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Influence of various excavation techniques on the structure and physical properties of ”near-field” rock around large boreholes

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SUMMARY

The procedure employed in the excavation of canister deposition holes affects the structure and physical properties of the "near-field" rock. Except for smooth blasting, the generated damage appears to be less important than the increase in "axial" hydraulic conductivity that is caused by stress release effects, but both combine to yield significant local flow passages. This is particularly obvious where the rock structure yield steep wedges, which is frequently occurring in granite.

Percussion drilling is concluded to cause rich fine-fissuring to a distance of up to one centimeter from the borehole wall, and "discing". Richer fissuring and some generation of new fractures and growth of preexisting ones are produced within several decimeters from the borehole wall by full-face drilling. Core drilling has the least effect on the rock structure.

Smooth blasting produces a particular form of regular fractures which appear to be determinants of the hydraulic conductivity of the near-field rock. Theoretically, its conductivity in the axial direction of blasted big holes or tunnels should be in the range of 10^{-8} - 10^{-6} m/s, which is in agreement with measurements in the Stripa mine.

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1 SCOPE

The conductivity of the "near-field" rock surrounding deposition holes with metal canisters is of fundamental importance for how effectively corrodants can be separated from the canisters and radionuclides excluded from the biosphere. Different processes in the preparation of such holes may combine to change the properties of the virgin rock, the major ones being changes in aperture and extension of existing fractures due to stress release, and generation of new fractures and propagation of old ones by mechanical fragmentation in the course of the excavation. Since it is not known whether they are both of significance or whether they actually interact to yield easy transport of water or dissolved ions in the vicinity of deposition holes, a pilot study reported in this document has been conducted to identify the various impacts on rock structure and to quantify the net effect with respect to the "near-field" rock permeability.

The excavation techniques that will be considered are:

1. Percussion drilling
2. Full-face (rotary) drilling
3. Core drilling
4. Smooth blasting (slim, closely spaced holes

We will consider here excavation of holes with a KBS3-type geometry in the first place, but since it appears that most conclusions have a bearing also on very deep boreholes, this application will be discussed as well.

2 EFFECT OF STRESS RELEASE ON THE HYDRAULIC CONDUCTIVITY OF ROCK AROUND DEPOSITION HOLES

2.1 General

While there seems to be general agreement on the concept that drilling of slim boreholes only causes an insignificant change in hydraulic conductivity of the adjacent rock, large diameter holes, like those represented by SKB's KBS3 or Very Deep Borehole concepts, may well have such an effect.

In principle, excavation of large diameter holes yields a change in stresses that will influence the hydraulic conductivity of the adjacent rock in the following ways:

* The general trend of rock material to move towards the opening is associated with a relaxation of radial stresses causing expansion of tangentially (axially) oriented natural fractures

* The associated build-up of high tangential stresses may cause overstressing resulting in failure and formation of series of tangentially oriented fractures (potential rock burst) or rich fissuring close to the rock wall

* Displacement of rock wedges formed by steeply oriented long-extending fractures that intersect close to or within the rock that is going to be excavated

We will consider a few representative cases here in order to find out to what extent fracture opening by stress release will actually take place, as well as to investigate the usefulness of simple computer codes like UDEC.

2.2 Influence of stress alteration on fracture apertures

2.2.1 *Geometry of virgin rock structure*

Granite bedrock will be focussed on here not only because of its abundance but also because it is expected to be more sensitive to stress changes than tougher and less regularly structured rock with respect to permeability.

Granite is normally characterized by relatively regularly spaced and oriented sets of fractures of significant extension and water-bearing capacity (Fig.1). Typical spacing, aperture, and length distributions are given in Fig.2, the degree of interconnectivity naturally being a determinant of the gross permeability. A generalized physical model that visualizes the distribution in fracture size and spacing is illustrated in Fig.3 (1).

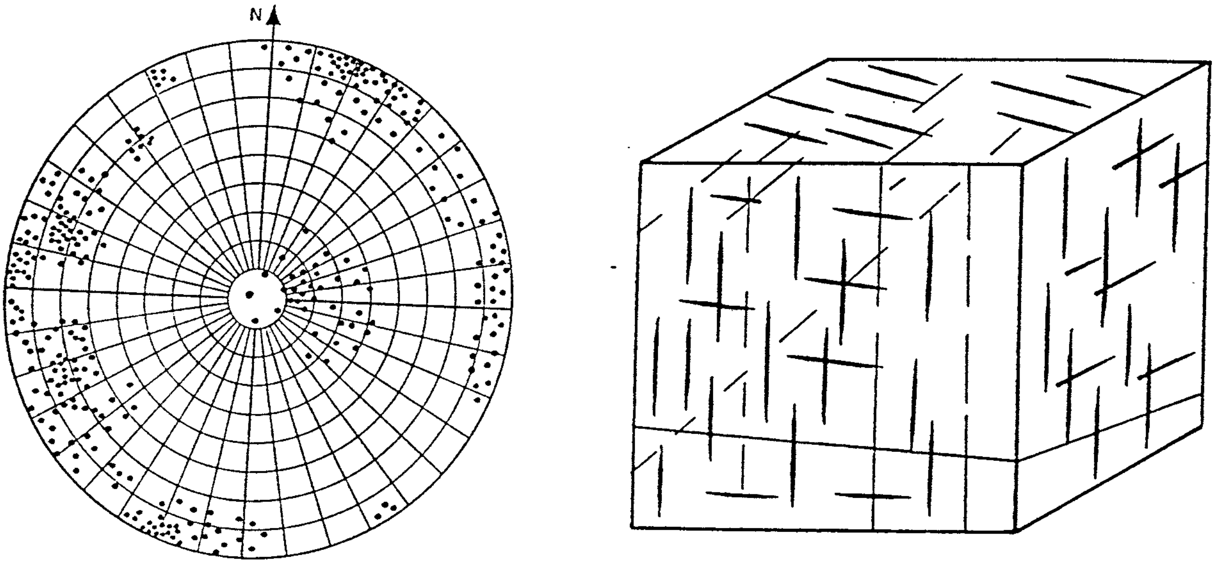


Fig.1 Characteristic pole diagram and schematic macrostructure of granite

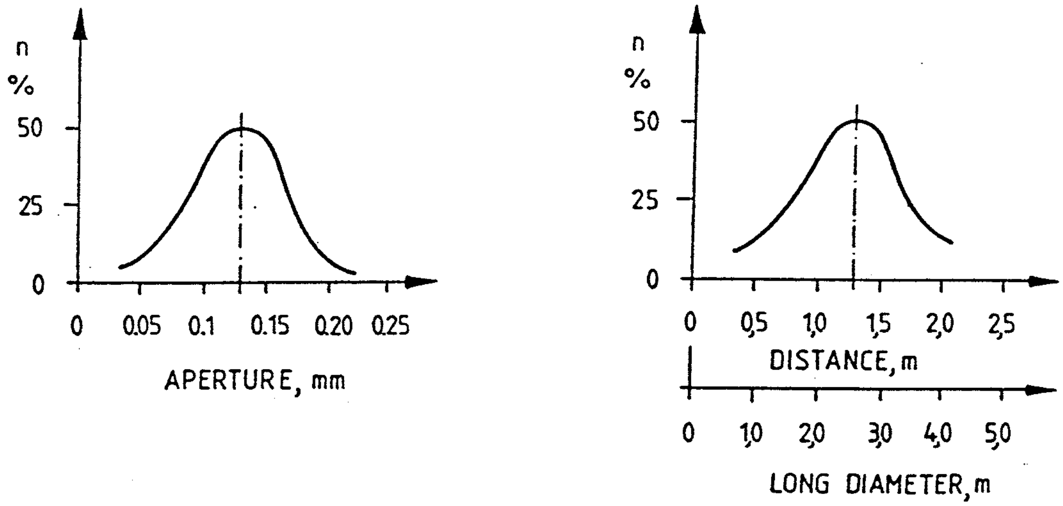


Fig.2. Example of distribution curves of apertures, length, and spacing of water-bearing fractures in granite

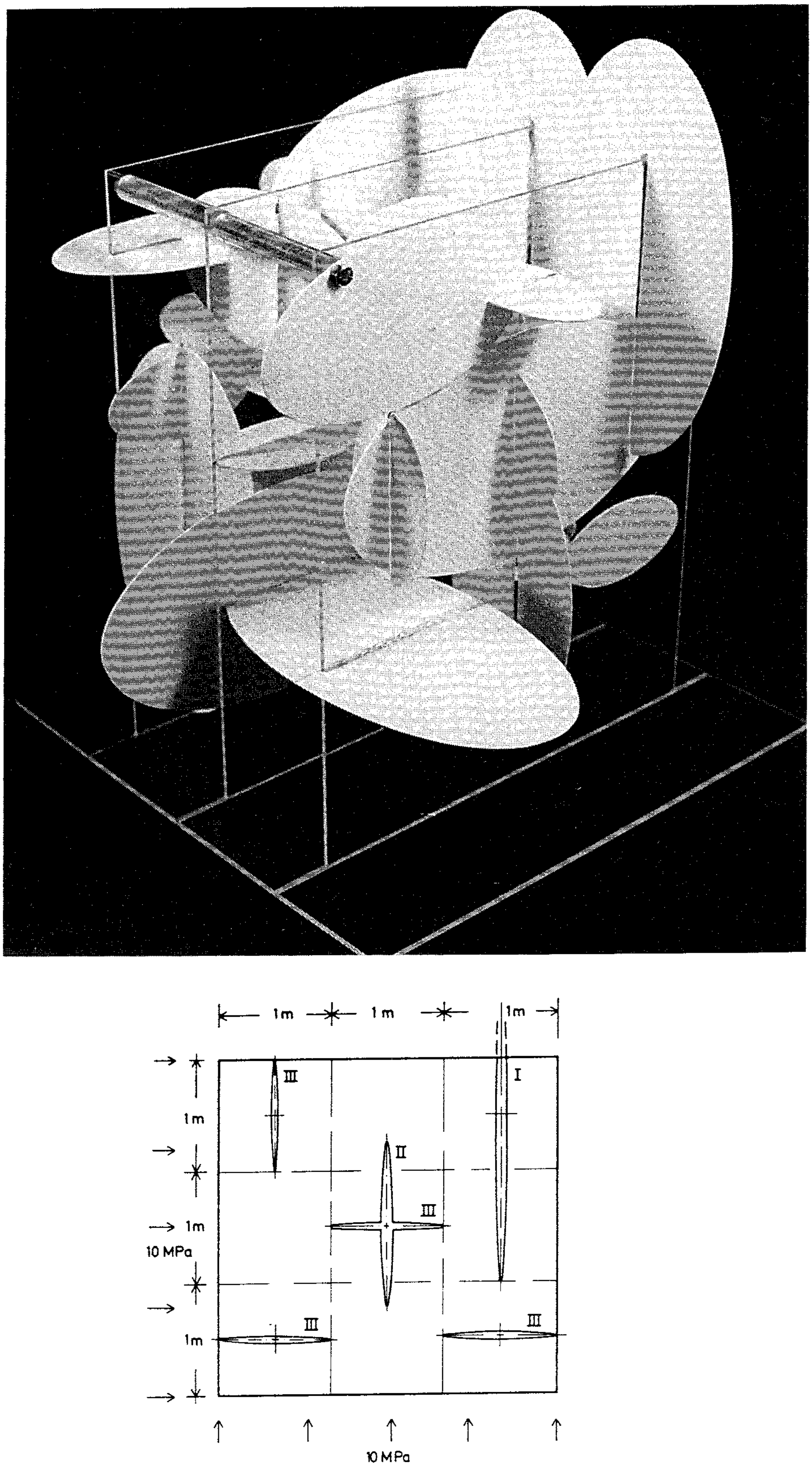


Fig.3. Physical fracture model with ellipsoidal fractures that appear as white discs. Lower picture illustrates an arbitrary cross section taken parallel to one of the outer boundaries of the cubical element

2.2.2 *General aspects of the effect of stress changes on the hydraulic conductivity of fractures*

2.2.2.1 Normal stress

This matter has been considered by various investigators but there does not seem to be an unanimous view or model that can be directly applied. A generalized relationship, based on simplified models like the one in Fig.3, would yield results that fit with the diagram in Fig.4, which illustrates the influence of normal effective stress changes on the hydraulic conductivity of a block of structurally isotropic granite with a volume of a few tens or hundreds of cubic meters. The actual flow pattern in the ellipsoidal fracture network is expected to be of the sort illustrated in Fig.5.

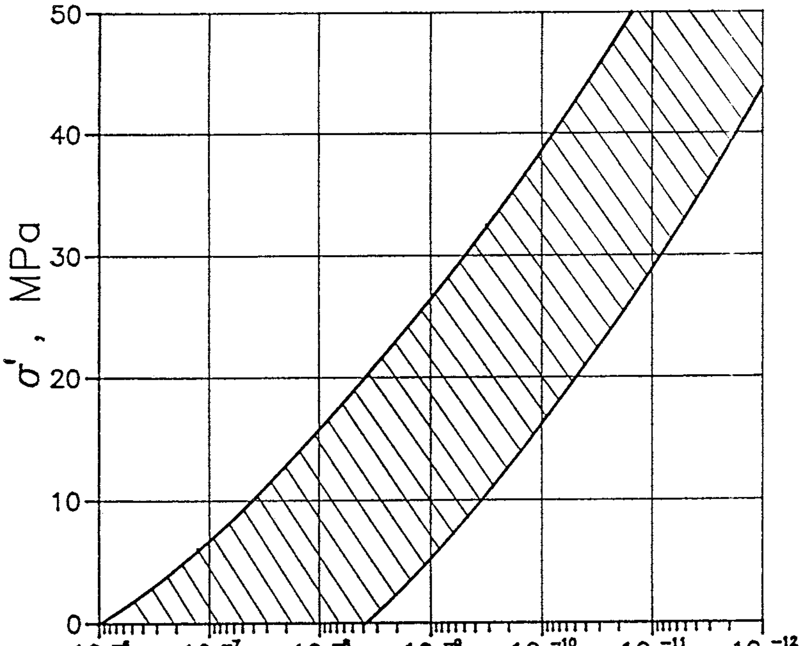


Fig.4. Estimated influence of uniaxial change in normal stress on the hydraulic conductivity of granite block

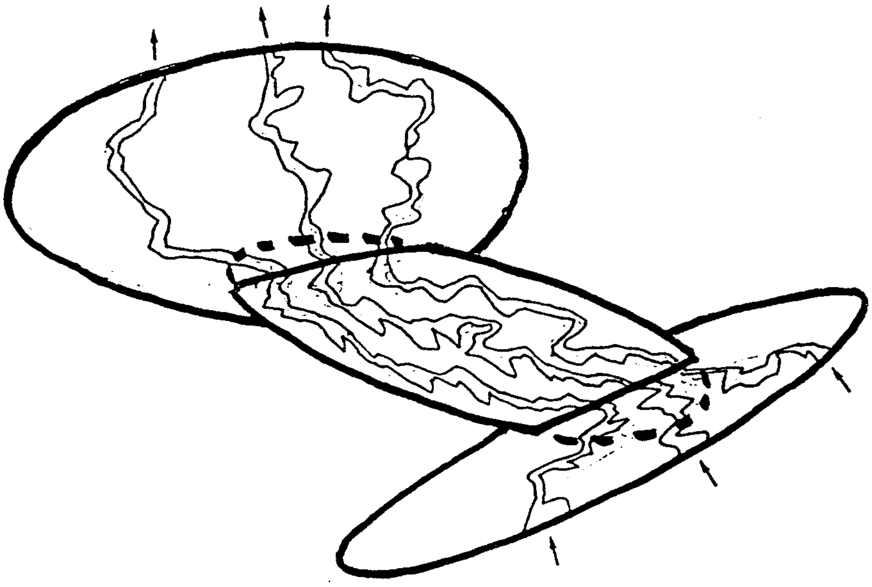


Fig.5. Concept of flow channels in a sequence of three interconnected fractures (after Tsang, 1987)

2.2.2.2 Shear

Shear will take place along pre-existing fractures in conjunction with the alteration of the general stress field caused by excavation, and it will also generate fissuring at the highly stressed tip of the boreholes, i.e. where the borehole wall meets the base of the hole at an angle of approximately 90^{o}, as well as in the close vicinity of borehole walls where very high tangential stresses prevail.

The matter has not been thoroughly investigated with respect to the associated change in hydraulic conductivity and no general laws have been proposed in the literature. However, the average order of magnitude of shear-induced changes in permeability can be estimated on the basis of available laboratory data from shearing initially intact rock under high compressive stresses, and from measurements of shear displacement of rock elements along pre-existing fractures.

Considering first shear at the tips and walls of boreholes, numerical solutions of the problem of stress/deformation and stability analyses have been obtained by employing the finite element method, taking into consideration nonlinear stress/strain behavior. Good agreement has been reported on comparing calculated and experimentally determined behavior using photo-elastic models, a study by Desai & Reese being particularly interesting since it concerns deep holes with a diameter of 30 cm (2). Thus, applying reasonable strength parameter values and using Mohr/Coulomb failure theory, it has been found that plastization to within several centimeters from the wall is expected at the borehole tip (Fig.6) at depths of a few thousand meters in the case of such large holes. Depending on the principal stress ratio, there may also well be plastization all along the borehole wall to a distance of a few centimeters in such deep holes. Naturally, highly stressed local zones may develop at the walls of boreholes of any size and depth provided that the tangential stresses are sufficiently high to produce plastization, which may cause rock-burst at the free surface and foliation just beyond it. At further distance from the free surface, the confining pressure prevents large strain but allows for considerable microstructural breakdown.

Triaxial shear tests on granodiorite, gneiss, and mylonite carried out at constant temperature (20 - 600^{o}C), cell pressures exceeding 100 MPa, and strain rates of 10^{-6} to 10^{-4} s^{-1}, have confirmed earlier experience that - under high compressive stresses - intense "cataclastic" fragmentation is produced and

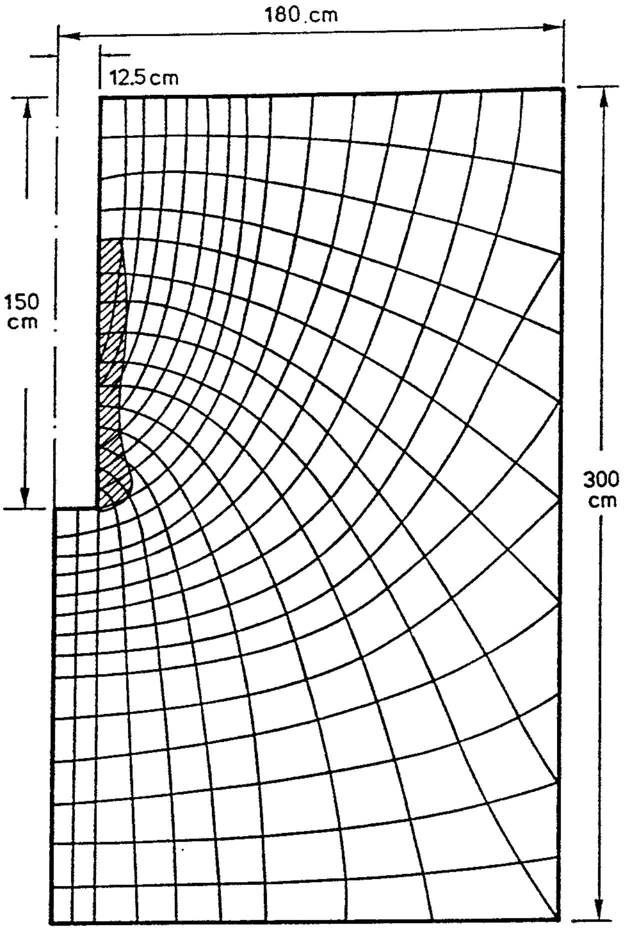


Fig.6 Plasticizing at the tip and walls of 30 cm borehole at a few thousand meters depth (2)

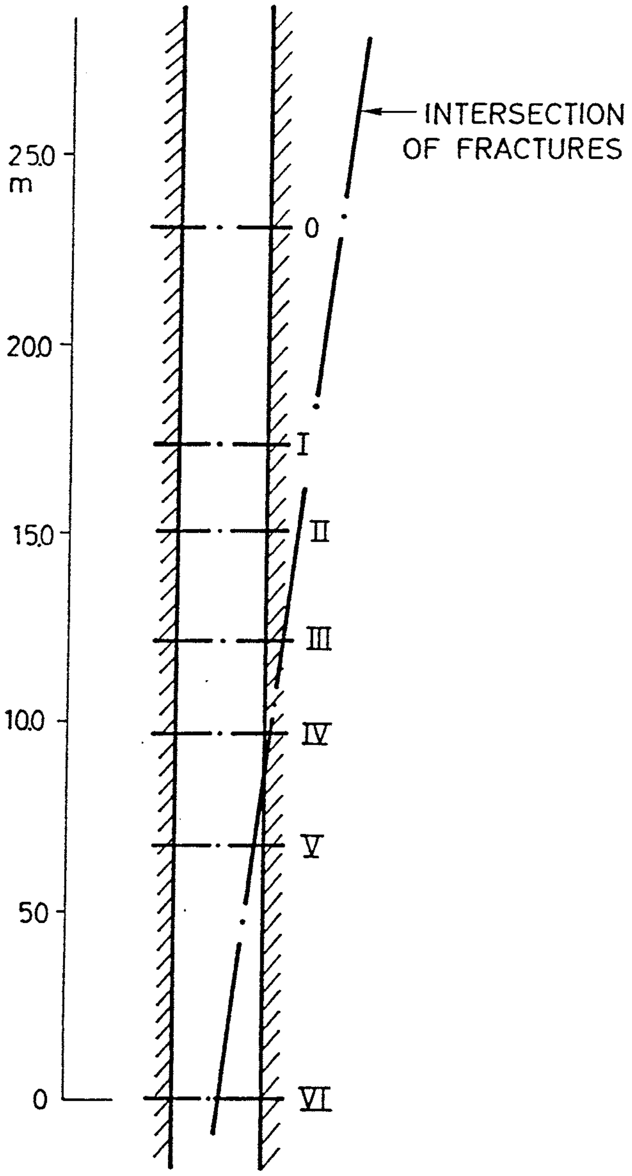
that large strain (10 - 20 %) can be sustained without significant loss in strength (3). Also, typical shear bands deviating more or less by 45° from the direction of the major principal stress were noticed, showing that the failure behavior of the very deformed materials was Mohr-Coulombian. It is clear from this that rock shear failure taking place at very high stresses is associated with rich fissuring but an insignificant change in porosity, which means that the hydraulic conductivity of the overstressed rock will be almost unaltered. It is even possible that the bulk conductivity will be decreased because continuous fractures may be disrupted and disconnected. However, close to the free rock wall, i.e. where unconfined compression takes place, shear failure can take place yielding break-out and a strong increase in porosity. In practice, all this means that large-diameter boreholes for rad waste disposal need to be supported by a suitable mud in order to avoid permanent increase in axial conductivity.

Considering now the second type of shear influence, i.e. aperture changes by shear displacement, literature data suggest that the matrix of compliance components of rock joints is pertinent and various investigations have led to some understanding of how contacting, irregularly shaped rock surfaces behave on tangential shearing (4,5). The matter is very complex and the variation in response to stress changes so large that not even a crude model of general validity can be formulated today. The subject will be touched on later in the text and we will confine ourselves here to conclude that changes in the normal stress appear to be of greater significance than shear stresses, at least when the former are in the range of 10 - 20 MPa. Referring to literature data it is concluded that the permeability of a discrete fracture is increased by about one order of magnitude by a 1 mm shear displacement under low and moderate normal stresses, while the increase may be twice this figure on shearing it by an amount of 5 mm.

2.2.2.3 Effects of stress changes on the conductivity of rock around large-diameter boreholes (UDEC study)

It is obvious already by simple phenomenological models that certain steeply oriented, "axial" fractures close to large-diameter boreholes will expand due to stress release. Thus, one finds, by conducting stress/strain calculations using the UDEC code, that rock wedges may represent critical rock components with respect to the "axial" hydraulic conductivity and that an appreciable widening can take place of their boundary fractures. We will consider a representative case here, which serves to illustrate the character and magnitude of the conductivity.

The example is based on the assumption that the rock structure is characterized by orthogonal, widely spaced plane fractures of long extension, two of the fractures oriented NW/SE and SW/NE intersecting close to or within the 1.5 m diameter hole that we will consider. The primary stress field is taken to be characterized by a major principal stress of 20 MPa, orinted W/E, and a minor principal stress of 10 MPA (N/S). The properties of the rock matrix are E=70 GPa, ν=0.21, and ρ=2.63 t/m^3, while those of the fractures are c=0 MPa and ϕ=25^o. The fracture aperture is not an input to the calculations, which refer to a 2D case and which do therefore not illustrate the true stress/strain conditions of the rock wedge and its surroundings. However, it is believed that the very steep orientation of the fractures (dip = 86 - 88^o) still yields a qualitatively correct picture and flow values of the right order of magnitude. Figs.8 to 13 show the principal stress distribution and the change in aperture of the steep fractures at different locations of the fracture crossing (Fig.7). The theoretical, average axial hydraulic conductivity of the near-field zone, assumed here to extend one diameter, i.e. 75 cm, from the periphery of the hole, is 1.09x10^{-9}- 2.7x10^{-9} m/s applying the cube law and assuming room temperature conditions, and an initial average fracture aperture of 20 micrometers.



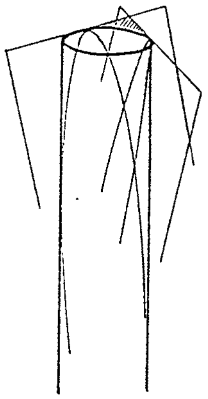


Fig.7. Cross section of 1.5 m borehole indicating levels that have been considered in the UDEC calculations. ("Rock wedge")

Level 0

Here, the fractures are located about 70 cm from the periphery of the large borehole. Fig.8 shows that the principal stress ratio in the right block is not too different from what it was before the excavation, while the rock at the northern and southern parts of the periphery is exposed to tangential compressive stresses of up to 45 MPa. The maximum shear strain along the fractures is about 100 micrometers, the maximum closing about 4 micrometers, and the maximum widening about 15 micrometers. *The changes in aperture yield a net increase in average "axial" hydraulic conductivity of the near-field to* 4.2×10^{-9} *m/s, i.e. a four-fold enhancement.*

Level I

Here, the shortest distance between the fractures and the periphery of the hole is about 35 cm. Fig. 9 shows that the stress situation is very similar to the one prevailing at the 0-level. The maximum shear strain along the fractures is about 130 micrometers, the maximum closing nearly 4 micrometers, and the maximum widening about 30 micrometers. *The changes in aperture yield a net increase in average "axial" hydraulic conductivity from* 2.4×10^{-9} *m/s of the virgin rock to* 1.8×10^{-8} *m/s, i.e. by 7 times.*

Level II

Here, the fractures are located about 18 cm from the borehole periphery. Fig.10 indicates that the stress situation is much the same as at the two upper levels, with the exception that the maximum tangential compressive stress is about 49 MPa, which means that the probable strength of the rock material is being approached. Fissuring is expected here with a possible enhancing effect on the bulk conductivity. *The changes in aperture yield an increase in axial hydraulic conductivity from* 2.8×10^{-9} *m/s to* 1.9×10^{-7} *m/s, i.e. about 70 times.*

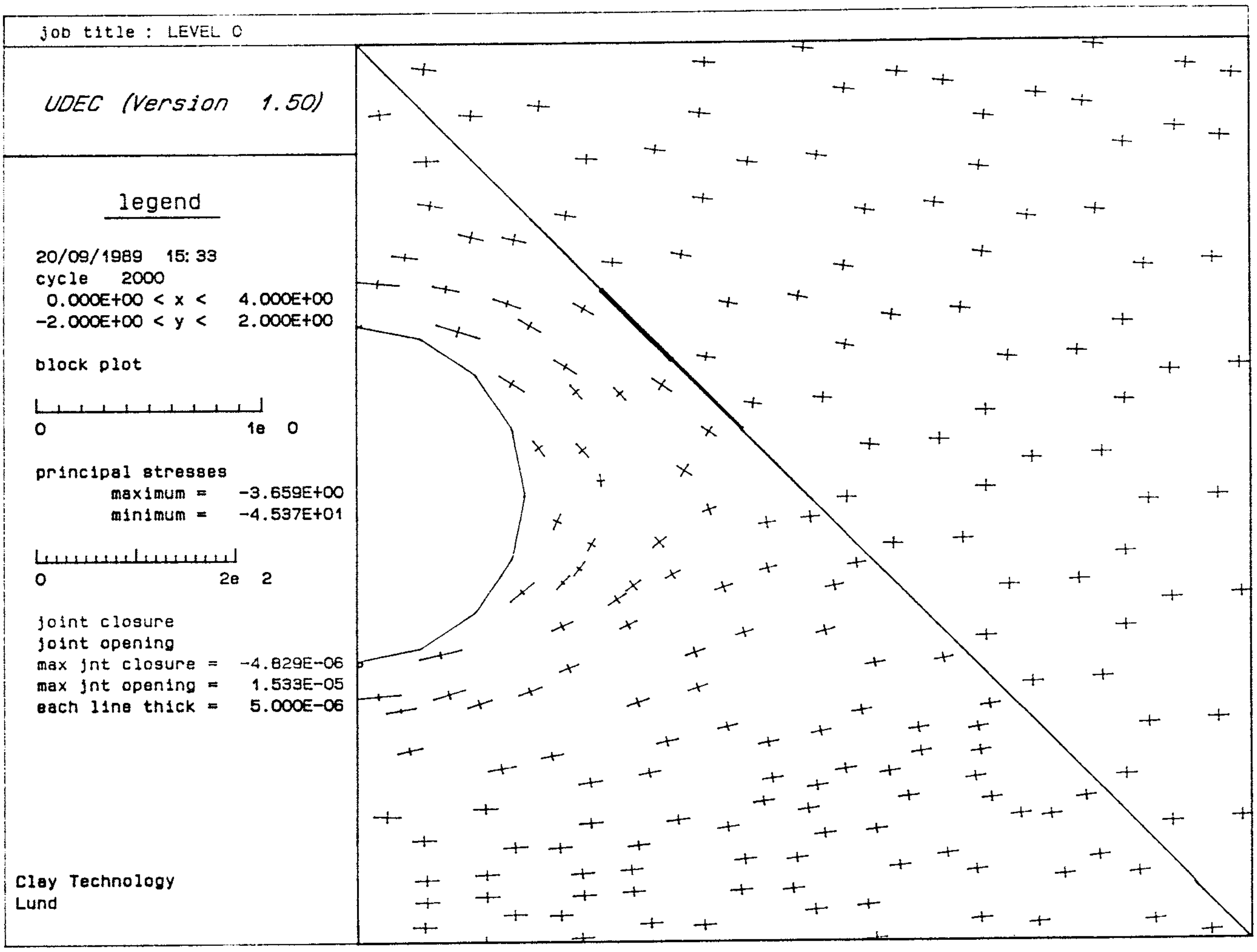


Fig.8 UDEC-calculated stress pattern and changes in aperture of fractures forming a rock wedge. Level 0

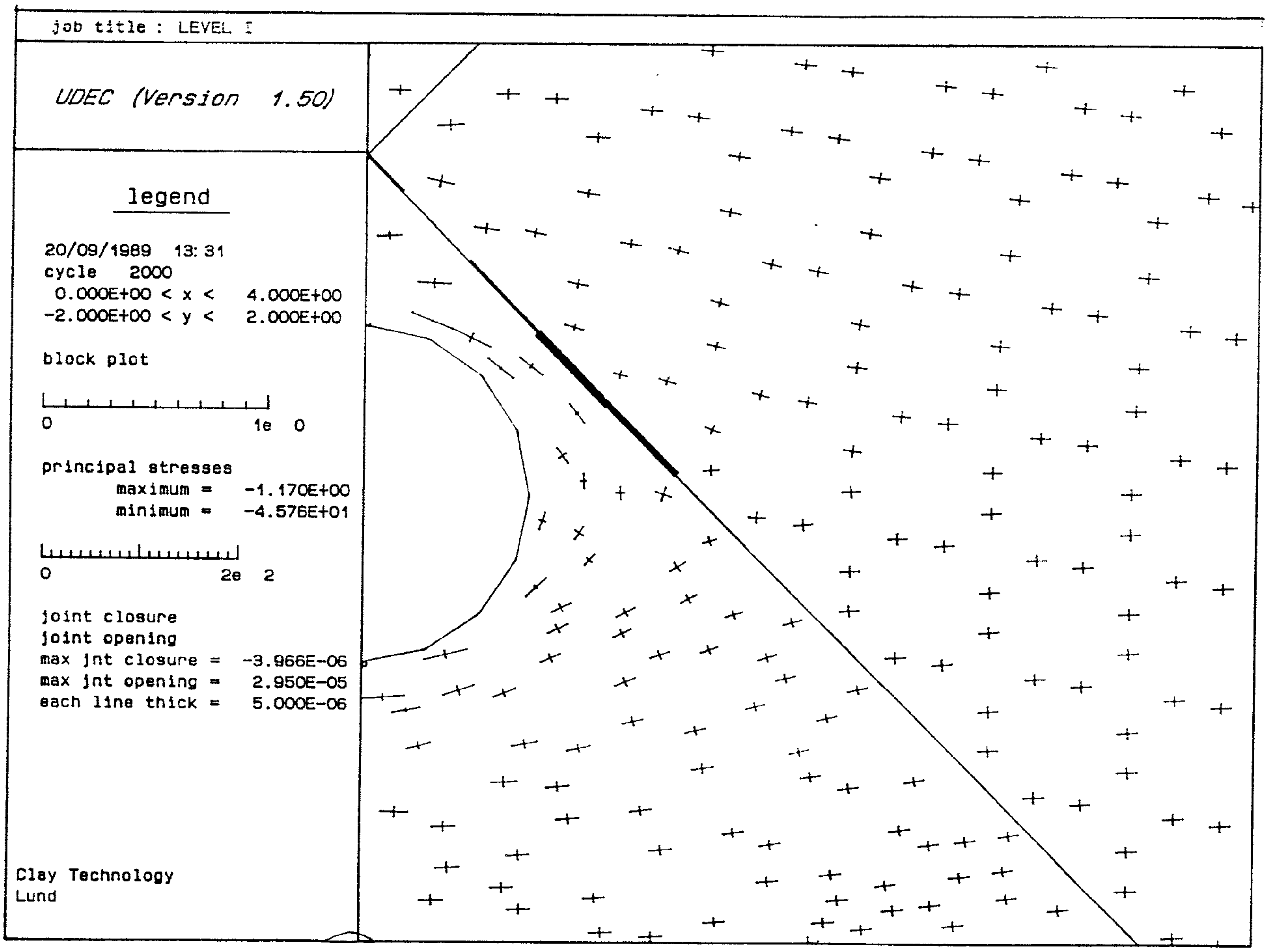


Fig.9. UDEC-calculated stress pattern and changes in aperture of fractures forming a rock wedge. Level I

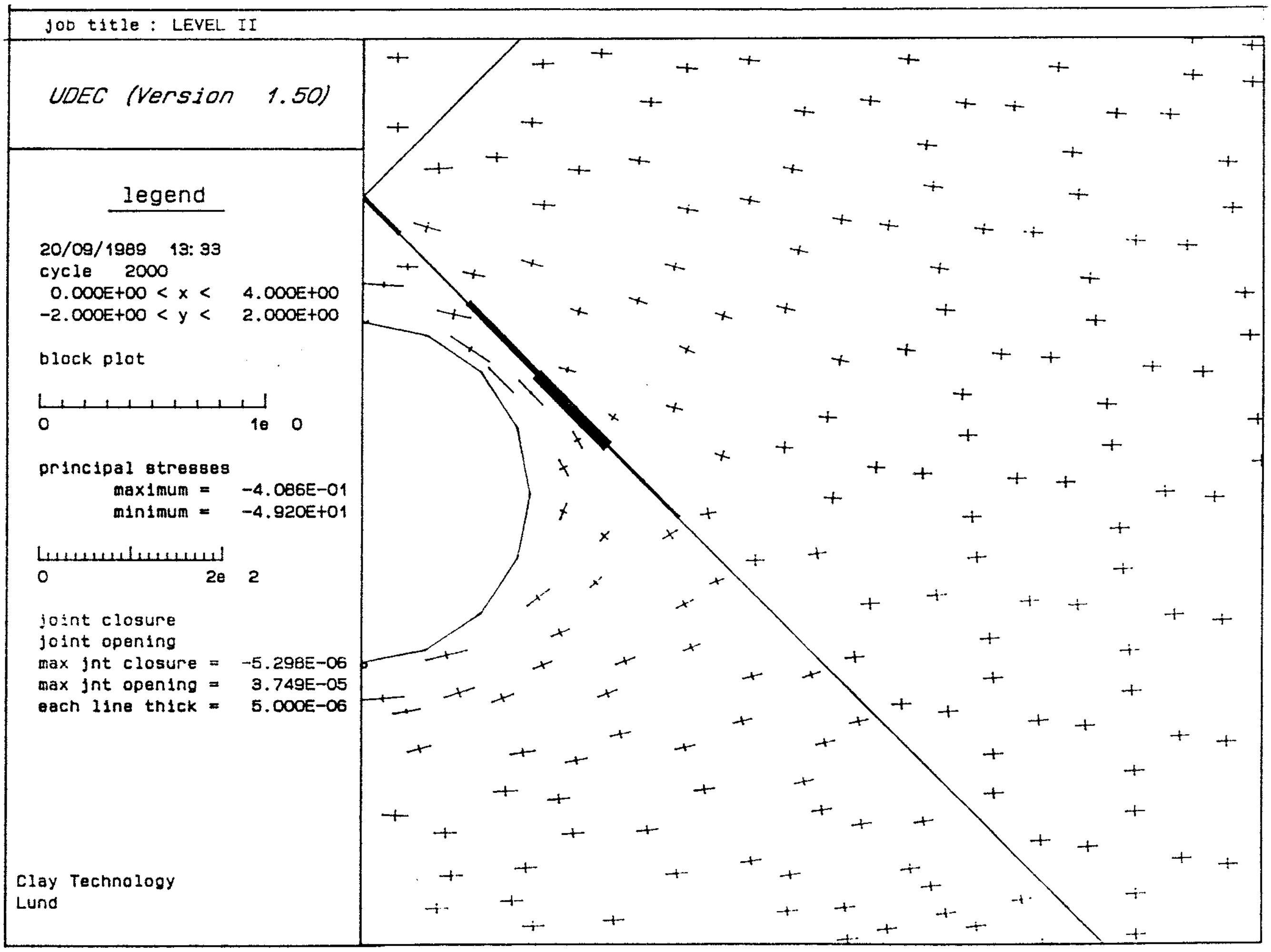


Fig.10. UDEC-calculated stress pattern and changes in aperture of fractures forming a rock wedge. Level II

Level III

At this level the fractures touch the periphery and thereby separate the "wedge" from the rock mass (Fig.11). This causes unstable conditions and fall of the wedge if it is not held in position by internal pressure in the hole (mud). The lack of stability is not obvious from the UDEC calculation since it assumes a constant horizontal cross section and infinite length of the wedge. Although the accuracy of the evaluated stresses and aperture changes are debatable they are considered to be on the right order of magnitude. Thus, it can be assumed that *the maximum tangential compressive stress is more than 50 MPa leading to fissuring and possible break-outs, that the maximum shear strain exceeds 400 micrometers, and that the changes in aperture yield an increase in average axial conductivity from the original* $2.9x10^{-9}$ *m/s to at least* $3.5x10^{-6}$ *m/s, i.e. by more than 1000 times.*

Level IV

At this level a very small wedge is located at the point of intersection of the fractures (Fig.12). Because of the smaller dimensions the accuracy of the derived data is less good and they will not be further discussed. However, it is seen that the results are qualitatively consistent with those of Level III with respect to stresses and to the tendency of the fractures to be widened locally.

Level V

At this level the fracture planes intersect within the hole (Fig.13). Very high tangential stresses still prevail (up to 50 MPa) and some local tensioning takes place in the rock matrix but there is no widening of the fractures. Actually, the fractures will be closed locally by an amount that equals their original aperture.

Level VI

At this level the point of fracture crossing coincides with the center of the hole, which yields compressive stresses in all parts of the rock mass and no increase in axial hydraulic conductivity.

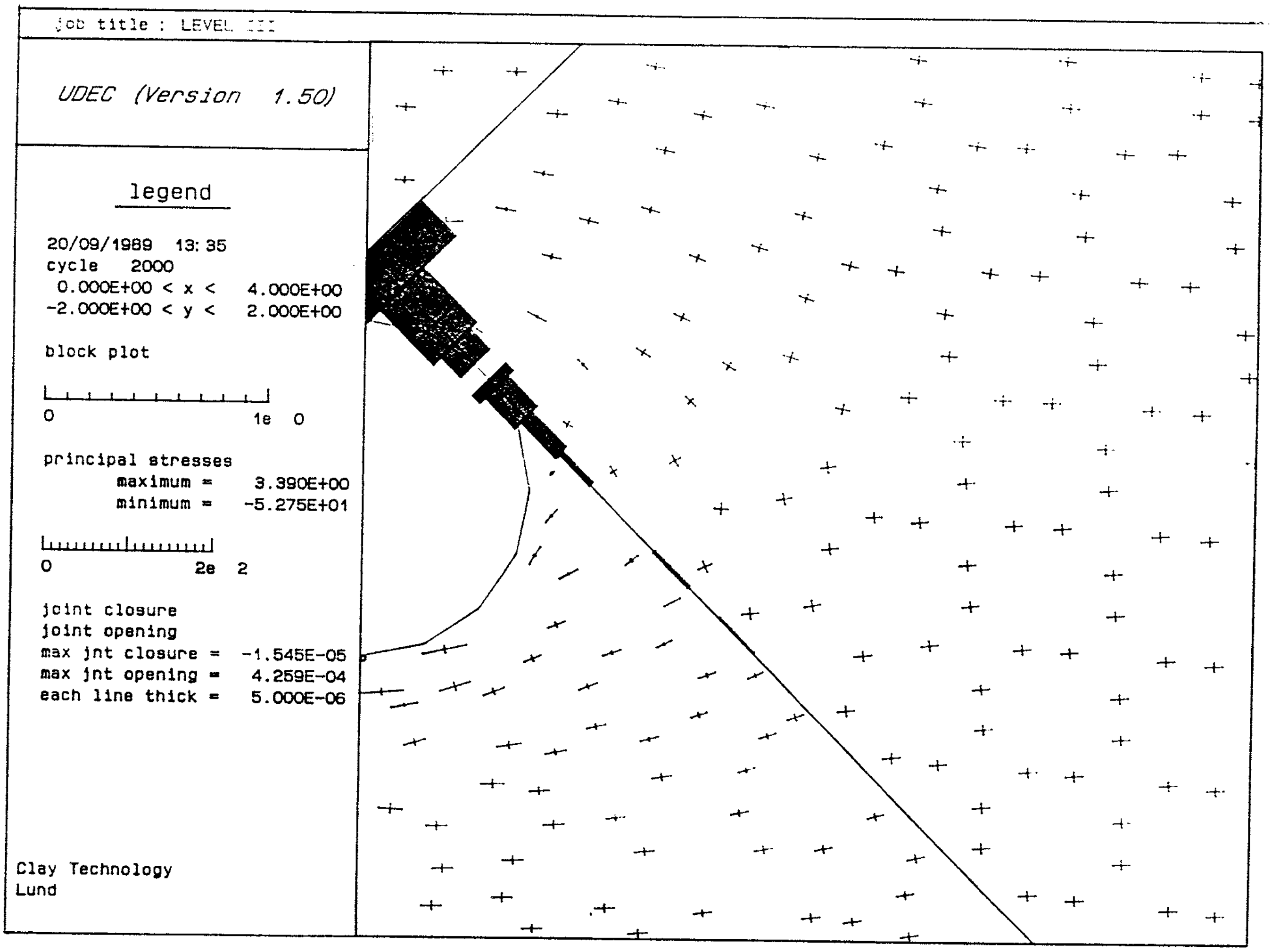


Fig.11. UDEC-calculated stress pattern and changes in aperture of fractures forming an unstable rock wedge. Level III

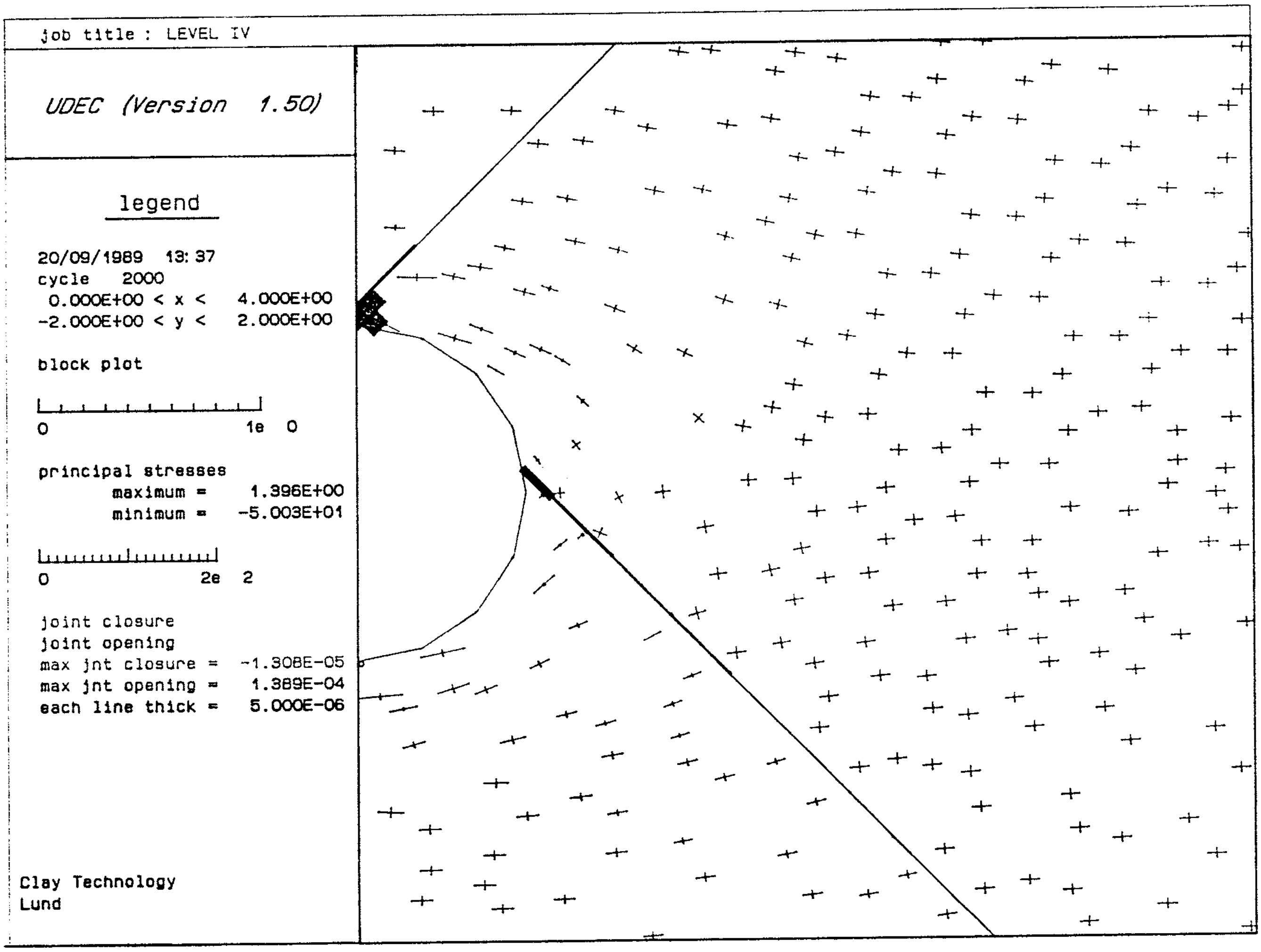
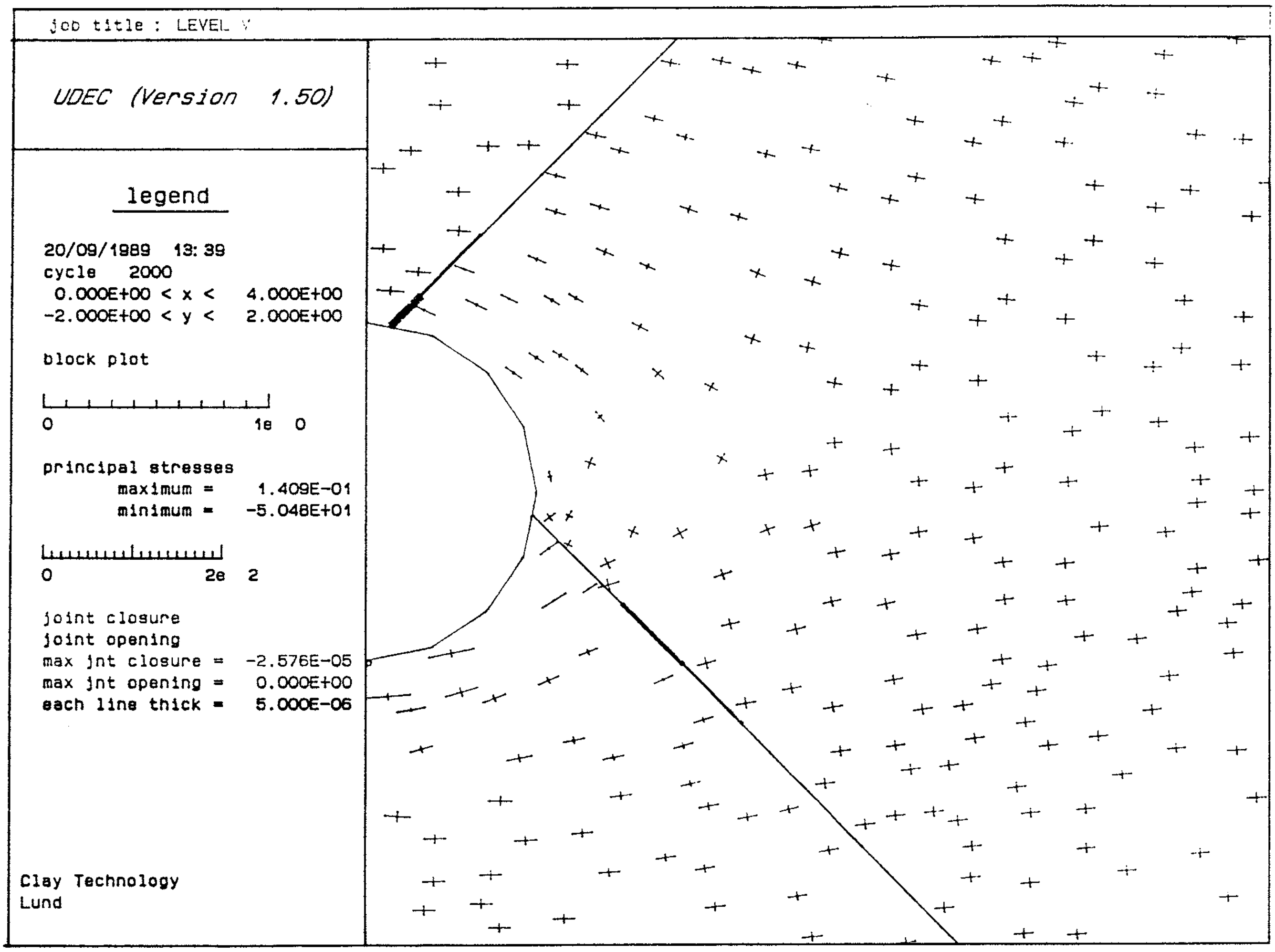


Fig.12. UDEC-calculated stress pattern and changes in aperture of fractures forming an unstable rock wedge. Level IV



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UDEC (Version  1.50)

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-2.000E+00 < y <   2.000E+00

block plot

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principal stresses
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        minimum =   -5.048E+01

0              2e  2

joint closure
joint opening
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max jnt opening =    0.000E+00
each line thick =    5.000E-06

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Fig.13. UDEC-calculated stress pattern and changes in aperture of fractures intersecting in large borehole. Level V

A number of conclusions can be drawn from this simple study, the major ones being:

1. The UDEC code for 2D analysis of stress conditions and aperture changes of axially oriented fractures yields values that are in reasonable qualitative and quantitative agreement with phenomenological/analytical models. Still, 3D analyses are asked for in order to get a safer picture of the aperture changes. On the one hand the presently determined fracture widening may be somewhat too large, while on the other hand it may be underestimated because of the applied condition of constant stiffness of the fractures. A further desired expansion of the study would be to investigate systematically the influence of other primary stress ratios and fracture parameters (cohesion, internal friction)

2. The general structural features of granite with respect to the orientation and frequency of *major, long-extending* fractures generate rock wedges in large vertical and horizontal boreholes. Such wedges represent unstable rock blocks, along which water passages will be created at common primary rock stress conditions, thereby increasing the "axial" hydraulic conductivity by tens or hundreds of times

3. The assumed average, initial fracture aperture of 20 micrometers is somewhat too large since it yields a bulk rock conductivity that is higher than one would expect at least at larger depths. This means that the evaluated relative increase in bulk

conductivity is underestimated, provided that the aperture changes given by the UDEC calculations are reasonably correct

4. Steeply oriented fractures that are located very close to deep, large-diameter boreholes are most strongly affected by excavation-induced stress alteration. This means that superimposed structural damage by excavation operations involving mechanical fragmentation, combine to yield significant changes in conductivity of the near-field rock

3 GENERATION OF STRUCTURAL DAMAGE AND ASSOCIATED INCREASE IN CONDUCTIVITY BY EXCAVATION OF ROCK THROUGH DRILLING OR SMOOTH BLASTING

3.1 General

In addition to the impact on rock structure by stress alteration effects, the dynamic agitation induced by percussion hammering and the very high contact pressure and shear stresses at the contacts between bits and the crystal matrix involved in other rock excavation techniques, affect pre-existing fractures and induce new ones in the walls of boreholes. Together, all these processes are assumed to have an influence on water movement and radionuclide migration in the "near-field" rock surrounding deposition holes.

The present report summarizes available information on the effect of rock excavation, centering on the influence of different drilling methods on the rock structure. *In estimating the influence on the hydraulic conductivity, reference conductivities of* 10^{-11} *m/s of an undisturbed rock mass and* 10^{-13} *m/s of fracture-free crystal matrix will be assumed.*

3.2 Fracture generation in borehole walls

3.2.1 *Drilling techniques*

Drilling of large diameter deposition holes can be made by percussion hammering (slot drilling) and rotary drilling (full-face or coring). In both cases the contact pressure between the drill bits and the rock will be very high and serve to disintegrate the crystal matrix through crushing and shearing, the first-mentioned type of drilling having a particularly strong impact on the structure by the imposed stress waves.

Percussion hammering

"Discing" in granite

Numerical calculation of the axial stress along the borehole wall using FEM has indicated that percussion drilling may cause "discing", i.e. formation of sets of plane, disc-shaped fractures oriented perpendicularly to the borehole axis (6). They are assumed to result from tension induced by the percussive stress waves since the study indicated that the axial tensile stress close to the hole can be up to 20 times higher than the tensile strength of fracture-free rock. Theoretically, the spacing of such fractures should be about the same as the borehole diameter (Fig.14).

The study also showed that preexisting fractures of this same orientation would be opened by an amount approximately equal to the elastic depression of a free rock surface loaded statically by the drillbit. While such expansions would be of elastic nature and short duration, one would assume that rock debris will be driven into expanded fractures causing partial permanent expansion and blocking of the fracture openings, yielding some weakening and alteration of the hydraulic conductivity of the fractures. The conductivity may either be increased or decreased by this process.

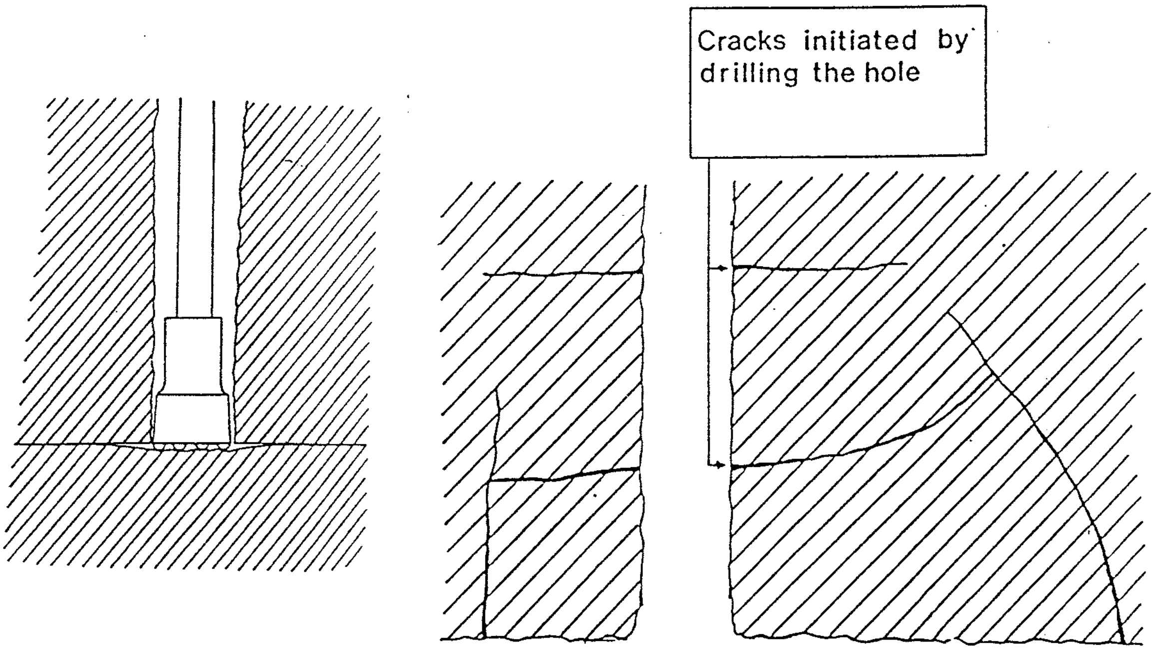

Fig.14. Creation of "discing" around boreholes drilled by percussion hammering (After Wijk)

The presence of regular sets of fractures induced by percussive drilling does not seem to have been documented in practice, possibly because of their relatively small apertures and since they should be more common close to the rock surface (tunnel floor and walls etc), where they escape identification by appearing among other fractures in the "disturbed" zone, than deeper down in boreholes.

The possible production of "discing" by percussive drilling should be further investigated since it may have a very significant influence on the validity of hydraulic data obtained by logging in boreholes of this sort, and since it may also be a determinant of the fracture pattern and rock structure in blasted rock. It would be possible to conduct such studies by applying percussive drilling in "virgin" rock with subsequent overcoring using diamond drilling.

"Fragmentation" of granite

The rock located immediately below percussive bits is naturally strongly damaged and it follows from various investigations that the immediate surrounding of the drillbits, forming the shallow part of the borehole walls, is also significantly affected (7). The major breakdown mechanisms that yield penetration of the drillbits are: 1) Generation of tension fractures around the loaded area, and 2) Crushing of the rock below the loaded area (Fig.15). Detailed investigations indicate that the "diagonal" fractures extending from the corners of the borehole are 2 - 10 mm in length, and that the intensely crushed zones below and around the drill bit are 1 - 2 mm in depth.

The fracturing induced by the drill bit is estimated to yield an increase of the porosity of the crystal matrix by 0.5 - 2.0 percent units, which in turn suggests that its conductivity is increased by one to three orders of magnitude. *For an initial conductivity of about* 10^{-13} *m/s, one would expect an increase to* 10^{-9} *m/s, at maximum.* In fact, the effect microstructural damage with respect to the hydraulic conductivity and migration of radionuclides is not well understood. Thus, freshly formed fractures have a very high energy potential and neoformation of tightening smectitic minerals may take place on shearing, rather than creation of a pervious medium. This matter will be discussed later in the report.

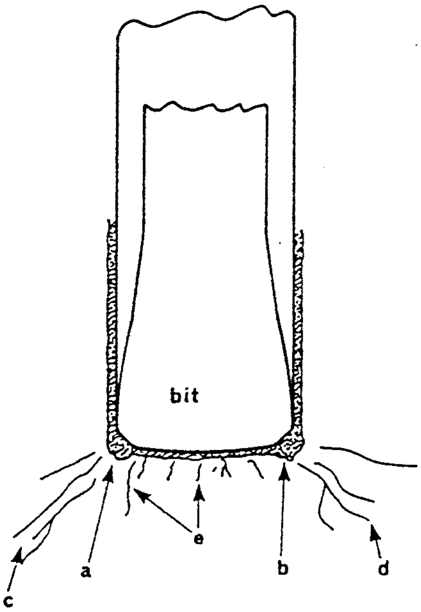

Fig.15. Characteristic indentation damage by percussion drilling. a,b Intensely crushed zones, c,d Diagonal cracks, e Vertical tensional cracks (8)

Rotary drilling

We will distinguish here between diamond core drilling and full-face drilling, the major difference being that the total load on the rock is much less in the first-mentioned case, and that the bits are smaller.

The cutting action of a diamond core drill bit is through surface failure, i.e. crushing due to thrust, and shear due to ploughing action of the bits. According to a model proposed by Wijk, crushing is produced when the lateral support of the loaded area is diminished by the development of the tension fractures, the whole process being very similar to the type of base failure under high static loads that has been reported from many field and laboratory tests (Fig.16, cf.9 and 10).

Considering the actual nature of the crystal matrix of igneous and methamorphic rock, which are both characterized by incomplete grain contacts giving rise to a certain permeability also of fracture-free rock elements, one can explain the nature of the fragmentation indicated in Wijk's model. Thus, Fig.17 shows, in a schematic way, the typical microstructure of the rock matrix with the existence of natural fine fissures that can be very local, and of incomplete crystal contacts, which, together with the fissures, represent almost randomly oriented Griffith defects.

Since the major principal stress (σ_1) is steeply oriented in the "active" zone below, and horizontally oriented in the "passive" surrounding zone, fractures in the latter are expected to be initiated at the tips of the elongated defects and to propagate parallel to the major principal stress as indicated in Fig.18. The resulting macroscopic failure would resemble that of Prandtl materials (Fig.19), yielding chips shaped as proposed by Wijk (Fig.16), although the involved fracture mechanics is different. Wijk's observation that the rock material is crushed below rotary drillbits is compatible with the wellknown fact that such disintegration occurs in brittle material at high deviatoric stresses when the confining pressure is significant.

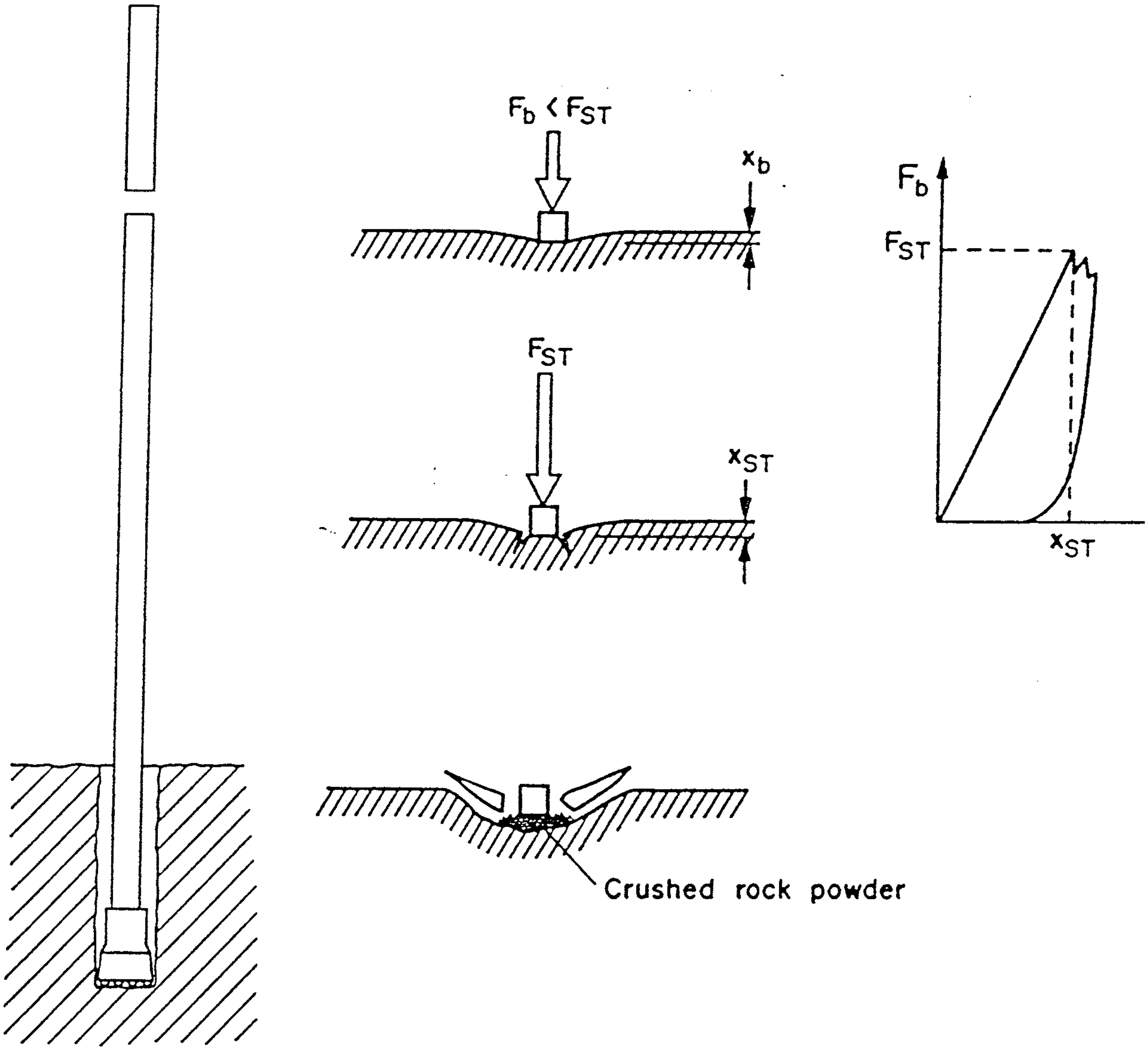

Fig.16. Fragmentation of rock below and around drillbit due to high contact pressure (Wijk).

Upper: Subcritical load, elastic depression
Mid: Critical load (F_{ST}), peripheral tension fracturing
Lower: Failure load, fragmentation

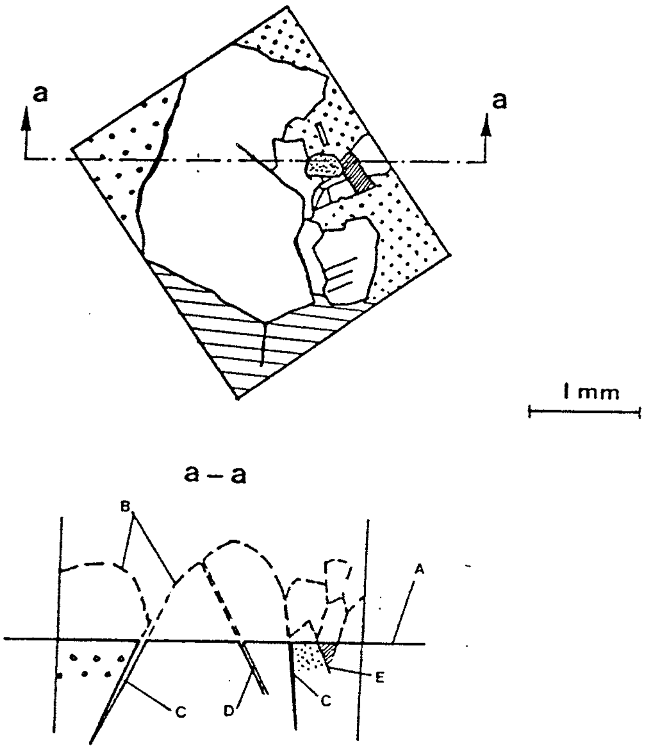

Fig.17. Graphical interpretation of actual rock section. A) Polished surface of the 30 microns thick section for microscopy. B) Irregular surface of virgin fracture. C) Incomplete crystal contacts. D) Fissure. E) Tight crystal contacts yielding matrix cohesion.

It should be mentioned that the views proposed here are in agreement with the concepts of fracture energy (11,12), and further work in this field may provide a deeper understanding of the involved fracture mechanics.

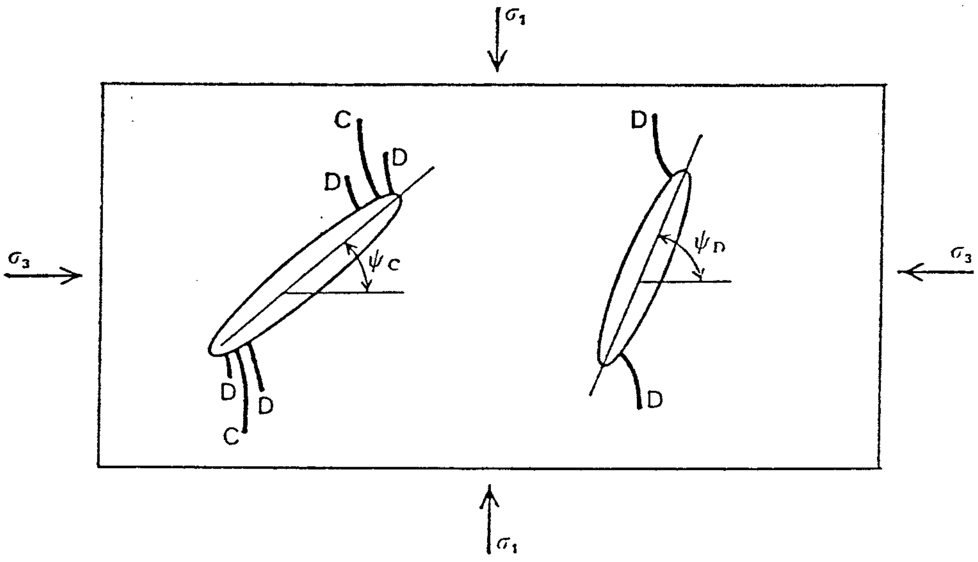

Fig.18. Tension fractures formed from the tips of critically oriented Griffith defects. C:s are formed first, D:s at higher stresses (Paul & Gangal).

According to Fig.19 the base failure under high static pressure normal to the rock surface and shear along it extends downwards and sideways to a distance from the bit that is controlled by its size, i.e. by the area loaded by the bit. Outside the failure zone one would assume that the rock is very little affected and this has also been demonstrated by detailed investigations (8). Thus, it is concluded that microstructural damage, which has the form of very fine shattering leaving the crystal matrix coherent, does not extend beyond about 2 - 3 mm from the free surface produced by diamond drilling. This damage appears to be less intense than that of the shallow disturbed zone at percussion drilling, and it is logical to assume that *the shattered zone has a hydraulic conductivity that does not exceed* 10^{-10} *m/s.*

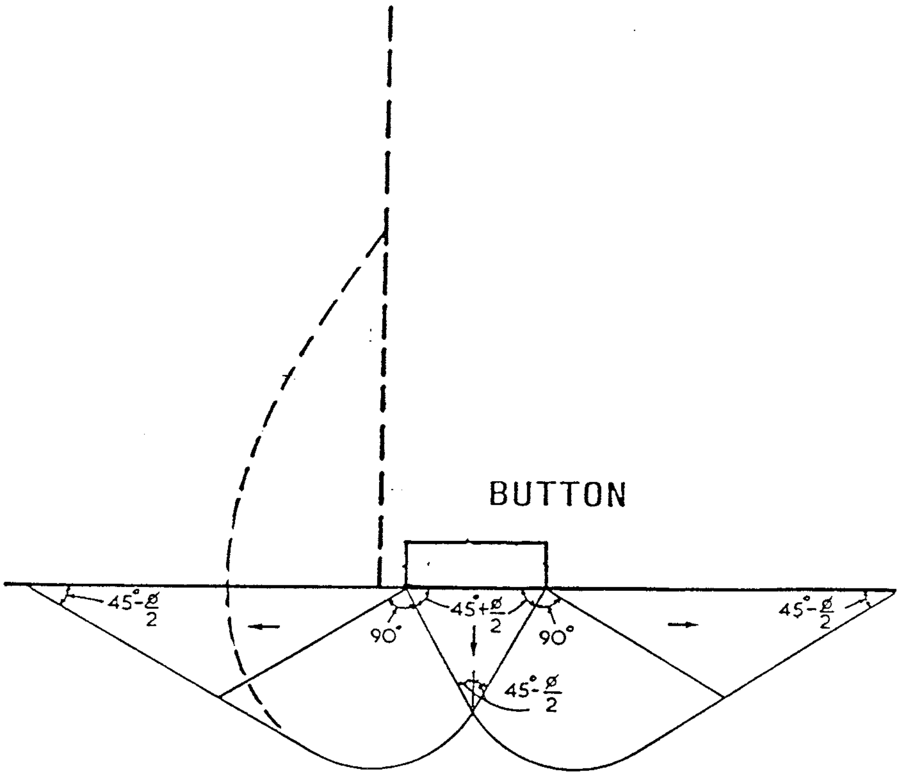

Fig.19. General failure mode of loaded rock. Broken curve illustrates fracturing when loading at borehole base. Arrows show orientation of the major principal stress.

Full face drilling

The damaging effect by full face drilling is due to the high thrust force at the front and to the afore-mentioned shattering caused by rotary drilling. Considering first the high load that is exerted on the rock, one finds that a thrust force of 1000 - 2000 t, transferred to the base of a 1.5 m diameter borehole a few meters down from a tunnel floor, would yield an elasto/plastic displacement of the base of about 0.5 to 2.0 mm. Most of this displacement is produced by elastic compression of wider fractures, but some of it is due to permanent, plastic deformation in the form of block movements in conjunction with reshaping of virgin fractures and creation of new ones. This latter effect can be assumed to appear in zones a - c indicated in Fig.20, and one concludes that it will be superimposed on the earlier mentioned fracturing due to the stress concentrations at the "corners".

An indication of what the extention may be of the zone of load-induced breakage or widened original fractures can be derived by use of the theory of elasticity, applying also a reasonable plasticizing criterion. Thus, Fig.21 shows the contact pressure distribution at different stress levels, expressed in terms of the factor of safety against base failure (F). Theoretically, a perfectly elastic medium yields an infinitely high contact pressure (p) at the edges of a rigid foundation (Boussinesq case), but in practice local plasticizing will take place here. In the case of rock it will have the form of fracturing and shear, the disturbed zone probably extending to a distance from the wall that is indicated in Fig.21. In practice, the factor of safety is more related to the magnitude of strain than to the nearness to a state of fully developed break-up of the rock, and it is estimated here that F can be taken as 3 - 10 in the case of full-face drilling. Hence, the disturbed zone will extend to approximately 5 to 15 cm from the wall of a 1.5 m diameter borehole.

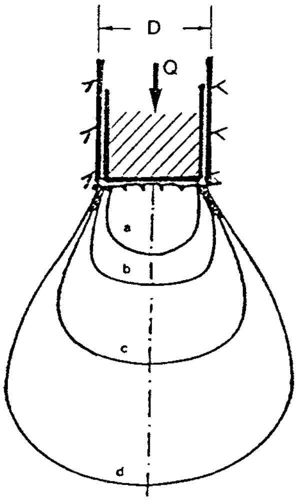

Fig.20. Influence zones of loading within which the generated normal and shear stresses may induce permanent structural changes.
ag) Strong, b) Moderate, c) Slight, d) Minor

Now considering the effect of fragmentation on the near-field rock it is realized that the contact area between drillbits and rock is somewhat larger than in the previously discussed cases (buttons are up to about 20 mm according to Gunnar Wijk, Atlas Copco) and the zone of influence of load and shear is consequently somewhat more comprehensive. It seems logical to assume that this zone will extend to 20 -50 mm from the borehole wall.

The combined effect of the unloading and loading processes, which is very much dependant on the primary stress situation and on the shape of the front of the machine (cf. Fig.22) is estimated to *cause an increase in bulk hydraulic conductivity from an assumed initial value of* 10^{-11} *m/s to about* 10^{-10} *m/s within about 1 decimeter distance from the* *borehole wall. The most shallow, 20 - 50 mm deep part of this zone, i.e. the part most affected by the fragmentation, is expected to have an average hydraulic conductivity of up to* 10^{-9} *m/s.*

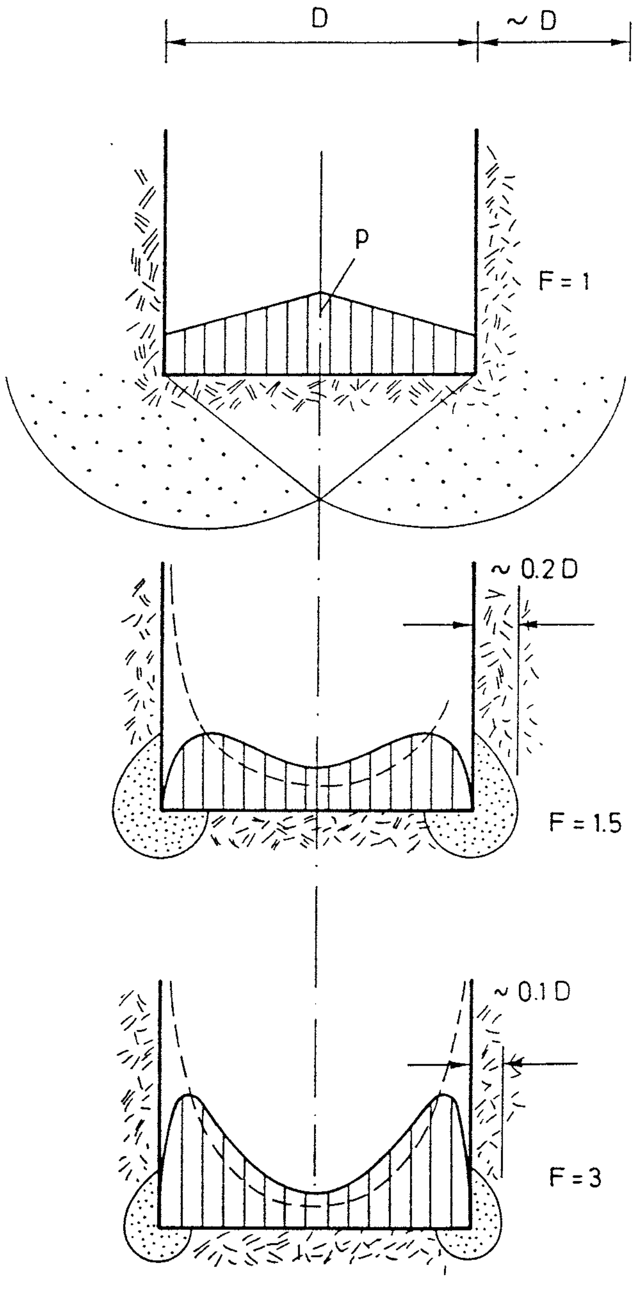

Fig.21. Schematic picture of the influence of the "factor of safety" (F) on the contact pressure (p) of rigid foundation on elasto/plasic base. The broken curves indicate the theoretical contact pressure for a purely elastic base

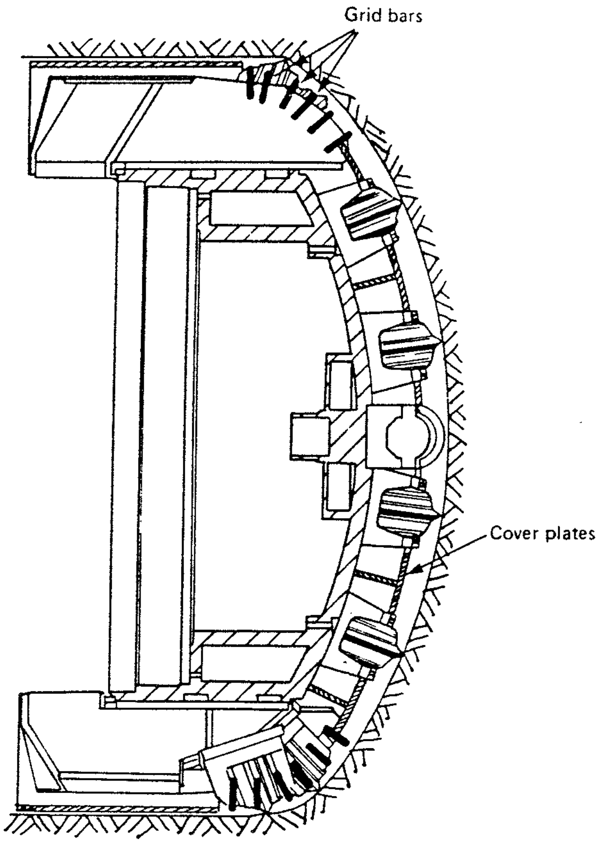

Fig.22. ROBBIN disc cutter head showing suitable shape of front to minimize stress concentrations at corners (After Graham)

3.2.2 *Smooth blasting*

The influence of blasting on rock structure and associated changes in hydraulic conductivity is a subject that has been dealt with in a large number of very comprehensive studies. We will confine ourselves here to consider, very generally, the effects of careful blasting, using minimum amounts of explosives and rather closely spaced slim holes.

Smooth blasting using 32 mm diameter holes with 20 cm spacing has been applied with considerable success by LBL for the production of a shaft in the Stripa mine (16). The resulting rock surface of the 1 m diameter shaft (half of the periphery of the shaft was produced by percussive drilling) was highly irregular with maximum and average "amplitudes" of about 20 and 10 cm, respectively, but the visible fracturing that can be ascribed to the blasting was moderate. Still, it is concluded that the formation of fractures was more intense than in the part that was drilled by percussive hammering.

The blasted shaft connected two parallel drifts which simplified emptying the blasted space, and half of the periphery was cut by use of percussive slot drilling, which preceded the blasting and facilitated the excavation very much. Also, it certainly minimized rock disturbances. A plugging test in the shaft comprised flow measurements which indicated that the axial hydraulic conductivity of the rock within 10 cm distance from the periphery was in the range of 10^{-8} to 10^{-6} m/s. This indicates considerable disturbance, most of which can be ascribed to mechanical effects generated by the blasting.

A general conclusion would be that the rule of thumb, suggested by Halen and Andersson (17) applies, i.e. that fractures are formed or widened to within a distance in meters from the periphery of a shaft or drift that is equal to the charge in kilograms per meter borehole length. It implies that also when using very careful blasting it is not possible to produce large diameter holes without creating a conductive zone extending to at least a couple of decimeters from the periphery. Since the matter is of considerable importance in the present context we will still consider careful blasting in some more detail here, aiming at a simple model for estimating the extension and conductivity of the disturbed zone.

Fracture formation

Charge detonation produces a very high gas overpressure of short duration and this breaks up the rock by brittle fracturing. Cracks are formed extending radially from the blasted holes and more or less prismatic blocks are released from the rock mass due to the tensile stresses that are set up by the reflection of the shock wave.

The extension of fractures generated by detonation can be roughly estimated by assuming that the volume of the fracture is equal to the reduction of rock volume due to its compression in the crack generation phase. Such calculations lead to penetration depths in homogeneous, isotropic granitic rock of only a few decimeters if the amount of explosives is kept at minimum. This supports the afore-mentioned simple rule relating the extension of damage to the amount of explosives, which is also in agreement with actual determination of the fracture depth by drill coring.

In short, blasting generates new fractures and affects original ones in the remaining rock mass in the following ways (c.f.Fig.23) :

1. Creation of one or a few plane, oriented fractures (I and II). Fig.24 serves as an illustration of such discontinuities

2. Local crushing of the rock at the tip, especially on using "starter" explosives

3. Natural fractures that are intersected by the blasted holes become expanded and they may propagate

4. Fine fracturing is produced in blocks with an initial stress state and orientation that make them vulnerable

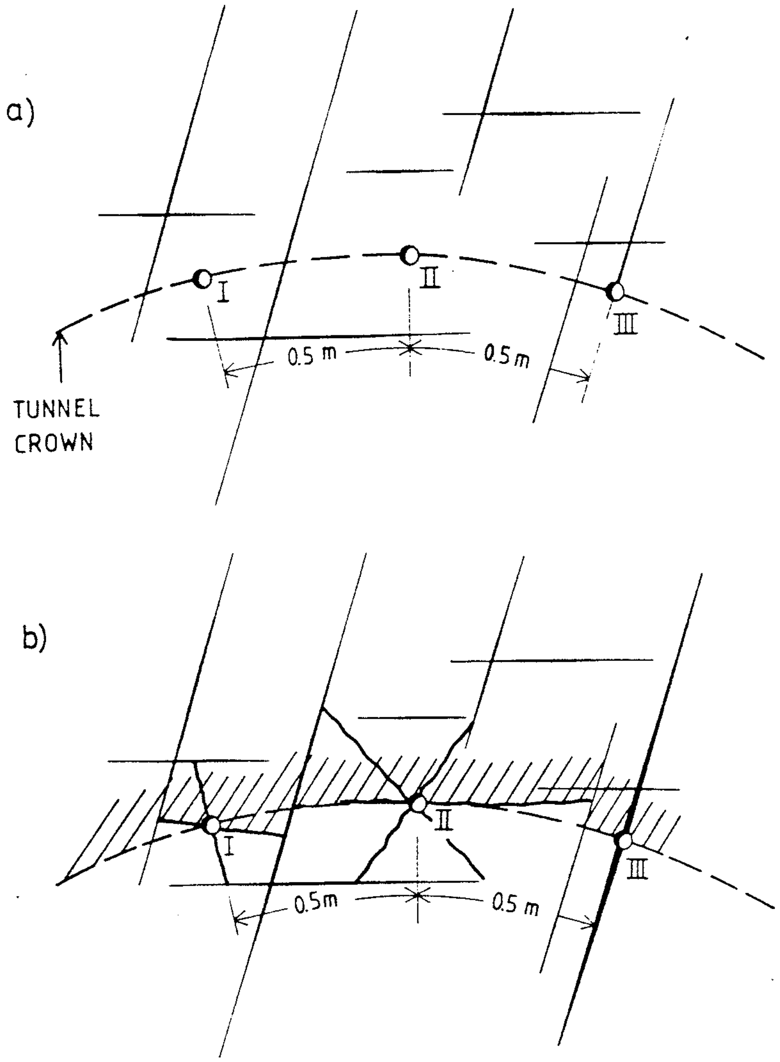

Fig.23. Hypothetic fracture pattern of granite (upper) with general influence of blasting.

Fig.24. Typical blasting-induced fracture extending radially from a 32 mm hole

Assuming an instantly produced gas pressure of 100 MPa and a reasonable compression modulus ($5x10^4$ MPa) one arrives at an average geometric aperture of blasting-induced fractures (I and II in Fig.23) of a few tens to a few hundreds of micrometers, which would roughly correspond to a hydraulic aperture of 10 - 100 micrometers. Preexisting fractures are concluded to be widened by more than that.

The Buffer Mass Test area in Stripa serves as an example of the net effect of the blasting. Here, the peripheral 32 mm boreholes were spaced about 60 cm, and they were charged with 0.3 kg/m Gurit over their entire length, using also about 100 g Dynamex at the tip as "starter". Momentaneous blasting was applied. It is estimated that practical and economical reasons speak against significantly less effective blasting in the excavation of deposition holes and tunnels in a repository, meaning that the Stripa BMT drift can actually be taken as representative of what one can expect, at least for some parts of future, blasted repositories.

The BMT case

In the BMT test drift in Stripa, where a considerable increase in (axial) conductivity of the shallow rock was induced by the excavation,there is usually only one blasting-induced fracture per hole and they extend radially to about 0.3 m into the rock. The holes are 3.6 m long and the fractures can be traced to about 1.5 m from the tips. This means that the sets of regular fractures that were produced by blasting do not form continuous passages of uniform aperture along the entire drift. Hence, if the 2 m long intermediate sections, separating the ones with regular fracture sets, were not affected at all by blasting, only stress relaxation would control the axial conductivity over longer distances. However, these intermediate sections have certainly also undergone structural changes because part of the blasted holes, being charged over their entire length, passed through rock which was already affected by the preceding detonation, and which were thus influenced twice by blasting. This is assumed to be manifested by the much higher frequency of fractures within about 30 - 50 cm distance from the walls than in the virgin Stripa granite (Fig.25). In the BMT case, this double effect on the intermediate sections may have been particularly strong since the drift strikes almost parallel to two major natural fracture sets, characterized by a fracture spacing of about 1 m, and widening of such fractures may have contributed to the increase in axial hydraulic conductivity (Fig.26).

Assuming that the hydraulic conductivity of the disturbed zone with regular blasting-induced fractures is entirely determined by these fractures, one arrives at the following net hydraulic conductivity values for axial flow, assuming the net hydraulic apertures to be 10 - 100 micrometers:

Hydraulic aperture μm	Average bulk conductivity m/s
10	$1.1\mathrm{x}10^{-9}$
20	$0.9\mathrm{x}10^{-8}$
50	$1.5\mathrm{x}10^{-7}$
100	$1.2\mathrm{x}10^{-6}$

Since the current field research work shows that the net axial conductivity of the shallow rock, i.e. to 0.3 to 0.8 m distance from the periphery, is in the range of 10^{-8} to 10^{-6} m/s, it is concluded that these regular fracture sets would yield an axial conductivity of the recorded order of magnitude. It would require, however, that the intermediate sections have at least the same conductivity, and in the BMT case this may well be due to widening of major natural, axially oriented fractures. In turn, this may suggest that in structurally different rock, or in a differently oriented drift, the net effect of blasting on the axial hydraulic conductivity may be less. At any rate, it is clear that the rich fine-fracturing that is generated by blasting brings the virgin hydraulic conductivity of the most shallow rock up by orders of magnitude.

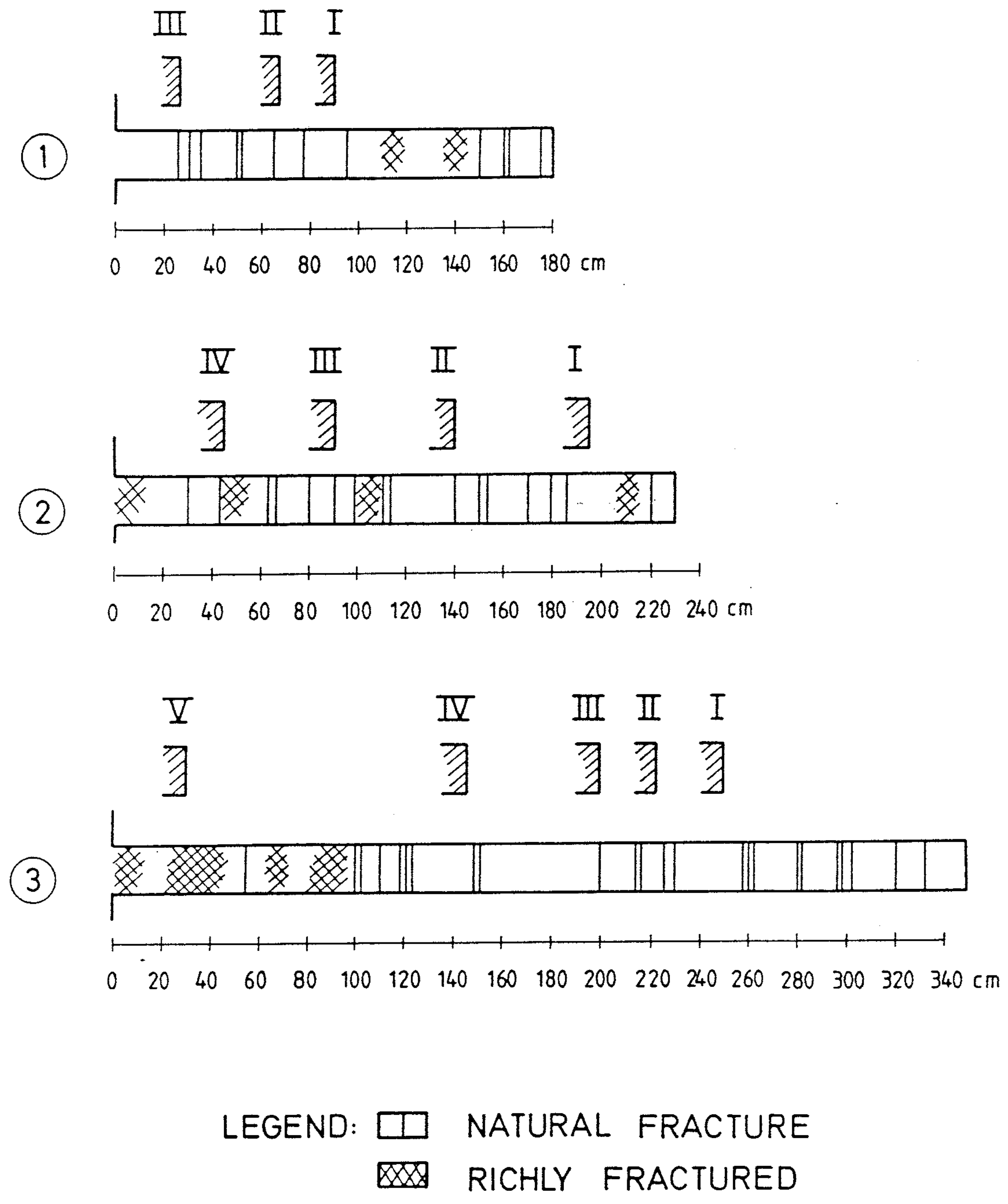

Fig.25. Core mapping of boreholes for grouting, drilled through a blasted wall at an angle of about 30° from the axis of a Stripa drift. The scales refer to the core length, meaning that the rich fracturing in hole 3 is all located within about 45 cm from the free surface

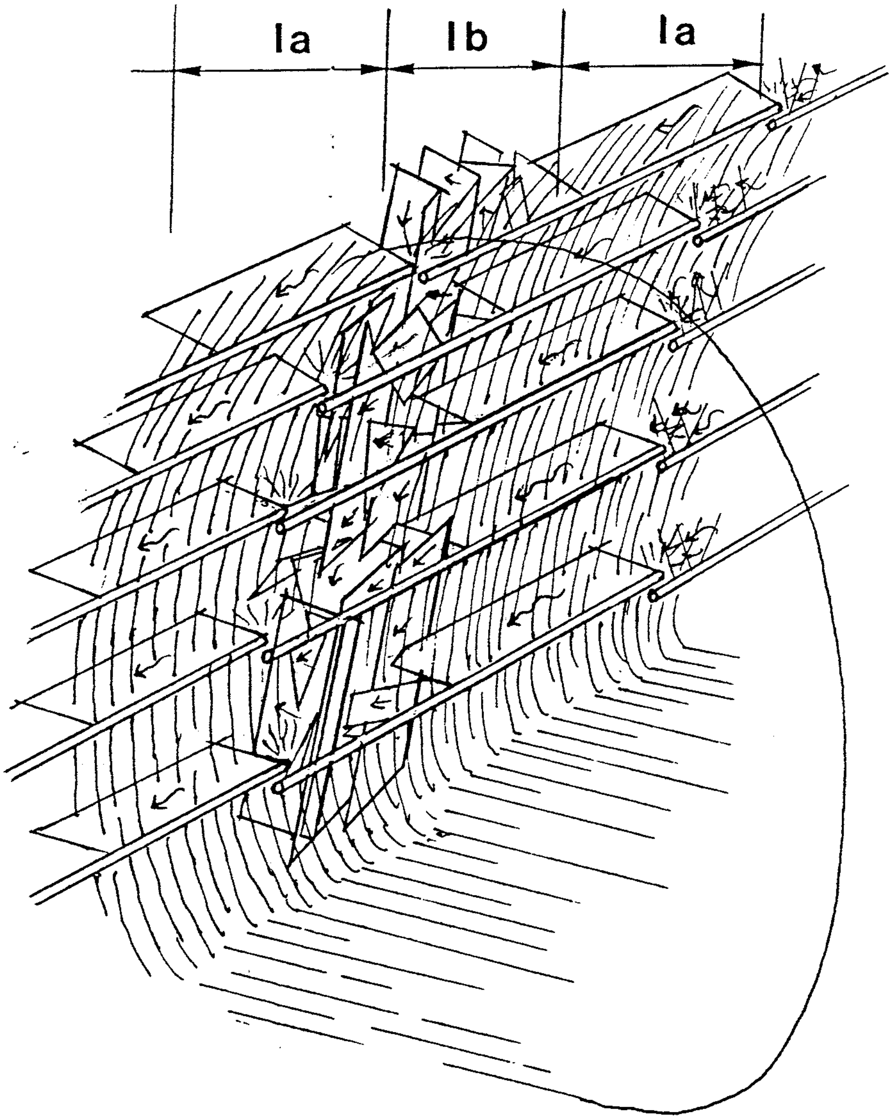

Fig.26. Schematic view of zones of blasting-induced defects in a tunnel wall. Ia represent zones of regular sets of plane fractures (Type I) extending radially from the blasted holes, the depth and length (in axial direction) being about 0.3 and 1.5 m, respectively, in the BMT case. Ib represents strongly fractured intermediate zone

4 PHYSICO-CHEMICAL EFFECTS ON DRILLING-INDUCED AND PREEXISTING FRACTURES

4.1 Hydration of neoformed fractures

It has been known for several years that freshly formed rock crystal surfaces are very reactive. Quartz and other silicates become hydroxylated almost instantly and aluminosilicates release constituents that may form true clay minerals, like smectites, in a fraction of an hour (13). This suggests that fresh surfaces of amphibole, hornblend, pyroxene, feldspar, mica, and chlorite minerals become covered with very thin smectitic films. Where this takes place on surfaces exposed on the borehole walls it has of course no impact on the physical stability of the walls, while fracture surfaces formed in the crystal matrix may have such an effect. Thus, swelling and softening of rock with neoformed smectite may release rock fragments from the borehole walls which may secondarily lead to displacement of larger rock blocks. Such effects would be expected within hours in very surface-near fractures while they may appear weeks or months later deeper into the rock matrix. Naturally, the practical importance of these effects are supposed to be very much greater in large-diameter holes than in slim holes.

4.2 Effect of shear on preexisting fractures

Naturally, the phenomenon described above would take place also in preexisting fractures that become sheared in conjunction with stress release at the excavation of rock with high, anisotropic stresses.

This has actually been demonstrated in a pilot test where contacting chlorite samples where sheared in a direct shear apparatus, applying a normal stress of 10 MPa and increasing the shear stress up to 4.8 MPa (14).

Cylindrical, 1 cm diameter samples of homogeneous chlorite were prepared by sawing, and careful grinding and polishing were made before mounting them in the shear box halves. The shear stress was increased stepwise under a constant normal stress of 10 MPa and the creep rate measured. The displacement at shear stresses below about 3 MPa was less than a few tens of micrometers per load step, while it was about 100 μm at the shear stress 4.8 MPa. The creep rate was rapidly retarded at all stress levels, approximately according to the following creep law:

$$\gamma = \alpha t - \beta t^2 \quad (t < \alpha/2\beta) \qquad (1)$$

where α and β are constants and t is time after the onset of creep (Fig.27). This law means that the initial creep rate is almost proportional to the time elapsed, then retarded approximately according to the log t law, and finally dying off completely. Applying stochastical mechanics one can show that this behavior is typical of systems in which thermally aided slip takes place on a molecular scale without significant structural breakdown but still with very large numbers of "jumps of slip units" (15).

The creep had come to virtual stop in about 20 minutes at the highest shear stress, which was maintained for 1 hour, and there was no indication of potential failure. However, on filling water in the shear box, failure occurred in less than one minute in the form of rapid displacement yielding complete translational separation of the two chlorite halves.

Samples were extracted from the sheared specimens in order to identify structural changes. Optical microscopy was applied using conventional thin sections (30 microns), which were prepared after embedding the samples, and it was found that strong exfoliation had taken place by which the initially rather homogeneous mass of aligned chlorite flakes had become strongly distorted (Fig.28). The major effect was that dispersion leading to a large number of separate, 5 to 50 micrometers thick stacks of flakes had taken place, by which the specific surface area may have been increased from much less than 1 m^2/g to 10 to 30 m^2/g.

What happened in the course of the shearing under air-dry conditions was that shear displacements took place in the homogeneous thick stacks of chlorite flakes, thereby splitting the stacks and exposing new internal surfaces. On subsequent wetting, rapid hydration took place with water entering the parts of the samples which were close to the interface between the big samples. Thereby, the new surfaces became hydrated by osmosis and direct hydroxylation, by which strong primary valence bonds were replaced by weaker hydrogen bonds, resulting in a drop in bulk shear strength and macroscopic shear failure.

One realizes that this mechanism of weakening, induced by intermittent shear displacements as well as by slow creep, may well be responsible for the long-term stability of any rock excavation, and it may be a determinant also of the short-term stability of deep, large-diameter boreholes. While this may i.a. generate block movements and some increase in aperture of certain critically oriented natural fractures, the formation of smectites through "mechanico/chemical" processes may have the opposite effect and instead cause self-healing of fractures which ultimately reach a stable condition. Thus, the "near-field" rock around deposition holes that is effectively supported by highly compacted bentonite, may get its fractures at least partially sealed by shear taking place due to high deviator stresses in the rock. The matter certainly deserves further investigation since it may not only offer "self-healing" but also a plausible explanation of the occurrence of smectite clay in crystalline bedrock where the conventional "hydrothermal" model may not apply.

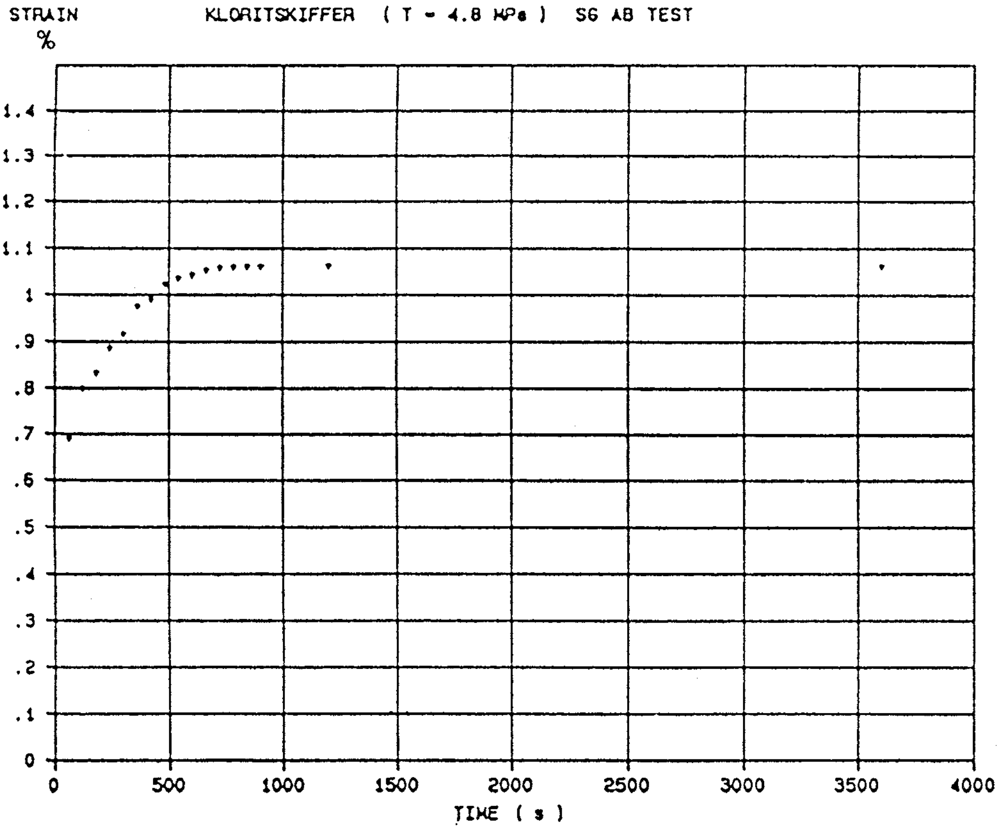

Fig.27. Creep of contacting chlorite cylinders at 10 MPa normal stress and 4.8 MPa shear stress

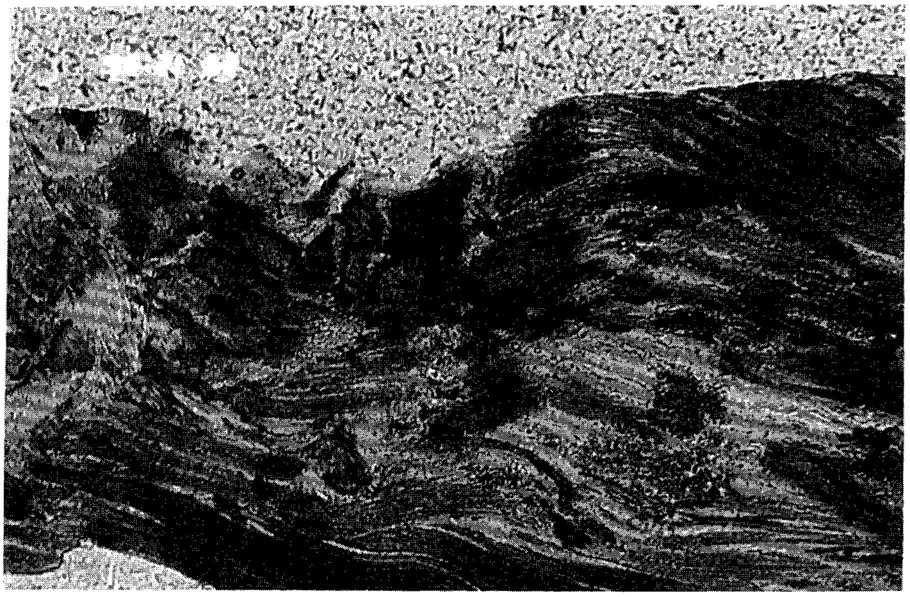

Fig.28. Dark-field micrograph of thin section of chlorite sample sheared along the upper boundary (Magn. 160 x). Photo: M.Erlström.

5 DISCUSSION AND CONCLUSIONS

5.1 Feasibility

The difficulty in excavating vertical deposition holes to some 7-8 m depth by use of smooth blasting without causing very significant damage to the near-field rock, suggests that it is not a primary candidate technique. However, it may still be considered feasible if it is a matter of producing long vertical, multi-canister holes that extend between horizontal tunnels, and if a permeable and rather strongly fractured near-field environment is acceptable. Thus, a rather high frequency of relatively wide blasting-induced fractures (apertures in the range of 100 - 1000 micrometers) would distribute possible tectonic shear movements in a way that is beneficial to the canisters, and it would also allow for significant penetration and self-healing of Na bentonite from the dense canister envelope of the KBS3 concept.

As to slot drilling by use of percussion hammering, it is anticipated that 1.5 m diameter holes of 7 - 8 m depth can be drilled from tunnel floors with reasonable accuracy. As indicated by certain experience one would assume that "discing" may appear and that some widening of preexisting, flat-lying fractures is expected to take place.

Hole excavation by use of large-size core drilling like the technique that was applied in drilling the six 0.76 m diameter, 3 m deep holes for the Buffer Mass Test in Stripa (18), appears to be feasible and is expected to give minimum rock disturbance.

Full face drilling of 7 - 8 m long vertical holes appears to be a new application of this rock excavation technique, and it is clear that some modifications and arrangements to handle the rock debris is required. Still, it is claimed by Wijk (pers. comm.) that the method has a great potential due to the high penetration rate.

5.2 Effect on the conductivity and migration of radionuclides by drilling

Returning to the basic question of whether structural changes with concomitant increase in bulk conductivity is more or less important than fragmentation due to drilling or careful blasting, the information gathered from the exploratory 2D UDEC study indicates that the typical granite structure yields considerable widening of steep fractures forming wedges. These become unstable rock components in the presence of ubiquitary flat-lying truncating joints, coated with chlorite, mica, or clay, which may produce rock-fall. It is clear that there will be an appreciably enhanced axial hydraulic conductivity of the "near-field" rock, i.e. by tens to hundreds and even thousands of times.

The fissuring that is produced in the borehole walls by percussion drilling as well as by all forms of rotary drilling, and also by the stress concentrations at the "corners", yields an increase in axial conductivity by orders of magnitude of a few centimeters deep zone around the boreholes. Such zones do not contribute much to the gross permeability of the near-field but will serve as short-circuits between major natural fractures and facilitate water flow along the holes. In this respect, full-face drilling appears to be somewhat more destructive than percussive drilling, which, in turn, is more damaging than core drilling. Even extremely careful blasting has considerable effects on the rock structure and certainly affects the bulk permeability of the near-field.

Fig. 29 is an attempt to illustrate the combined effect of rock wedging and short-circuiting of damaged zones produced by the rock drilling techniques discussed in this report.

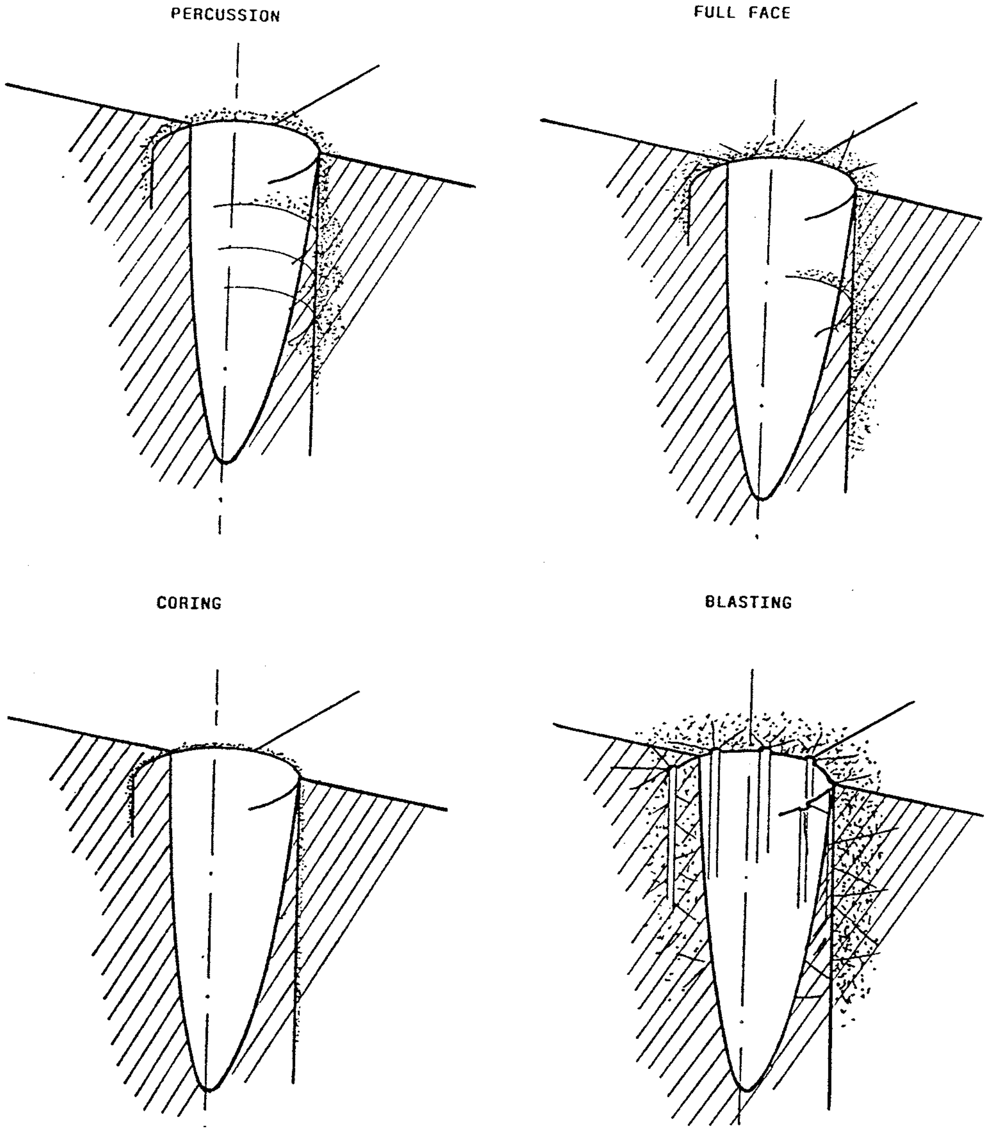

Fig.29. Possible modes of interaction of major flow paths along rock wedges (cross-lined) and conductive damage zones generated by excavation (dotted)

5.3 Additional

It should be pointed out that the fine fissuring and shattering that may not be visible to the naked eye but which is concluded to be characteristic of borehole walls irrespective of the applied drilling technique, is very beneficial for the wetting of highly compacted bentonite, applied in the holes for sealing purposes, since it yields very uniform water uptake (Fig.30). This phenomenon was first observed at the Stripa Buffer Mass Test.

A further matter of interest is the probability that the large specific surface area that is created by the fissuring and shattering, provides large amounts of adsorption sites for radionuclides, a phenomenon that may be much enhanced by the aforementioned neoformation of smectitic minerals at fracture surfaces. This issue needs to be considered in conjunction with an evolution of the total physical and chemical interaction of the canister/clay/rock system.

From a practical point of view it is important to notice that only core drilling and full face drilling offer a sufficiently smooth borehole wall to allow for grouting by use of megapacker technique. Percussive drilling may also yield a sufficiently smooth wall but this requires special technique which has been outlined but is not yet commercially available.

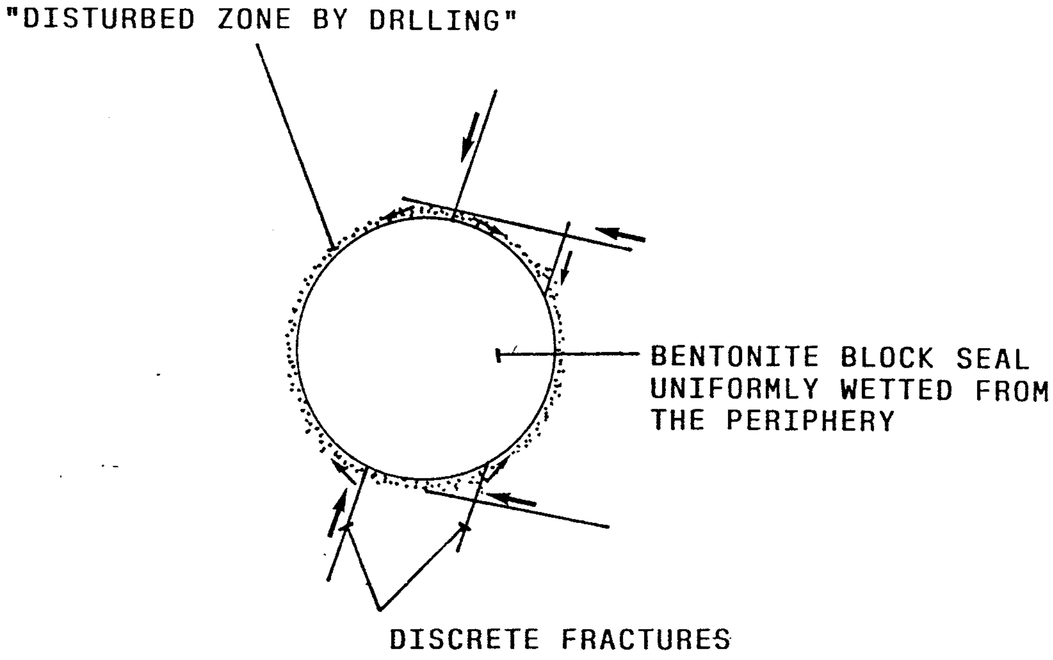

Fig.30. The wetting process that ultimately yields fully saturated bentonite in a KBS 3 deposition hole, becomes uniform by the "wall" disturbance caused by rotary or percussive drilling

6 RECOMMENDATIONS

The present pilot study indicates that the procedure employed in the excavation of canister deposition holes has a considerable impact on the conditions for water flow in the near-field. Many of the tentative conclusions forwarded here need to be tested and particular emphasis should be put on the follow items:

1. Formulation of a general philosophy with respect to required properties of the near-field rock: 1) suitable rheological properties, 2) self-healing by penetrating bentonite, 3) groutability

2. Systematic use of UDEC or 3DEC for safer identification of critical water flow paths and for quantitative prediction of changes in hydraulic conductivity of near-field rock

3. Exploration of mineral neoformation in fractures as a natural self-healing mechanism

4. Experimental identification of structural damage induced by the various excavation techniques

As to the last of these three issues it is recommended that drilling experiments be conducted with subsequent permeability measurements in the field as well as on carefully extracted samples, and that samples be taken for laboratory documentation of the character and extension of the disturbance. The Stripa Mine offers very good facilities for the field experiments except for the lack of full-face drilled drifts but it is believed that suitable drifts or tunnels of this sort are available elsewhere in Sweden.

7 ACKNOWLEDGEMENTS

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[1] The Royal Institute of Technology, Department of Chemical Engineering, Stockholm
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  [2] Swedish Geological Company, Göteborg, Sweden
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[1] Kemakta Konsult AB
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