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THE TIME-DEPENDENT TRANSMISSIVITY OF JOINTS
(Mechanism of Closure, by C.H. Scholz)

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ABSTRACT

When rock is subjected to a stress cycle during which cracks open and close, hysteresis is observed in the stress-strain curves, which has usually been attributed to friction. Scanning electron microscope studies, however, have shown that shear cracks are scarce in rock that has been deformed in the dilatant region. Stevens and Holcomb [1980] and Holcomb and Stevens [1980] have argued further that crack friction models are incompatible with the rheology of dilatant rock and are virtually untenable. They asserted instead that cracks are reversible in the sense of the Griffith energy balance. Here we demonstrate that two nominally flat rock surfaces in contact subject to a cycle of applied normal stress exhibit all the properties of crack opening, closing, and hysteresis exhibited by a dilatant rock and that in this case the mechanism must be friction. We conclude that an axial crack in dilatant rock will exhibit frictional interactions on opening or closing if the crack walls are not in perfect registration, and that there is no justification for accepting the reversible 'Griffith' crack concept.

INTRODUCTION

One of the principal characteristics of rock is that it is an elastic solid that typically contains an abundance of cracks. The presence of the cracks has a marked effect on many of the properties of rock, and since the cracks may open or close in response to applied stresses, many properties of rock have a strong and sometimes complex dependence on the state of stress. Consequently, a considerable amount of work has been devoted to understanding the behavior of cracks in rock in response to applied stresses.

A principal finding has been that whenever rock is subjected to a stress cycle in which cracks open and close, as can be determined by measurement of a variety of macroscopic properties, hysteresis occurs in the stress-strain behavior. This is equally true when cracks close, then open again in response to a cycle of hydrostatic pressure [Brace, 1965] as when cracks open, then close again during dilatancy in response to a cycle of nonhydrostatic stress [Brace et al., 1966]. This observation led those workers to conclude that when cracks open and close, they must expend some energy in work against friction, accounting for the energy loss during the cycle. Brace et al. [1966] offered some simple conceptual models of how this could occur.

These models were ones in which axial cracks (opening mode cracks nearly parallel to the maximum applied compression) open in concert with shear movement on cracks aligned obliquely to maximum compression, as illustrated in Figure 1. This type of model was first seriously challenged by Tapponnier and Brace [1976] who found by scanning electron microscope examination that stress induced cracks in rock

were almost entirely of the axial type and that cracks in shear configuration were scarce. This observation, which has since been confirmed by others [Kranz, 1979; Batzle et al., 1980], led Tapponnier and Brace to conclude that the simple models such as shown in Figure 1 were not likely to be appropriate descriptions of the mechanism responsible for hysteresis in rock, though they were unable to suggest an alternative to friction as the dissipative process.

In a series of papers [Holcomb, 1978; Stevens and Holcomb, 1980; Holcomb and Stevens, 1980; Holcomb, 1981], Holcomb and Stevens have attempted to demonstrate that frictional models such as shown in Figure 1 are incompatible with the rheological behavior of dilatant rock. They then proposed, as an alternative to friction as the process responsible for hysteresis, that cracks in dilatant rock are reversible, i.e., that they molecularly heal when the stress is removed.

Although Obriemoff [1930] showed that mica, when carefully cleaved under clean conditions, was capable of healing and recovering a large portion of its surface energy, the idea that this is a general property of rock-forming minerals, and hence presumably of brittle solids in general, and that the Griffith energy balance can be considered reversible under ordinary conditions is a startling new concept. Therefore more is at stake in this issue than just the mechanism for hysteresis in dilatant rock.

The purpose of this paper is to show that friction is generally involved in the opening and closing of a nominally flat crack that is subjected only to applied normal stresses, so that one can expect

hysteresis to occur as a result of friction even in a rock that contains only axial cracks.

However, before doing so, we shall have to examine the contention of Stevens and Holcomb [1980] that friction on cracks is incompatible with the rheological behavior of dilatant rock and the assertion of Holcomb and Stevens [1980] that reversible 'Griffith' cracks are the agents responsible for hysteresis.

A RESTATEMENT OF THE PROBLEM

When a rock is cycled to moderate stresses in the dilatant region, it exhibits marked hysteresis. After several cycles, the permanent strains induced in each cycle become small and the hysteresis loops become nearly reproduceable [Zoback and Byerlee, 1975] although in general cyclic fatigue will eventually occur [Scholz and Koczyński, 1979]. This strongly implies that under these conditions the dilatancy is caused by the same cracks opening and closing in each cycle, and Brace et al. [1966] and Scholz and Kranz [1974] suggested that the hysteresis was due to frictional interactions on cracks as they open or close.

Following the results of Tapponnier and Brace [1976], Stevens and Holcomb [1980] set out to show that frictional models could not work by assuming a model that was itself contradicted by Tapponnier and Brace's observations. Their model is one in which the rock contains a population of crack systems like that of Figure 1. When friction is overcome on the shear crack, it slips and the axial cracks open.

They emphasized that in addition to producing dilatancy and hysteresis, a successful model must satisfy the following criteria: 1) It must reproduce the memory property: i.e., at peak stress the volumetric strain is nearly the same as in a previous cycle. By nearly we mean that we exclude new permanent deformation that has occurred during the cycle, since that can be made to be arbitrarily small. 2) Some cracks must begin to close at the start of unloading, since there is evidence for that from both strain and velocity measurements. 3) The model must contain many axial cracks and few shear cracks. The last criterion is not satisfied by Stevens and Holcomb's model, but it must be satisfied by a successful one.

Stevens and Holcomb assumed two types of frictional behavior for the shear cracks in their model, either that they stick-slip with stress drops comparable to the applied stresses (ca. 100 MPa), or that they slide stably. A model in which the cracks slide by stick-slip with stress drop small when compared to the applied stresses (say, 1-10 MPa) would be very similar to the stable sliding model.

They found with their stick-slip model that the cracks became out of phase in their loading cycles which produced very erratic stress-strain behavior which, among other things, does not reproduce the memory property. This type of model, however, could have been ruled out on other grounds. After the first several cycles, the rate of acoustic emission falls to very low levels in rock subjected to cyclic loading under these conditions [Goodman, 1963; Sano, 1978; Sondergeld and Estey, 1981; Holcomb, 1981]. It appears that acoustic emission is proportional to the amount of new permanent deformation produced in each cycle, hence it is very doubtful that stick-slip or dynamic crack propagation can play a dominant role in the recoverable dilatancy that we are discussing here.

Their stable sliding models gave better results. They produced smooth and regular stress-strain curves which mimicked many of the properties of the experimental data, including memory. The only property that they failed to mimic was the one mentioned as (2), above, i.e., that some cracks begin to close at the onset of unloading. In their models, substantial 'dead bands' occurred at the onset of loading and unloading during which no dilatancy occurred. Having achieved this level of success in producing a model that fit the data, Stevens and Holcomb chose to overstate their case by concluding that models with frictional interactions between crack walls are virtually untenable.

In the sequel, they introduced their reversible Griffith crack model [Holcomb and Stevens, 1980]. In this model, axial cracks propagate during loading, and heal up again on unloading. The healing is molecular, hence the surface energy is recovered. No positive evidence is offered in support of this mechanism; the only arguments made are that their frictional models do not work very well. Indeed, the mechanism is probably unverifiable. The only way one might verify it would be to observe a crack grow in a high resolution SEM and then see it disappear on unloading, and even that would not prove it could occur under general conditions. Although it is theoretically possible for a crack to reheal, the reason for the general observation that when things break that they stay broken is the extremely stringent requirements for healing. Firstly, the crack walls must not be displaced (in shear) relative to one another by more than an interatomic distance during opening and closing, and secondly, there cannot be any molecules present that can be adsorbed onto the highly charged walls

of the new crack. Conditions within a dilatant rock that contains a pore fluid (air, at the very least) do not seem auspicious for either of these conditions to be met.

Nonetheless, let us list some objections to this model. 1) The model fails to account for the dissipation of energy in the hysteresis loop. Since the crack is reversible, no dissipative mechanism is available except for elastic radiation when the crack dynamically propagates on opening and on closing. Thus all the energy loss must be through radiation, yet the acoustic emission observations we discussed earlier seem to preclude elastic radiation as being the principal dissipative process. Incidentally, the discussion of Holcomb and Stevens [1980] of energy loss is in error. They need to integrate around the entire loop FBCEF of their Figure 1 rather than just consider the paths BC and EF.

2) The first time a rock is cycled, significant permanent dilatancy occurs, indicating that the first time cracks open they do not reheal or close completely again. Since the cracks are not reversible on the first cycle, why should we assume they become reversible on subsequent cycles?

3) Observations by Sondergeld and Estey [1981] showed that acoustic emission events that occur when rock is cycled produce both compressional and dilatational P wave first arrivals. That is direct evidence that shear motion occurs within the rock since a propagating tensile fracture will not emit dilatational P-wave first arrivals. This is less evidence against the reversible Griffith crack model than evidence for a frictional model.

4) For the model to work, surface adsorbants must not be present. Yet a rock cycled under saturated conditions with a pore

fluid under a positive pore pressure shows the same dilatant hysteresis as we have been discussing. Velocity measurements made under conditions appropriate for the cracks to remain saturated during dilatancy are quite consistent with theory and show that the majority of cracks within the rock are in communication with the pore fluid and remain saturated [Hadley, 1975; Scholz, 1978]. Are we to believe that the cracks completely purge themselves of these fluids and reheal? Even Obriemoff's mica flakes would not have clung together again if he had first sprayed them with water, or more to the point, kerosene. No finer example of the difficulty in purging contaminants from rock can be found than the oil droplets exuded from fine stress-induced cracks in the figures of Tapponnier and Brace [1976].

5) When a rock that contains cracks is cycled under hydrostatic pressure, hysteresis is also observed in the part of the stress-volumetric strain curve in which cracks open and close [Brace, 1965]. With the reversible Griffith crack model, this observation would have to be interpreted as meaning that the application of hydrostatic pressure causes pre-existing cracks to heal, then grow again when the pressure is released. It seems much more likely that the cracks simply close and then open, with some frictional interaction between crack walls. In the next section we will show how such frictional interaction arises, even under hydrostatic pressure conditions.

CLOSURE OF A NOMINALLY FLAT CRACK

Since stress induced cracks in rock are observed to be primarily axial, we need to consider the opening and closing behavior of a crack subject to normal stresses. Because of the heterogeneity of rock and because axial cracks are not perfectly straight and aligned, an axial crack in rock may also have shear stresses applied to it, but for the purpose of this argument we wish to consider only the extreme case in which there are no applied shear stresses.

In this case we assume that on closing and opening, an axial crack behaves as two nominally flat surfaces in contact. By nominally flat, we mean that the two surfaces are flat and parallel at wavelengths comparable to their overall dimensions but have random unmatched topography at short wavelengths. The randomness of surface topography is well established [Sayles and Thomas, 1978], and our assumption that opposite walls of the crack are unmatched at some short wavelength is simply the opposite of Holcomb and Stevens [1980] assumption, i.e., we assume the cracks are generally out of registration by more than the interatomic scale. This assumption is supported by the SEM studies referred to earlier.

Experimental technique. The experimental arrangement is shown in Figure 2. Two rectangular prisms of rock are in contact at surfaces which have been ground flat and parallel to the ends of the specimen to high tolerances. The surfaces were then lapped against one another to produce a finish with close long wavelength matching. Two frames are attached to the specimen with set screws and lined up parallel to

one another. Three sets of LVDT cores and barrels are clamped in the frames and three strain gauges are attached to the upper block in a vertical direction between the frames.

The assembly is placed in a loading frame, carefully aligned, and loaded vertically with a hydraulic piston. The loading platens are made of the same rock as the specimen to reduce stress inhomogeneity resulting from end effects, as described by Peng and Johnson [1972]. The LVDT outputs were averaged to provide the measurement of change of distance between the frames. The average output of the strain gauges was amplified by a corrective factor and subtracted electronically from the averaged LVDT output to correct for the strain that occurred in the rock between the frames. The resulting signal is the change in displacement across the two contacting surfaces. The corrective factor was first estimated based on the distance between the frames and then fine tuned by conducting the experiment on the specimen before it had been cut in two and adjusting the gain of the strain gauge amplifier until the fracture closure signal was zero over the entire stress range. In order to determine if the loading was uniform, all three LVDT's were monitored individually. If their outputs differed by more than 2% over the entire loading range, the assembly was realigned and the experiment repeated.

Observations

The fracture closure observations we shall discuss in this paper are for surfaces of Barre granite [described in Kranz and Scholz, 1977] lapped with 80 grit compound. A profilimeter record, at 20:1 vertical exaggeration, of the surface topography is shown in Figure 3. During the first two loading cycles to 50 MPa with these

surfaces, permanent closure occurred, indicating permanent damage to the surfaces. In subsequent cycles, permanent closure was less than the experimental resolution, $0.1 \mu\text{m}$. We show in Figure 4 the closure of the surfaces in the fourth loading cycle.

The closure closely follows the theoretical predictions of Greenwood and Williamson [1966] and Walsh and Grosenbaugh [1979] with one important exception: the hysteresis that is observed. In the theory it is assumed that the local stresses applied to the surfaces are normal stresses, and hence no hysteresis is expected. It can be readily seen, however, that if two surfaces with topography as in Figure 3 are placed in contact that there will be places in which oblique contact occurs. In those places shear tractions, and frictional resistance, will occur, and it is this frictional resistance that produces the hysteresis. It is equally clear that in this example the reversible Griffith crack hypothesis is not applicable, since the two surfaces are clearly not in registration at the molecular level. Notice the similarity between the closure behavior of this single 'crack' to the linear compressibility curve of a rock that contains an ensemble of cracks [Brace, 1965, Fig. 1]. All the features of the latter are contained in the former, including hysteresis.

The result described above demonstrates that two nominally flat surfaces in contact exhibit hysteresis when cycled under an applied normal load. Let us consider how this applies to the behavior of an axial crack in a dilatant rock. It is presumed in that case, that application of an axial stress acts to reduce the normal stress across axial cracks so that they open [Tapponnier and Brace, 1976; Holcomb and Stevens, 1980]. The normal stress may eventually become tensional so that some cracks may completely open, i.e., the crack walls lose

contact across all or part of their surfaces. We will discuss the effect of this latter behavior in the next section. Here we will discuss only the opening behavior of a crack in which some contact still exists between the crack walls.

The opening of an axial crack with its walls in contact due to an increase in axial stress should be the same as the opening of the crack in our experiment due to a decrease in normal stress. In Figure 5 we show a detail of another loading cycle with the same surfaces in which several small cycles have been made, resulting in hysteresis loops. The coordinates have been rotated with respect to Figure 4 in order to ease comparison with the dilatancy loop figures in Holcomb and Stevens [1980] and Holcomb [1981]. Thus normal stress decreases to the right (the equivalent of increasing axial stress for an axial crack) and crack opening is up in the figure.

The outer (incomplete) loop in Figure 5 is the loop to the total peak stress of 7 MPa. Reducing the load from, say, A to B is the equivalent to increasing the axial stress on an axial crack, and the crack opens. The hysteresis loop BCB, and the smaller loop inside it, exhibit the memory property. Several cycles were also done from the other side of the large loop in order to compare with the reloading loops of Holcomb [1981]. Again, the behavior is very similar, and shows that the surfaces exhibit discrete memory of stress maxima and minima.

We have therefore demonstrated that a single nominally flat crack in which the crack walls are in contact, subject only to an applied normal stress, exhibits all of the dilatancy and dilatancy hysteresis properties of a rock subject to an axial differential stress. Since it is not possible for this crack to be reversible, the only viable

mechanism for the dilatancy hysteresis is friction between the crack walls. Thus in the latter case as well it is not necessary to assume that the axial cracks are reversible, only that some of them are in contact over part of their surfaces and that they are not in perfect registration.

DISCUSSION

Let us now consider as our model an axial crack in rock subject to an applied axial stress such as shown in Figure 6a. The crack has topography which is not in perfect correlation in three dimensions between both crack walls. This resembles many cracks illustrated in SEM studies. Even cracks that appear smooth in the SEM will be expected to have topographic roughness on much smaller length scales, according to the topographic scaling law of Sayles and Thomas [1978] and the crack walls may be expected to be out of registration at an appropriately small scale which is still large with respect to an interatomic distance. There is no need to be overly restrictive, however. In an ensemble of cracks in rock, there may well be smooth cracks with well mated walls, as well as cracks which remain entirely open during a complete loading cycle. Such cracks may contribute to dilatancy but not to the hysteresis; they only serve to remove the 'dead bands', which, after all, will only be expected if all cracks are locked by friction, an overly restrictive assumption in the model of Stevens and Holcomb [1980].

The inset to Figure 6a illustrates the solution to the mystery of the missing shear cracks. Tapponnier and Brace found few macroscopic shear cracks, i.e., few shear cracks of similar dimension to the axial

cracks, as in Figure 1. What can be observed, however, and what is illustrated in Figure 6a, are shear segments of axial cracks, which act as shear cracks that are microscopic with respect to the axial cracks.

When the normal stress across the crack is reduced due to an increase in axial stress, the crack will begin to dilate though the walls of the crack are still in nominal contact, as in the experiment reported in the previous section. Some or all of the crack surfaces may completely open, as in Figure 6b, but if the open section of the crack lengthens, work must be done against friction. In a model like this then, in which some cracks are completely open, we would expect some crack closure to occur immediately on reduction of load, as observed. The large 'dead bands' produced by the models of Stevens and Holcomb [1980] result from their assumption that all axial cracks are locked by friction. A modification of their model in which a mixed population is assumed of shear-axial crack systems and isolated axial cracks would eliminate the dead band which was the only feature that did not agree with the data. Even this, of course, is overly simplistic. As Tapponnier and Brace [1976] pointed out, many different types of crack configurations can occur, and a variety of them can produce frictional interactions. The model developed by Holcomb [1981] of the behavior of a population of microcracks can be reinterpreted in the light of these results. The model is described by Holcomb in terms of reversible Griffith cracks but it is simply a model in which a given crack opens at a characteristic stress σ_0 and closes at σ_c , where $\sigma_c < \sigma_0$. The model is therefore equally applicable to the behavior of a crack opening and closing with fric-

tional interactions and its success in describing the dilatancy of rock can in no way be construed as providing any verification of the reversible Griffith crack hypothesis.

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REFERENCES

- Batzle, M. L., G. Simmons, and R. W. Siegfried, Microcrack closure in rocks under stress: Direct observation, J. Geophys. Res., 85, 7072-7090, 1980.
- Brace, W. F., Some new measurements of linear compressibility of rocks, J. Geophys. Res., 70, 391-398, 1965.
- Brace, W. F., B. W. Paulding, Jr., and C. Scholz, Dilatancy in the fracture of crystalline rocks, J. Geophys. Res., 71, 3939-3953, 1966.
- Goodman, R. E., Subaudible noise during compression of rocks, Geol. Soc. Am. Bull., 74, 487-490, 1963.
- Greenwood, J. A., and J. B. P. Williamson, Contact of nominally flat surfaces, Proc. Roy. Soc. London A 295, 300, 1966.
- Hadley, K., Comparison of calculated and observed crack densities and seismic velocities in Westerly granite, J. Geophys. Res., 81, 3484-3494, 1976.
- Holcomb, D. J., A quantitative model of dilatancy in dry rock and its application to Westerly granite, J. Geophys. Res., 83, 4941-4950, 1978.
- Holcomb, D. J., Memory, relaxation, and microfracturing in dilatant rock, J. Geophys. Res., in press, 1981.
- Holcomb, D. J., and J. L. Stevens, The reversible Griffith crack: A viable model for dilatancy, J. Geophys. Res., 85, 7101-7107, 1980.

- Kranz, R. L., Crack growth and development during creep of Barre granite, Int. J. Rock Mech. Min. Sci., 16, 23-35, 1979.
- Kranz, R. L., and C. H. Scholz, Critical dilatant volume of rocks at the onset of tertiary creep, J. Geophys. Res., 82, 4893-4898, 1977.
- Obriemoff, T. W., The splitting strength of mica, Proc. R. Soc. London A 127, 290, 1930.
- Peng, S., and A. M. Johnson, Crack growth and faulting in cylindrical specimens of Chelmsford granite, Int. J. Rock Mech. Min. Sci., 9, 37-86, 1972.
- Sano, O., Fundamental study on the mechanism of brittle fracture of rocks, Ph.D. thesis, Kyoto Univ., 267 pp., 1978.
- Sayles, R. S., and T. R. Thomas, Surface topography as a nonstationary random process, Nature, 271, 431-434, 1978.
- Scholz, C. H., Velocity anomalies in dilatant rock, Science, 201, 441-442, 1978.
- Scholz, C. H., and T. A. Koczyński, Dilatancy anisotropy and the response of rock to large cyclic loads, J. Geophys. Res., 84, 5525-5534, 1979.
- Scholz, C. H., and R. L. Kranz, Notes on dilatancy recovery, J. Geophys. Res., 79, 2132-2135, 1974.
- Sondergeld, C. H., and L. H. Estey, Acoustic emission study of microfracturing during the cyclic loading of Westerly granite, J. Geophys. Res., 86, 2915-2925, 1981.
- Stevens, J. L., and D. J. Holcomb, A theoretical investigation of the sliding crack model of dilatancy, J. Geophys. Res., 85, 7091-7100, 1980.

Tapponnier, R., and W. F. Brace, Development of stress induced micro-cracks in Westerly granite, Int. J. Rock Mech. Min. Sci., 13, 103-112, 1976.

Walsh, J. B., and M. A. Grosenbaugh, A new model for analyzing the effect of fractures on compressibility, J. Geophys. Res., 89, 3532-3536, 1979.

Zoback, M. D., and J. D. Byerlee, The effect of cyclic differential stress on dilatancy in Westerly granite under uniaxial and tri-axial conditions, J. Geophys. Res., 80, 1526-1530, 1975.

FIGURE CAPTIONS

- Fig. 1. A schematic model of two axial cracks keyed to a shear. This was the model suggested by Brace et al. [1966] and employed by Stevens and Holcomb [1980].
- Fig. 2. The experimental arrangement used in measuring the closure of two surfaces in contact as reported in this paper.
- Fig. 3. A surface profile, at 20 to 1 vertical exaggeration, of the surfaces of Barre granite used in the experiments.
- Fig. 4. The closure of the surfaces as a function of applied normal stress. This is the fourth loading cycle, in which permanent deformation is less than $0.5 \mu\text{m}$ and reproducibility is better than that. Notice the pronounced hysteresis in the 'toe' of the closure curve.
- Fig. 5. A detail of a subsequent loading cycle. The coordinates have been rotated and inverted with respect to Fig. 4, to aid comparison to dilatancy loops illustrated in Holcomb and Stevens [1980]. Several small loops have been generated to demonstrate the memory property.

Fig. 6. a) A schematic representation of an axial crack in dilatant rock. Inset shows a microscopic shear segment. b) The opening of the crack due to the influence of an axial load.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6