

GROUND WATER IN GRANITE ROCKS AND TECTONIC MODELS

INGEMAR LARSSON

Royal Institute of Technology, Stockholm.

A systematic study has been carried out concerning ground water in faults and fractures in a granite rock and the results are compared with those of uniaxial testing of granite specimens in rock mechanic laboratories. Dikes of diabase intersect the granite and indicate the plane of deformation syntectonic to the dikes. A collection of the tectonic data from the granite is statistically treated and the tectonic picture of the area fits very well into the deformation plane, indicated by the intrusion (Jotnian).

The faults and fractures of the granite are, according to their position in relation to the plane of deformation, hypothetically interpreted as tension and shear faults. The faults in shear position are supposed to be tight and have very little ground water. The tension faults, on the other hand, are supposed to be open and to be capable of a high yield of ground water. This hypothesis is tested by core-drillings, percussion drillings and test pumping.

It is known that, in the Baltic shield, in spite of equal infiltration conditions, different types of faults and fractures give different yields of ground water. It is natural, then, to ask: why and how has this difference come into being? The answer is to be found in reference to the geology of the rock, and especially to its tectonic history. Therefore a study of the ground water in such a region must involve an exhaustive geologic investigation leading to a tectonic analysis of the fault and fracture pattern of the area.

In impermeable rocks the ground water yield is entirely dependent on the rate of infiltration in the faults and fractures. This, in turn, depends on whether

the fractures are open or tight. We can state quite simply that a tight fracture contains no water, while an open one may produce a considerable yield of ground water.

From what is said above, it is obvious that an important aspect of studying ground water of a crystalline rock is determining the degree of openness of the cracks. In most cases this factor can be related to tension or shear phenomena in the ruptural deformations of the rock.

An orogenic ruptural deformation of a rock may, within certain limitations, be simulated in the laboratory. Uniaxial compression and tensile tests of rock



Fig. 1.

Failure of cylindrical rock test specimen, shear failure, granite, under uniaxial compression (After Hawkes & Mellor 1970)

specimens may provide valuable information on the tectonics of a rock body in the field when attention is paid to such elements as, e.g. the orientation of grain fabric, and anisotropy and homogeneity of the rock.

According to Hawkes & Mellor (1970), there are three broad modes of failure which are observed in uniaxial compression tests. The first, cataclasis, consists of a general internal crumbling by formation of multiple fractures in the direction of the applied load. When the specimen collapses, conical end fragments are left, together with long slivers of rock from around the periphery. The second is "axial cleavage", or vertical splitting, in which one or more major cracks split the sample along the loading direction (Fig. 1). The third mode is the shearing of the test specimen along a single oblique plane (Fig. 2). Hawkes & Mellor found that it is difficult to distinguish these different modes in a failed specimen, and that occasionally all three modes may appear to be present (Fig. 3). They found shear planes to be characteristic of some types of rotation or lateral translation.

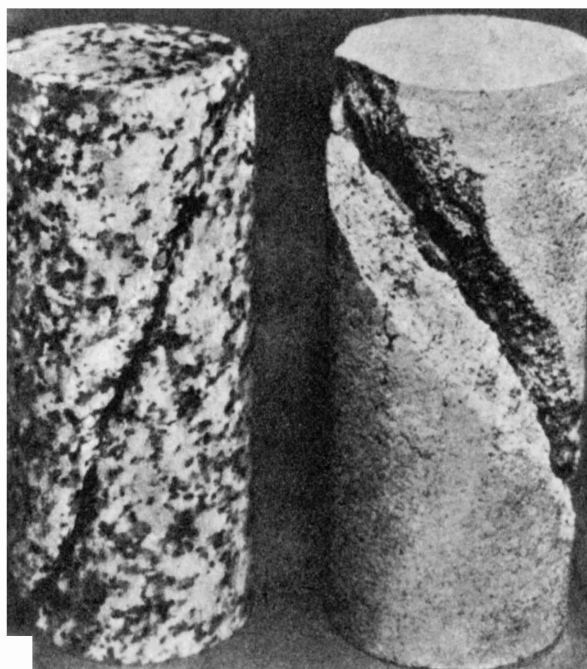


Fig. 2.

Failure of cylindrical rock test specimen, shear failure, granite, under uniaxial compression. (After Hawkes & Mellor 1970)

As a matter of fact, however, it seems to the author that it would have been valuable if Hawkes & Mellor, in the paper cited, had shown, beside the pictures of the test specimens (Fig. 1, 2, 3), also some diagrams of the orientation of the grain fabric of the specimens. The significance of such a consideration has been stated exhaustively by several authors (cf. Griggs & Handin 1960 and papers cited therein) and has also been pointed out by Hawkes & Mellor themselves (1970, p. 185).

In principle, the results of the testing procedures mentioned above can be applied, in a cautious way, to tectonic studies on a regional scale. Thus the



Fig. 3.
Failure of cylindrical rock test specimen, combined cataclasis and cleavage, granite.
(After Hawkes & Mellor 1970)

ruptures of "axial cleavage" type, which are open cracks parallel to the direction of compression (Fig. 2), may be compared with the tension fractures (dikes) in the field, now filled up with diabases. These dikes may represent the direction and the plane of a ruptural deformation, which is syntectonic to the dikes. According to this assumption, other faults and fractures parallel to the dikes, but not filled up with diabase, can be considered as open cracks, which consequently may be capable of yielding a reasonable quantity of ground water.

The third case of failure discussed by Hawkes & Mellor, shearing along an oblique plane, may also be applied hypothetically to field conditions. Two different cases may occur. If a shear plane in the field is still under some type of residual compression which is almost static, it will be relatively tightly compressed and can therefore be expected to have very little ground water. If however, a sliding movement has occurred along the shear plane and caused crushing of the rock into a breccia, this will increase the chances for ground water to be collected in the shear zone.

Interactions between the second and the third case of failure may appear.

There are many problems associated with transferring to field conditions the evidence from laboratory tests. Apart from achieving true-to-scale conditions, the rate and directions of anisotropy in the test specimens demand a very careful extrapolation to conditions in the field even if both originate from the same rock. The homogeneity of the large-scale "test specimen" (investigation area in the field) and the space problem, especially in connection with dilatation movements, must also be considered carefully. But in view of the problems discussed above, evidences of the ruptural behaviour of the rock specimens under significant and ideal test conditions can be most helpful in comprehending the often very complicated pattern of faults and fractures in a region.

A prerequisite for judging the significance of the tests is determining the degree of isotropy, since mechanical properties are only scalar for isotropic material. Strictly speaking, probably no natural rock material may be considered quite isotropic in dimensions of a test specimen. On a larger scale, however, in terms of square kilometres, a rock may be looked upon as "isotropic".

Owing to these considerations, a granite area was chosen for research work in order to find a rock as "isotropic" as possible. The granite, called Karlshamn granite, is situated in southern Sweden on the Baltic coast, east of the town of Karlshamn (Fig. 4 a). According to Welin & Blomqvist (1966), the age of the

granite is 1455 m.y. ($\frac{\text{Pb } 207}{\text{U } 235}$). To the West, North, East and also partly to the South, the granite is surrounded by different types of gneisses (Fig. 4 b). The

border line between the gneisses and the granite is a diffuse transition zone (from gneiss to granite) as a result of granitisation (Larsson 1954).

Apart from some minor inclusions of gneiss areas (Fig. 4 b), the granite may be considered – in terms of square kilometres – as a homogeneous rock body comparable to the granite specimens investigated by Hawkes & Mellor in uniaxial compression tests (op. cit.).

As mentioned above, dikes of diabase in a rock indicate tension action in the crust. The Karlshamn granite is intersected by a set of parallel dikes of Jotnian age (Fig. 4 b). The width of the dikes decreases considerably from the coastline northwards. The one which passes through the town of Karlshamn has a width in the south of about 200 m which, after a couple of kilometres, has decreased to 20 – 30 m.

Further to the North the dikes narrow to a width of a couple of metres, become intermittent, and finally disappear (Larsson & Stanfors 1968).

This is an indication that the dikes have originated by means of a lateral compression and not by a downbending tension of the area. The direction of the dikes is constant, towards N 23°E. This direction is supposed to be that of compression, syntectonic to the dikes. As the granite is very close to the southern border of the Baltic shield, it is apparent that a compression action with tension cracks directed from SSW to NNE will rapidly fade out towards the big bulk of the Baltic shield.

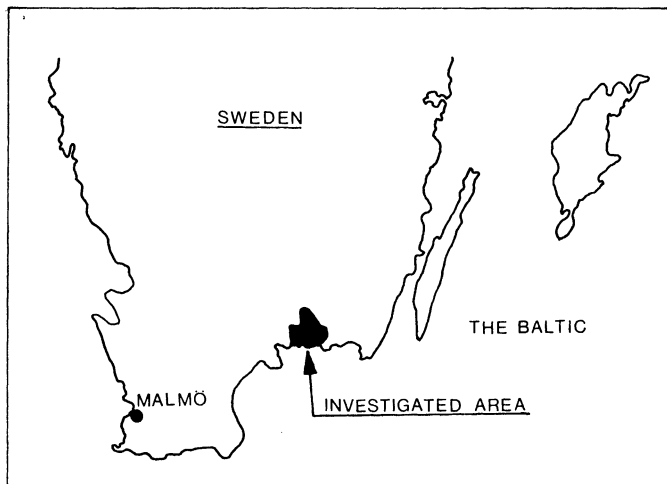


Fig. 4 a.
The location of the invstigated area.
(Asklund 1945)



Fig. 4 b.
The rocks of western Blekinge, south Sweden.
(Asklund 1945)

The area studied in this ground water project included about 30 km² and was mapped geologically with special reference to the homogeneity and isotropy/anisotropy of the rock. In specimens from cross-sections straight across the border between the granite and the surrounding gneisses, the orientation of the grain fabric of the rock was made by petrofabric analyses. An investigation of the general magnetic properties of the rocks, together with chemical analyses, gave the definite limits of the research area.

As mentioned previously, the selected granite area was assumed to be a homogeneous "isotropic" rock body, the fracture pattern of which would be the true response to the ruptural deformation, syntectonic to the dikes. Furthermore

it was assumed that it would be possible to compare the fracture pattern with the results of uniaxial compression tests.

TECTONIC INVESTIGATION OF THE AREA

A careful tectonic registration and examination of all kinds of joints, faults and fractures in the research area produced a collection of data which was tackled statistically by computer techniques. A separation was made between vertical planes and those with a dip. Each of these groups was divided into classes of 5° , the frequencies of which were studied. By means of these operations major groups of fault- and fracture directions were observed to cluster in some preferred orientations around the compass.

The histogram in Fig. 5 shows the frequencies of strike of vertical planes of faults and fractures collected in the investigation area (total number of planes is 2,120). Two major directions occur. One with a NNE – SSW direction and another almost perpendicular to it in WNW – ESE direction with a satellite bundle in E – W. A very small number of planes strike in NNW – SSE and NE – SW direction.

In Fig. 6 the general orientation of the dipping planes, with a total number of 1,122, is shown to be in a preferred direction of WNW – ESE and E – N.

The interpretation of this fracture pattern is based upon the assumption that the direction of the dikes corresponds to the plane of deformation. The mean direction of the dikes (Fig. 4) is $N\ 23^\circ E$. This coincides well with the NNE –

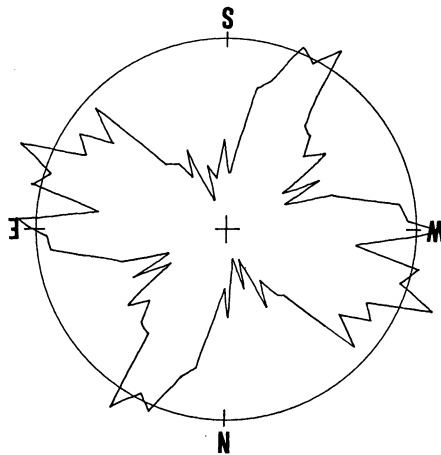


Fig. 5.

Frequencies of the strike of vertical fault and fractures in the Karlshamn granite.
Total number of strikes 2,120.

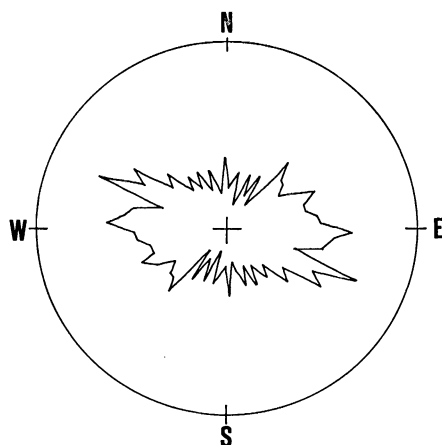


Fig. 6.

Frequencies of the strikes of dipping faults and fractures in the Karlshamn granite.
Total number of strikes 1,122.

SSW direction of the vertical fractures in Fig. 5. Being parallel to the plane of deformation, these fractures must be considered as open tension fractures and consequently capable of holding a reasonable amount of ground water.

The fractures of low frequency in NNW and NE are considered to be shear fractures, assumed to have very little ground water.

The high frequency of fractures in WNW – ESE and E – W is due to a secondary movement perpendicular to the general stress direction and is due to local circumstances.

The general strike of the dipping planes in Fig. 6 corresponds to overthrust planes dipping to the north or south. The directions of movements in these planes coincide quite well with the stress direction, which is parallel to the dikes of diabase.

In order to visualise this fracture pattern in a three-dimensional way, a model of the most frequent directions of the fractures according to Figs. 5 and 6 has been constructed (Fig. 7). The research area is about 5×6 km with the southern flank of the block located on the coastline of the Baltic Sea. A dike of diabase intersects the granite body in the NNE direction. Tension in the perpendicular direction has opened up the dike of diabase and caused the big valley which heads towards NNE. The other fractures from the histograms cited above complete the picture.

A large portion of the fracture planes is covered with slickensides, indicating shear movements. The bulk of the vertical planes in WNW and E – W, con-

sidered as secondary, are heavily coated with slickensides, bearing evidences of movement normal to, or at least at a great angle to the main plane of deformation.

Fractures in NNW – SSE and NE – SW directions are almost always covered with slickensides. In the tension direction, N 23° E, slickensides on fracture planes are very subdominant.

In Fig. 8 a contour map shows the southernmost part of the investigated area. The model in Fig. 7 is drawn in close agreement with this map. The central

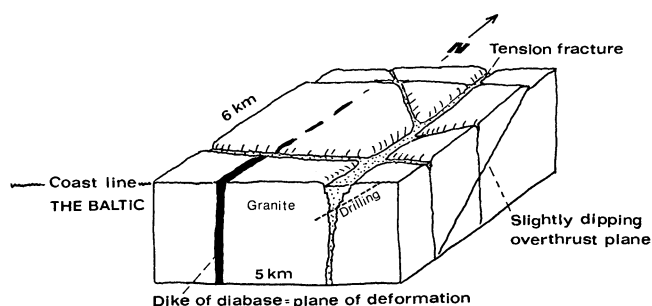


Fig. 7.

Model of the raptural deformation of the Karlshamn granite. The fractures and the overthrust zone in the model are means of data shown in Figs. 5 and 6.

valley A – B, considered as a tension fracture, intersects the granite rock. Some other types of fractures, discussed above, may be recognised on the map.

Previously in this paper the idea of a comparison between the fracture pattern of the research area and the failure of test specimens was discussed. The tension fractures, called “axial cleavage” by Hawkes & Mellor, Fig. 1, seem to be very similar to those that occur in the field parallel to the plane of deformation. The shear failure in Fig. 2 may correspond to the NNW and NE fracture planes in the model. The combination of cataclasis and cleavage in Fig. 3 seems to correspond very well with the fracture pattern of the research area. The author would not, however, like to press this comparison further than to the level of an interesting similarity, since coexisting structural and rockmechanic investigations are lacking.

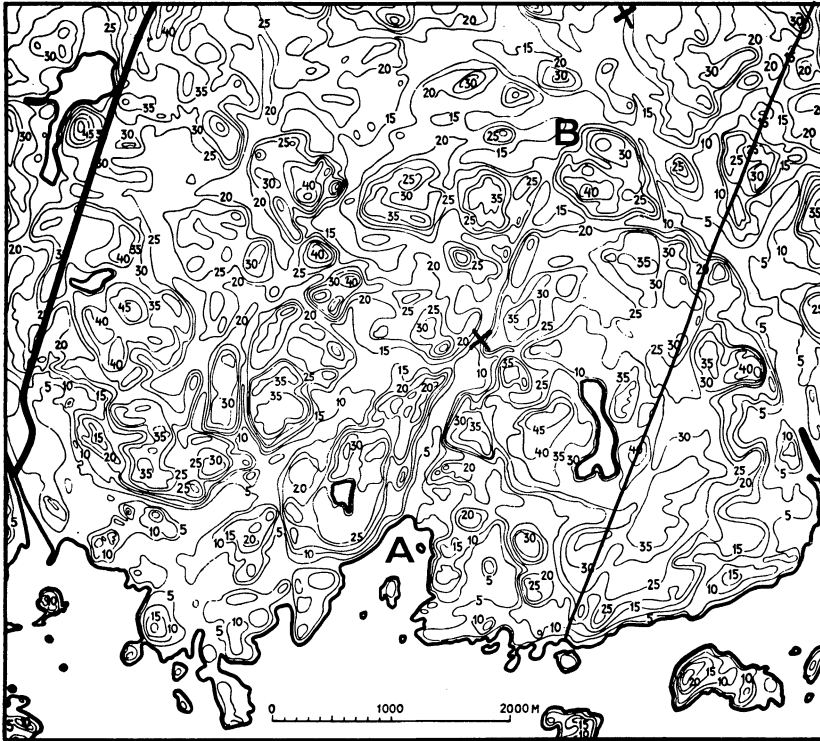


Fig. 8.

Contour map of the southernmost part of the Karlshamn granite area.
Black lines: diabases. A-B: tension-fracture-valley. x = drilling locality.

GROUND WATER INVESTIGATIONS

In the general hypothesis discussed above, the author has assumed that tension fractures may be capable of a great yield of ground water. Shear fractures, still under compression with no or moderate movement, are assumed to be tight and may contain small quantities of ground water while those in which movements have caused a crushing of the rock may produce a moderate yield of ground water.

In order to test these ideas, a drilling programme was set up. The purpose was to investigate typical tension and shear fractures by means of core-drillings and percussion drillings. The core-drillings (46 mm) were inclined 45° and

directed from one side of the valley through the central zone of fracture to the undisturbed rock on the other side. Because of the high costs, the core-drillings were, in some cases, restricted in length to pierce the side of the valley and pass through the central zone of fracture, but not to continue further. The percussion drillings (100 mm) were vertical and located in the central zone of the fracture. The location of the drillings was controlled beforehand by means of conventional seismic operations. These operations also gave the thickness of the soil cover in the bottom of the valley and information on the seismic velocity in the fractured zone.

After the drillings had been completed, pumping tests were made in the bore holes. From these drillings and the seismic operations, it was possible to construct fairly good cross-sections through the valleys. Two characteristic examples are shown in Figs. 9 and 10.

The drilling locality, Hällaryd, Fig. 9, is situated in the big tension fracture A - B shown in Fig. 8. The cross-section shows a strongly fractured zone in the center of the valley, enclosing slabs of solid rock. This is characteristic of the tension fracture type. In the fractured zones core losses were frequent, amounting to a total of 2.7 m in the horizontal direction. These open fractures were filled mainly with sandy material. Further to the south, around Sandvik, the same valley was investigated similarly. In principle, the cross-section through the valley was identical. Here the total core loss amounted to 2.0 m.

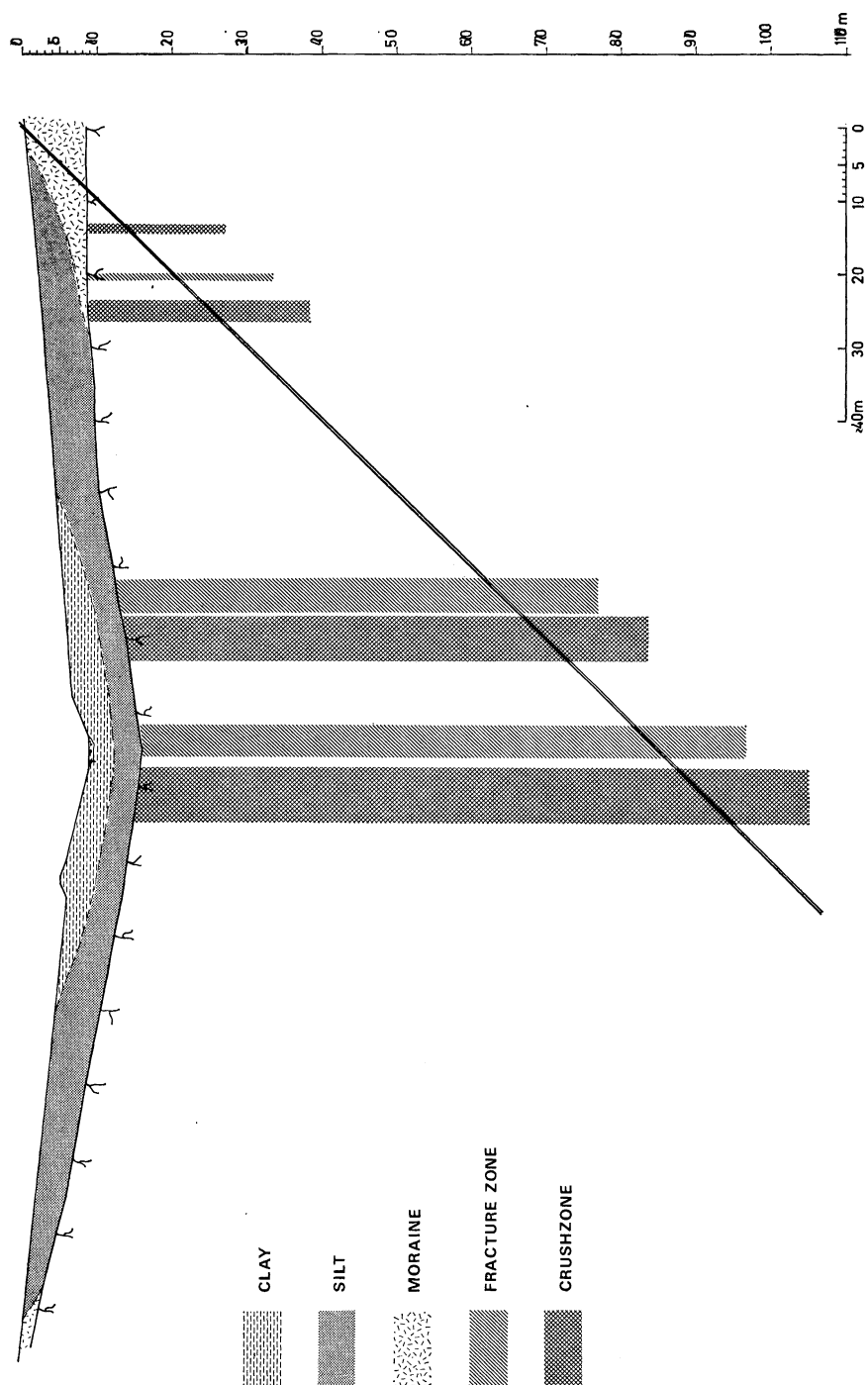
The pumping tests in the fractured zone in this valley gave a yield of 9.7 l/sec with a drawdown of 60 m. Thus the specific yield is 0.16 l/sec per metre. The mean precipitation in this region is about 500 mm/y and the mean evapotranspiration is between 400 and 450 mm. In relation to the climatological conditions the result of the pumping must be considered fairly good.

The other type of fracture, the shear type, is shown in Fig. 10. The drilling locality is named Tranelid and is situated in a characteristic narrow shear valley of NNW direction (cf. Fig. 5). The walls of the valley are coated with slickensides. The cross-section shows a major disturbed zone in the centre of the valley. The core-drilling revealed that the rock in the central zone was broken up into thin slices, all with strong signs of movement. This phenomenon is found to be very characteristic of this type of fracture zone.

The pumping tests at this locality gave a result of 0.04 l/sec at a drawdown of 30 m. This implies a specific yield of 0.001 l/sec per metre. As the clima-

Fig. 9.

Cross-section of the drilling locality of Hällaryd. Thin lines: core-drilling.
Tension-fracture-valley.



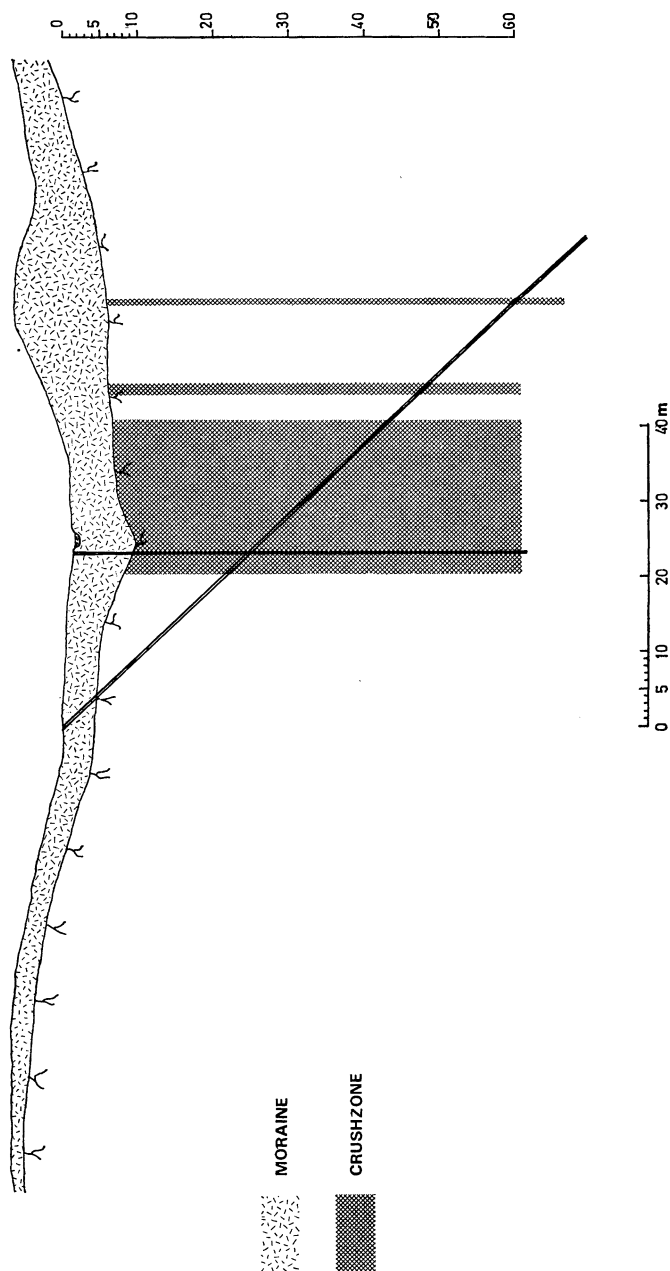


Fig. 10.

Cross-section of the drilling locality of Tranelid. Shear-fracture-valley.
Thin lines: core- and percussion drillings.

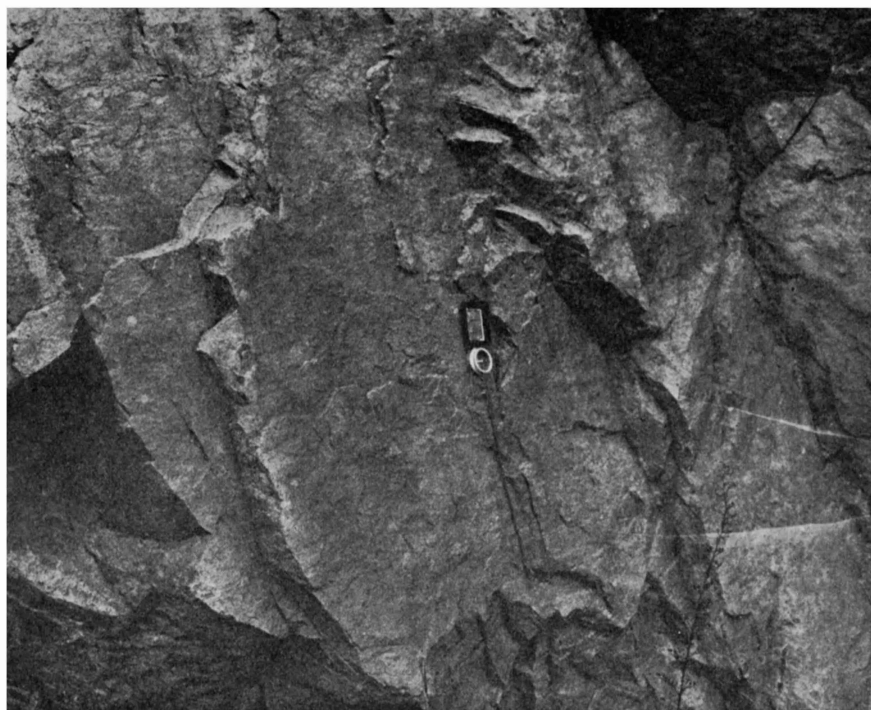


Fig. 11

Tight shear zone with slickensides. Granite. East of Karlshamn.

tological conditions at Tranelid are identical to those of Hällaryd and Sandvik, the ground water yield at Tranelid must be considered very poor.

The slight dipping overthrust planes of the area, assembled in Fig. 6 and sketched at the side of the model in Fig. 7, have not been investigated in the same systematic way as the other two types. General experience from commercial drillings for ground water indicate that these planes are very good collectors of ground water, depending on the thickness of the thrust zone and the infiltration conditions (Fig. 12).

In the previous description, faults and fractures have been discussed in the order of valley dimensions, where the granite massif has been dissected into minor blocks, cf. Fig. 8. Even on a smaller scale, the faults and fractures have identical qualities. A shear zone with typical slickensides, Fig. 11, may be an example of a tight fracture; another shear zone with considerable crushing of the rock is shown in Fig. 13. Ground water yield of 7 l/sec was obtained here.

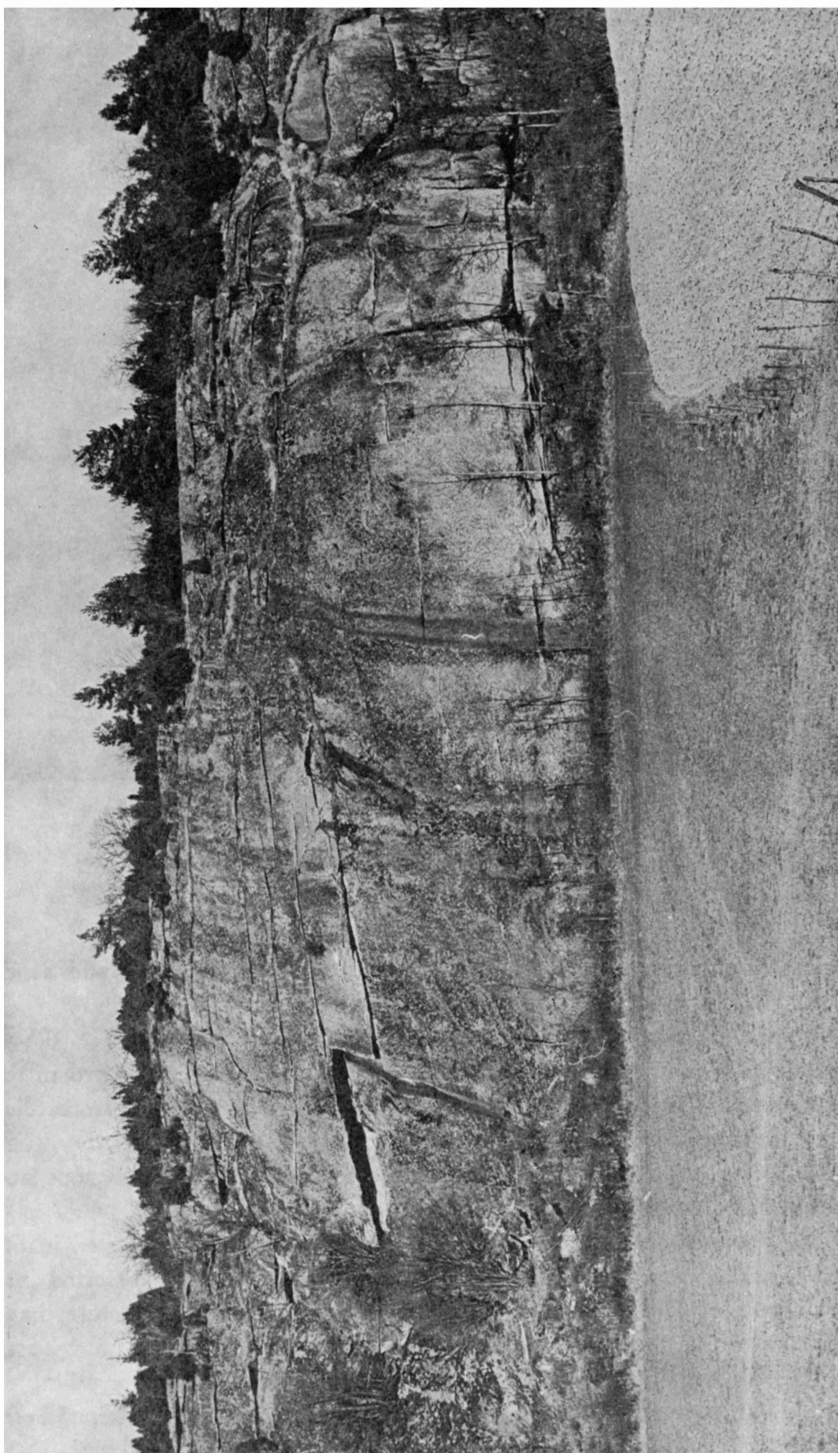




Fig. 13.

Shear zone. Granite. Markim, Uppland. Strong movements in the zone have caused a crushing of the rock. Drill pipe in the foreground. Ground water capacity about 7 l/sec.

Fig. 12.

Granite hill. The top cut by sets of joints parallel to the surface. At bottom a slightly dipping overthrust zone with an average width of the crushed part of about half of a metre. Dalhejaberg, east of Karlshamn.

DISCUSSION

The experiences obtained from the investigations of the Karlshamn granite area may be applied to other granite areas with the same structural properties. An investigation of an area near the city of Stockholm, using identical techniques of tectonic studies, drillings, geophysical explorations and pumping tests, etc. has, in principle, produced identical results.

Certain limitations, however, must be made. The ruptural tectonics of a Precambrian shield are very often a mixture of several different deformations, varying in strength and direction. Thus the fault and fracture pattern of an area may owe its origin to very different stress actions in the crust. It is assumed, however, that once a thorough fracture pattern is established from the action of a particular stress, the successive actions will "use" the already existing fractures for release of the stresses produced. This means a reinforcement of the preexisting ruptural pattern, probably with rotational effects as a consequence, if the new direction of stress does not coincide with the older one.

In fact, there are disturbances which must be taken into consideration, but it is astonishing to find in the Karlshamn granite that the Jotnian fracture pattern is still so easily recognisable in spite of later deformations.

The fracture model thus obtained will indicate the tension or shear activities existing in the crust and will produce a valuable background for other more intricate exploration methods such as geophysical exploration and drilling.

REFERENCES

- Asklund, B. (1947) Svenska stenindustriområden 1-11. Gatsten och kantsten. *Sveriges Geol. Unders. Ser. C. No 479*.
- Griggs, D. T. & Handin, J. (1960) Rock deformation. *Geol. Soc. Amer. Mem.* 79.
- Hawkes, I. & Mellor, M. (1970) Uniaxial testing in rock mechanics laboratories. *Engineering Geology*, 4, (3).
- Larsson, I. (1954) Structure and landscape in western Blekinge, south Sweden. *Lund Studies in Geography. Ser. A. No 7*.
- Larsson, I. & Stanfors, R. (1968) Observations on magnetic properties of diabase dikes in a Precambrian area in southern Sweden. *Geophysik und Geologie*. Folge 15, Leipzig.
- Welin, E. & Blomqvist, G. (1966) Further age measurement on radioactive minerals from Sweden. *Geol. Fören. Stockholm Förh. Vol. 8*.

Ground Water in Granite Rocks and Tectonic Models

Address:

Dr. Ingemar Larsson,
Dept. of Land Improvement and Drainage,
Royal Institute of Technology,
S-100 44 Stockholm 70,
Sweden.

Received 18 November 1971.