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INFLUENCE OF PHYSICAL PROPERTIES OF ROCK ON RATE OF PENETRATION OF A WATER-JET DRILL

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ABSTRACT

Drilling experiments show that there is only moderate correlation between rate of drilling by a jet of water and grain size of rock. This probably indicates that the rate of water-jet penetration in rock is influenced by other factors. Fractures induced by a water jet are found to propagate around grain boundaries in most rocks. The exceptions are rocks that contain minerals with a well-developed cleavage, such as calcite and amphibole. Here, fractures tend to follow the cleavage planes. The surface area of grains occupying a 1-cm cube (a function of grain size) and the volume of cracks per unit volume of rock are shown to be the main factors determining rate of water-jet penetration.

Keywords: water-jet drill, rocks, penetration, pressure, fracture, surface area, cracks, granite, sandstone, quartz diorite, norite.

SOMMAIRE

On montre, par mesures expérimentales, que la corrélation entre taux de forage par un jet d'eau et granulométrie d'une roche n'est que médiocre. D'autres facteurs viendraient influencer ce taux. Les fissures qui résultent du jet se propagent le long de la bordure des cristaux dans la plupart des cas. Seules sont exceptionnelles à cet égard les roches qui contiennent un minéral à clivage bien développé, comme la calcite ou l'amphibole. Dans ces roches, les fissures se propagent le long des clivages. L'aire de la surface des grains dans un cube d'un centimètre d'arête (fonction de la granulométrie) et le volume des fissures comparé au volume de la roche sont les facteurs principaux qui déterminent le taux de pénétration d'un jet d'eau dans une roche.

(Traduit par la Rédaction)

Mots-clés: foreuse à jet d'eau, roches, pénétration, pression, fissure, aire de la surface des grains, fractures, granite, grès, diorite quartzifère, norite.

INTRODUCTION

Water-jet drilling is a relatively new technology that is still largely in the developmental stage. Water-jet drills can be used for drilling or slotting a wide variety of materials; for example, they have been used for shot holes in mining and quarrying (Lefin & Hurel 1984). Other applications include cutting leather for shoes (Burns & Mohaupt 1984) and removing deteriorated concrete from bridge decks (Wallace 1985). Water-jet drilling has also been proposed as a method of breaking human gallstones to facilitate removal (Classen *et al.* 1984). In some applications a single jet is used; in others, for example, rock drilling, twin- or multiple-jet systems are usually employed. Water jets may also be used in conjunction with an abrasive that is fed into the jet (Nakaya *et al.* 1984) or as an assist to tungsten carbide bits (Lefin & Hurel 1984). Water pressures in the range 35–350 MPa have been used, but in practical applications problems are likely to be encountered at higher pressures owing to failure of seals.

It is the purpose of this investigation to attempt to define the rock properties that control the rate of penetration of a water jet in hard rock. It was previously hypothesized (Rehbinder 1980) that the resistance of a rock to erosion should be proportional to the slenderness ratio of its pores and inversely proportional to the mean diameter of its grains. The slenderness ratio of the pores should presumably be a function of the permeability of the rock. During the course of the present investigations, permeability was measured for a number of rocks for which rates of water-jet drilling were also determined. Analysis of the results did not indicate much correlation between the two. This may have been due to a lack of homogeneity in some of the rocks or to difficulty in obtaining meaningful values for the permeability of some low-porosity rocks. In order to test the second half of Rehbinder's hypothesis, the mean grain-sizes of the rocks used by the present authors in water-jet drilling experiments were determined and plotted against drilling rates (Fig. 1). The graph shows that drilling rate D increases with increasing grain-size L according to the equation

$$D = 0.8166 + 0.0222\ L \qquad (1)$$

The correlation of the line fitted to the points in Figure 1 is, however, relatively poor ($R = 0.74$). Two points representing granite samples with roughly similar grain-sizes but drilling rates of 30.3 and 13.4 cm/min indicate that other factors must influence the rate of water-jet penetration in rock.

It was shown previously (Vijay *et al.* 1982) that commonly measured physical properties of rocks, for example, compressive strength, tensile strength,

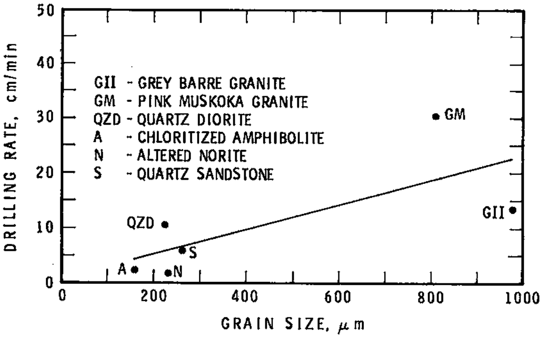

FIG. 1. Plot of drilling rate *versus* mean grain-size of rocks.

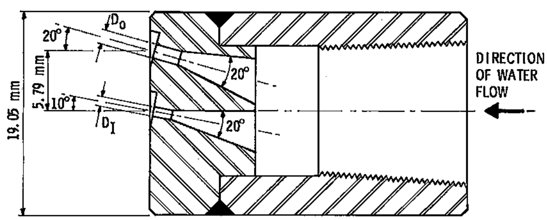

FIG. 2. Cross-section of body of drill nozzle of twin-jet system used in this research. Arrows indicate direction of water flow. D_0: 1.321-mm diameter jet, D_I: 1.092-mm diameter jet.

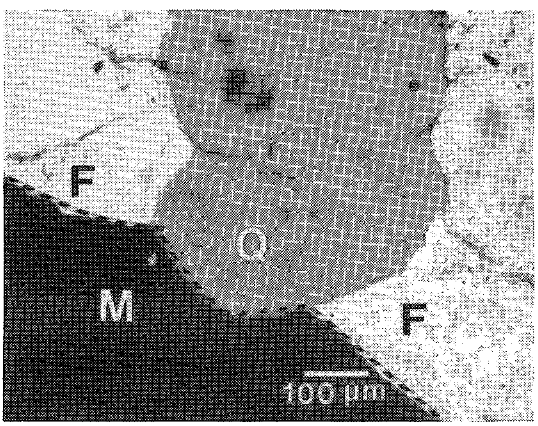

FIG. 3. Optical micrograph of fragment of quartz diorite recovered from hole drilled by water jet. The fracture path is indicated by the dashed line separating the rock from the plastic mounting medium M. When the fracture passing through the feldspar F reached the quartz Q, it detoured around two faces of the subhedral grain rather than cutting across it. This provides evidence that water jets usually penetrate rock by fracture propagation around the grain boundaries.

specific gravity and porosity, do not correlate with rate of water-jet penetration. With some exceptions the drilling rate shows little correlation with mineralogical composition and no correlation with the hardness of the rock. For example, a soft calcarenite limestone (Carozzi & Textoris 1967) is more resistant to water-jet penetration than a granite, which is much harder. Owing to the large requirements for power in water-jet drilling, it is important to optimize the energy consumption of the system for a particular rock. To do this the physical factors and mechanisms of water-jet penetration must be understood.

APPARATUS

The drill consists of a generator, a high-pressure pump, and a twin-jet nozzle that rotates at about 200 rpm (Vijay *et al.* 1984). In the experiments reported here a water pressure of 68 MPa was used, with jet diameters of 1.321 and 1.092 mm for jets D_0 and D_1, respectively (Fig. 2). The following rock samples were used: granites GII (medium-grained grey granite from Barre, Vermont) and GM (medium-grained granite from Muskoka, Ontario), calcareous Nepean sandstone from Ottawa, Ontario, assorted fine-grained rocks from the Sudbury basin, Ontario (quartz diorite, chloritized amphibolite, altered norite and Ottawa limestone).

RESULTS AND DISCUSSION

To investigate the mechanism by which a water jet penetrates rock, some chippings recovered from drilling experiments were made into thin sections and examined with the aid of a petrographic microscope. Most of the fragments are multigranular, but particularly in coarse-grained rock such as granite some single-grain particles were observed. The petrographic examination showed that fractures generally appear to have propagated along grain boundaries rather than through the grains. This is illustrated in Figure 3, which is a photograph of a fragment of quartz diorite recovered from a test hole. Examination of this micrograph reveals that the fracture passes along the grain boundary of a feldspar crystal, then follows around two faces of a subhedral quartz grain before passing along another feldspar grain boundary. Similar observations were made with other minerals.

Exceptions occur in coarsely crystalline limestone, in which fractures frequently traverse the calcite grains by following the cleavage planes, and in coarse-grained amphibolite, in which fractures follow amphibole cleavage planes or existing microfractures common in this mineral. Figure 4 is a micrograph of a fragment of calcite recovered from a drilling experiment on a block of coarse biosparite limestone. In this particle the fracture clearly propagated along one cleavage plane, then changed direction to an intersecting plane.

Based on these observations, a preliminary hypothesis was presented to account for the penetration of a rock by a high-pressure jet of water (Vijay *et al.* 1984). The water jet appears to penetrate the rock by propagating cracks along the grain boundaries. It is evident that the pressure and hence the energy of a water jet will be reduced by friction as it passes between grain boundaries in penetrating several grain diameters before finally dislodging a chip of rock. The frictional forces will be proportional to the surface area *Sa* of the grains per unit volume. Although the surface area is not a readily measurable parameter, an approximate value per unit volume of rock can be calculated from the mean grain-size by assuming that the rock is composed of uniformly sized, spherical particles having a diameter equal to the mean grain-size (clearly an oversimplification).

The procedure is as follows. The volume of a sphere of diameter equal to the mean diameter of the grains is calculated and the number of such spheres that can be fitted into a 1-cm^3 cube is estimated. It can be shown that in a cubic close-packed array the spheres occupy 73.1% of the space (Evans 1964), so that the number of spheres per cubic centimetre can be obtained by dividing the volume of one sphere into 0.741 cm^3. The surface area of one sphere is calculated, and the resulting value then multiplied by the number of spheres to obtain an estimate of the surface area of grains per cubic centimetre. In Figure 5 the drilling rate for a number of rock types is plotted against the surface area of the grains per cubic centimetre. The plot reveals that the surface area *Sa* of the grains is inversely proportional to the drilling rate *D*:

$$D = 23.37 + (-0.0753\ Sa) \tag{2}$$

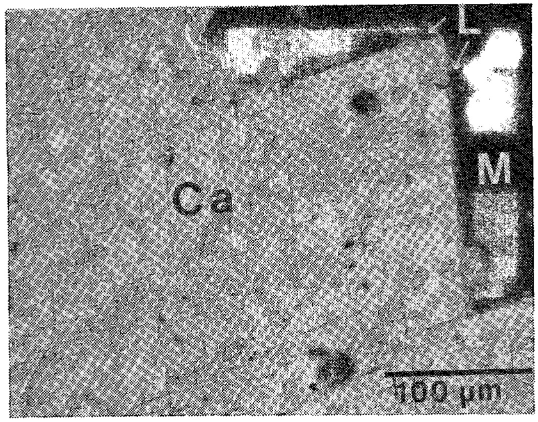

FIG. 4. Optical micrograph (crossed polars) of the periphery of a calcite drill chipping from biosparite limestone, showing fracture along two cleavage planes in the calcite. Ca calcite, L cleavage planes, M plastic mounting medium.

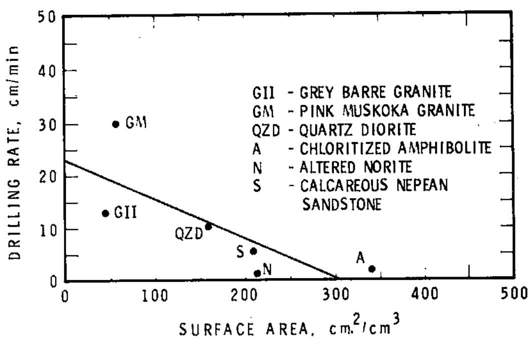

FIG. 5. Graph of drilling rate *versus* surface area of grain boundaries per cubic centimetre of rock.

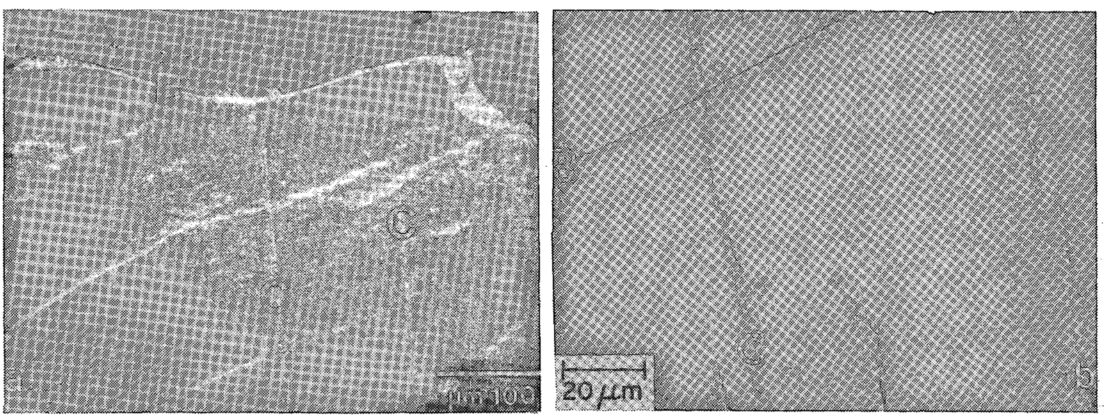

FIG. 6. (a) Optical micrograph (Nomarski differential contrast) showing fractures C traversing grain boundaries B in granite GM. (b) SEM micrograph showing open fractures C cutting across grain boundaries B in granite GM.

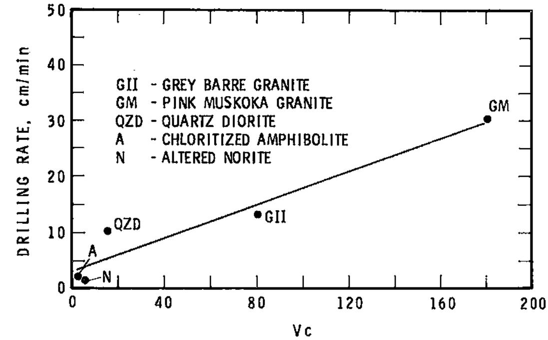

FIG. 7. Graph of drilling rate D *versus* volume of cracks per unit volume of rock Vc for a number of rocks.

It may be seen by comparing Figures 1 and 4 that the correlation between drilling rate and surface area of the grains per cubic centimetre is about the same as that between drilling rate and mean grain-size, suggesting that drilling rate is affected by other factors.

Examination of polished ion-milled sections of granites GM and GII by optical microscopy showed that granite GM contains many hematite-filled fractures cutting across the grains (Fig. 6a). Further examination by SEM (Fig. 6b) revealed that many cracks are open; these would facilitate penetration by a water jet. In contrast, granite GII contains few cracks other than those along grain boundaries. From this it was concluded that the differences in drilling rates observed in the two granites are due to the presence of cracks traversing the grains in granite GM. Observation of other rocks in the SEM confirmed that open cracks are largely confined to the grain boundaries. Few defects other than cracks along grain boundaries were observed in the rocks studied. It may therefore be concluded that permeability may be largely determined by the volume of cracks Vc per unit volume of rock.

It would, of course, be very difficult to determine accurately the volume of cracks per unit volume of rock. A rough estimate was obtained using the following procedure: a point-count method (Hutchinson 1974) similar to that employed for modal analysis of rocks in thin section with a petrographic microscope was used in conjunction with the SEM to obtain an estimate of the volume of cracks per unit volume of rock. Considerable error is involved in this procedure owing to the narrowness of the cracks and the possibility that owing to their length, some cracks may be counted more than once. The volume of cracks Vc is plotted against drilling rate D for a number of rock types (Fig. 7). The drilling rate is shown to increase with the volume of cracks in the rock (equation 3).

$$D = 3.206 + 0.149\ Vc\ (R = 0.97) \qquad (3)$$

It is concluded that the rate of penetration of a water jet in rock is largely controlled by two factors: the calculated surface-area of the grains per cubic centimetre and the volume of cracks per unit volume of rock. Additional drilling experiments should be carried out to verify this hypothesis.

ANOMALOUS RESULTS

In a few instances the drilling rates calculated for particular rocks (equation 2) were not achieved in practice. This is generally due to inhomogeneities in the rock. For example, in a block of Nepean sandstone with a mean grain-size of 270 μm, the water

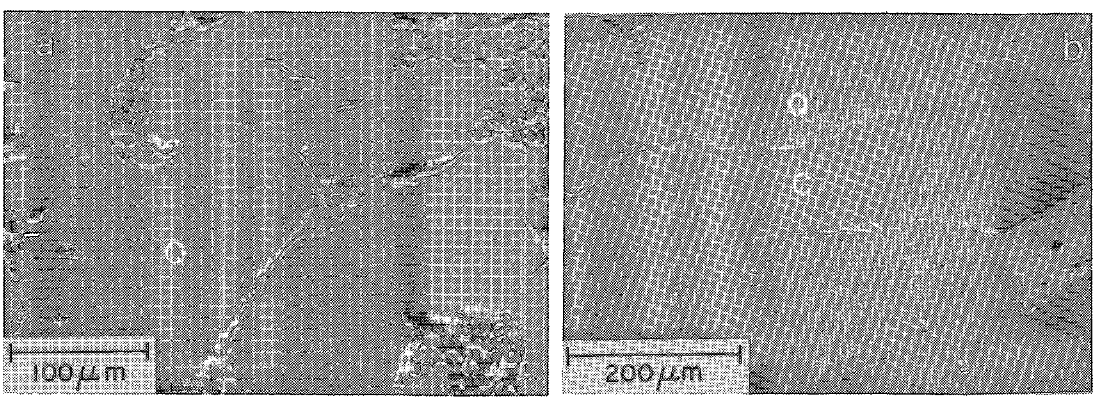

FIG. 8. (a) SEM micrograph of polished ion-milled section of Nepean sandstone showing quartz grains Q with interstitial clay minerals. (b) Polished ion-milled section of calcareous zone in sandstone. Q quartz, C calcite.

jet penetrated rapidly for some time, then slowed before finally speeding up again. Examination of thin sections taken from beside the hole shows that in regions offering most resistance to drill penetration the quartz sandstone contains calcareous zones. Figure 8 presents SEM photographs of polished sections of sandstone: Figure 8a shows a relatively pure quartz sandstone with only minor amounts of interstitial clay minerals and calcite; in Figure 8b, calcite is a major constituent of the rock, in some zones comprising about 30% of the rock. The variation in drilling rate with calcite content of the limestone is illustrated diagrammatically in Figure 9.

It was shown previously that, in calcite, cracks induced by a water jet tend to follow cleavage planes rather than propagate along grain boundaries. The following hypothesis is proposed to account for the slow rate of water-jet penetration in calcareous sandstone: assume a crack tip with energy EV greater than the threshold energy required for crack propagation in the sandstone. It moves along the boundary between two quartz grains until it enters an area of calcite, where it splits into a maximum of three cracks; these follow the cleavage planes. The energy at each of the three new crack-tips will be less than the original energy. The process will continue until the energy EV of the original crack-tip is dissipated by subdivision to such an extent that the energy of the individual crack-tips is reduced below the threshold value required for crack propagation along the boundaries of the quartz grains.

A second rock that appears to give anomalous results is Ottawa limestone. Again, there was rapid initial penetration, followed by slowing of the drill and subsequent speeding up in a manner similar to that for sandstone. Examination of thin sections taken from beside the hole showed, however, that variations in the drilling rate were due in this case to changes in the grain size of the rock. Rapid penetration was obtained in coarse-grained biosparite limestone with a mean grain-size of 1000 μm (Fig. 10a), but the rate decreased when the water jet entered layers of fine-grained calcarenite limestone with a mean grain-size of 120 μm (Fig. 10b).

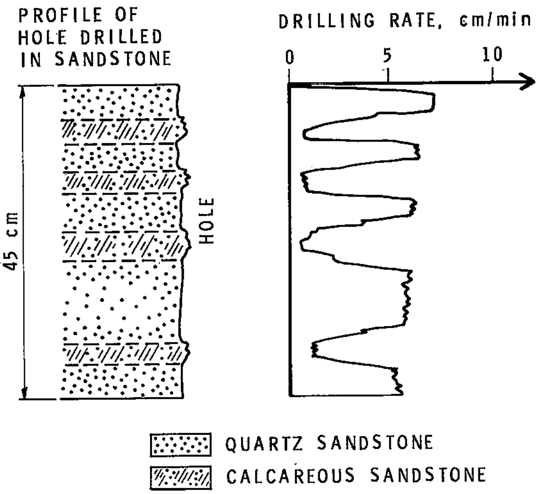

FIG. 9. Schematic diagram of section through hole drilled in sandstone, showing dependence of drilling rate on calcite content of sandstone.

CONCLUSION

The mean grain-size L, its related property, the surface area Sa of the grains per unit volume of rock,

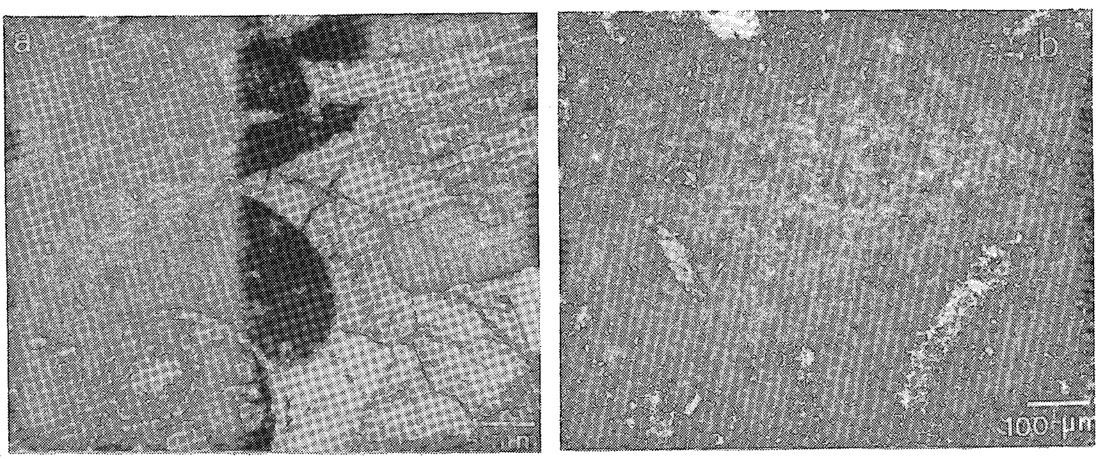

FIG. 10. Optical micrographs of limestone. Rapid penetration was obtained in (a) biosparite showing coarse grain-size, compared to (b) fine-grained pisolitic calcarenite, with poorly defined grain-boundaries.

and the volume of cracks *Vc* per unit volume of rock are the major factors determining rate of water-jet penetration of rock. Measured permeabilities do not correlate well with drilling rates. The lack of correlation may be due to difficulties in making accurate measurements of the permeability of these low-porosity rocks and to lack of homogeneity in some of the samples.

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