picture frames" and forks. In this group, too, the pyroxenes have to a large extent been converted into a dark brownish-green serpentine material (Fig. 16).

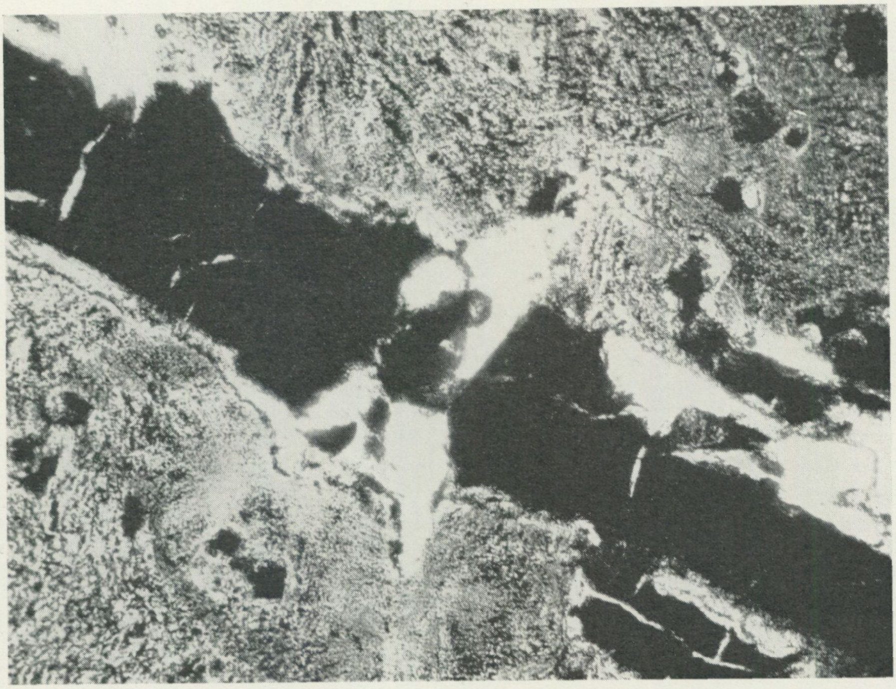

Fig. 16. Iron-rich lava with fluidal structure and serpentinized pyroxene (black). Thin section magnified 125 ×. Photo N. Sundberg 1955.

Occasional pyroxene residues are sometimes seen in the serpentine material.

As regards their chemical composition, the various generations of Dellen andesite differ little from one another, but they do differ in more than one respect from normal andesite. The following table shows the chemical analyses of all the groups examined. The average composition of normal pyroxene andesites is included for comparison.

Table 2. Chemical analyses

	Dellen andesites[1]				Average composition of normal pyroxene andesites[2]
	Group I	Group II	Group III		
			A	B	
SiO_2	68.26	69.48	70.77	68.36	59.59
TiO_2	—	—	—	—	0.77
Al_2O_3	14.39	13.88	13.18	13.24	17.31
Fe_2O_3	1.30	2.67	0.93	1.29	3.33
FeO	2.34	1.53	2.34	3.39	3.31
MnO	0.70	0.15	0.30	0.27	0.18
MgO	1.13	0.71	0.38	1.15	2.75
CaO	2.85	2.39	1.54	2.51	5.80
Na_2O	2.45	3.74	2.57	2.05	3.85
K_2O	3.64	4.44	4.86	5.34	2.04
H_2O	3.17	1.19	2.96	2.63	1.26
P_2O_5	—	—	—	—	0.26

[1] According to H. Santesson — Chemical analyses of Swedish rocks.

[2] According to Turner & Verhoogen — Igneous and metamorphic petrology.

As the table shows, the Dellen andesites are quite similar to the liparites in their chemical composition, but, with the exception of the xenoliths, no free quartz or orthoclase occurs in them. They can thus be considered as a transition group between andesites and liparites. W. C. Brögger introduced the name "dellenite" for them.

In the Dellen andesites, the SiO_2 content is considerably higher than in the normal andesites, and the same applies to the content of K_2O. The CaO content, on the other hand, is considerably lower. This may be due to the large number of quartzite and gneiss-granite xenoliths, which have been carried up from the depths and have been partly assimilated into the andesite magma, doubtless altering the chemical composition of the magma and, in particular, increasing the content of SiO_2 and K_2O in the lavas. But the content of Al_2O_3 is much lower than was to be expected. This suggests that the Dellen andesites probably originate from another magma than that which formed the normal tertiary andesites.

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