MASTER

CRACK SPECTRA ANALYSIS

Technical Summary Report

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Abstract

Crack spectra derived from velocity data have been shown to exhibit systematics which reflect microstructural and textural differences between samples (Warren and Tiernan, 1980). Further research into both properties and information content of crack spectra have yielded the following: Spectral features are reproducible even at low pressures; certain observed spectral features may correspond to non-in-situ crack populations created during sample retrieval; the functional form of a crack spectra may be diagnostic of the sample's grain texture; hysteresis is observed in crack spectra between up and down pressure runs- it may be due to friction between the faces of closed crack populations.

Introduction

The study of moduli-pressure behavioral systematics parallels and complements quantitative petrostructural analysis (Warren, 1980). The curve-fitting and similarity testing which we reported on last year were shown to be useful analytic procedures in both establishing and quantifying the systematics of mechanical moduli-pressure dependence (Warren and Tiernan, 1980). This work also indicated that crack spectra clearly reflect petrostructural patterns and, consequently, constitute a powerful diagnostic tool.

Our current work has been directed toward establishing both the properties of this tool and its information content. Thus, studies were conducted which considered spectra reproducibility, crack origin, hysteresis, and the relation between rock texture and crack spectra shape. This involved the generation of crack spectra for new Conway samples and the further analysis of existing Conway crack spectra.

The following segments of this report detail these studies. The results of this work strongly support our initial findings that crack spectra derived from acoustic velocity data are an extremely powerful tool for analyzing and modeling the microstructural dependence of mechanical moduli in real rocks. In light of this year's achievements, further research in the areas of crack origin, spectral modeling and the influence of rock texture on spectral shape should be very productive.

Crack Spectra Generation: A Review

Model crack spectra can be generated by twice differentiating precise strain-pressure data (Feves et al., 1977; Siegfried and Simmons, 1978). The assumption is made that the bulk non-linear strain of a rock is caused by a superposition of strains by various populations of cracks. Cracks within

any one population close linearly with pressure. The populations are distinguished by their closing pressure P_c .

The crack spectra is thus the distribution function $v(P)$

$$v(P) = P \frac{d^2 \epsilon}{dP^2} \quad (1)$$

where ϵ is the volumetric rock strain and P is pressure. The absolute magnitude of v is the zero pressure porosity of the crack population which closes between P_c and $P + dP_c$.

Simmons et al. (1974) generates crack spectra by differential strain analysis (DSA) of carefully taken static strain data. In the study here, the crack spectra are directly generated from the dynamic compressibility data $\beta(P)$

$$\beta(P)^{-1} = \rho(V_p^2 - \frac{4}{3}V_s^2) \quad (2)$$

where V_p is the compressional wave velocity, V_s is the shear wave velocity and ρ is the density.

The first coefficients of a spline curve through $\beta(P)$ are the slope of compressibility. Therefore, we generate crack spectra from the first derivative of the dynamic compressibility data rather than from twice differentiating strain data. The spectra obtained for Westerly Granite from Dynamic moduli data are similar to those generated from static strain data (as shown on page 4).

Crack Spectra for Westerly Granite

A comparison of crack spectra generated from acoustic velocity data (WG #1 and WG #2) with crack spectra from strain data using the DSA technique.

Crack Spectra Analysis of Conway Granites

Previously, (Warren, 1979; Warren and Tiernan, 1980) we have shown for the Conway Granite Sample Suite that:

- a) the pressure-dependence of their mechanical moduli exhibit systematics
- b) the samples divide into three distinct recognizable groups
- c) characteristics of each group are apparent in crack spectra which may be generated from a sample's dynamic compressibility-pressure curve
- c) the distinction between the groups can be qualitatively related to textural characteristics such as the grain size differences of a specific mineral component

In this section we present data for 4 previously unanalyzed samples of Conway Granite, and draw tentative conclusions about the physical significance of some features in the spectra.

Crack spectra have been generated for four new Conway samples: CG-197.2, CG-575.7, CG-534.7 and CG-771.1. As can be seen by comparing figures 1 - 4 with figures 5 and 6, these new spectra readily fit into the previously established Group I sample set. Additionally, comparisons were made between the new sample thick-sections and those already studied. Preliminary results clearly show that the grain texture of all four samples matches that exhibited by the Group I samples. There is also an indication that similarities in spectral shape within Group I may be reflected in similarities in the grain texture of the samples. This, however, will require further study.

Reproducibility of Spectra

The question arises as to how reproducible is the functional form of any one given crack spectra. We have started to address this problem by analyzing

data from multiple pressure runs on single samples. Some of the data are from aborted runs. That is, the data is of inferior quality due either to problems with the pressure vessel or with the preparation of the sample itself. In many instances, although the data is not of the best quality, it is sufficient for the construction of crack spectra in order to examine the reproducibility of the gross functional form. Multiple crack spectra for each of the following samples are available: 197.2, 771.1, and 301.8 (Figures 1, 4, and 7). Looking at these figures it will be noted that although the amplitude, exact shape and pressure at which the various features are located change somewhat between the two spectra, the distinctive shape of a sample's spectrum remains apparent. Consequently, the specific features constituting spectra are real and not merely artifacts of the data processing. The role that physical processes vs. data quality plays in the changes seen in the spectra of a particular sample is an area we will look into further.

Stress Release Cracking

In beginning to interpret the significance of the functional forms of the crack spectra (specifically with respect to Group I for which we have a good data base), we note several points:

- a) The lithostatic pressure, P_L , from which the sample was recovered serves as a point dividing the features of the spectra into two categories
- b) the features below P_L are narrow and sharp and they always have pressures that are tens of bars less than P_L .
- c) the features above P_L are broad and rounded and sometimes spill over into pressures tens of bars less than P_L .

It has been previously postulated that crack populations with closing pressures less than P_L were not originally present at depth but rather are the result of releasing the overburden pressure during sample exhumation (Simmons and Cooper, 1976). Our interpretation of specific features in the Conway Granite crack spectra suggest two additional phenomena which modify this

line of thinking:

- 1) The energy loss due to the formation of new surfaces during non-in-situ crack growth
- 2) The role of residual in-situ stress in keeping open in-situ cracks which actually have closing pressures lower than P_L

The energy loss due to the inelastic aspect of crack growth would result in the creation of crack populations with closing pressures, P_C , lower than P_L . The "spikes" in the spectra of samples 197.2, 301.8, 419.0, 515.7, 537.4, and 771.1 may be such features. (In passing, we note that it is not unreasonable to expect the "catastrophic" growth of non-in-situ cracks to generate crack populations with approximately delta-functions in closing pressures. We plan to investigate this further).

In-situ residual stresses exist on the scale of grains due to anisotropy of mechanical and thermal mineral properties and existing crack networks. Thus, some of these stresses may hold open cracks which otherwise would be closed at P_L . When the sample is exhumed, such cracks may be found. This may be the case for samples 448.1, 537.4, 523.3, and 771.1. Note that in their spectra the population distribution smoothly continues through the P_L line apparently indicating a common genesis with those cracks whose P_C is greater than P_L .

In summary, it is apparent that the individual features in the spectra of the Conway Granite samples are real and that they behave in ways which are consistent with their closing pressures versus their depth of origin. We plan to continue our investigations into the significance of their characteristic shapes, and also to examine theoretical models concerning their formation.

Fig 1a-Crack Spectra #1 for Conway Sample 197.2
 P_L denotes lithostatic pressure

Fig 1b-Crack Spectra #2 for Conway Sample 197.2

Fig 2-Crack Spectra for Conway Sample 515.7
 P_L denotes lithostatic pressure

Fig 3-Crack Spectra for Conway Sample 537.4
 P_L denotes lithostatic pressure.

Fig. 5

Fig. 6

Fig 7a-Crack Spectra #1 for Conway Sample 301.8

Fig 7b-Crack Spectra #2 for Conway Sample 301.8

Mineralogical Texture and Spectral Shape

Having seen that systematics in the functional form of the crack spectra seem to be related to textural characteristics of the samples within the Conway Granite suite, it is reasonable to ask whether this might also hold true for other samples. The answer appears to be yes. The functional form of the crack spectra for two samples, a Westerly granite and a diorite, suggest such a relation.

We observed in the Conway suite that the fine-grained granites (i.e., the Group II samples) had spectra dominated by a tall narrow feature at pressures less than 500 bars (see Fig. 6). Looking at the Westerly granite (Fig. 8), we see a similar spectral shape and we note that Westerly is also a fine-grained granite. The spectrum of our diorite sample (Fig. 9) looks like the spectra of the Conway Group III-- the lamprophyre dike rocks (Fig. 6). This similarity is especially striking for the Conway sample 610,2. Both it and the diorite show little structure at low pressure and are dominated by a broad triangular feature. Texturally, the diorite is a dark, very fine-grained rock-- much more similar to the lamprophyre dike rocks than to the granites. We plan to continue our studies concerning this relationship between texture and spectral shape over a large range of samples.

Crack Spectra Models

At this point, it is also useful to consider how the shape of the crack spectra for a given sample may be interpreted in terms of the distribution of crack populations (which, in turn, seems to be controlled by the underlying grain texture). Consider a low-porosity rock with open microcracks. Let the cracks form a single population; that is, they have the same length a and, at zero pressure, a distribution of widths b_i which is uniform from closed ($b = 0$) to some maximum value b_m .

Fig. 8

Fig. 9

Assume further that all the cracks close linearly with pressure, the crack characterized by b_m closing at a pressure P_{cm} .

An elastic compliance of the rock is then simply a linear and decreasing function of pressure up to P_{cm} . At higher pressures, the compliance has its limiting value (assuming the high pressure pins all the closed cracks so they cannot slip). The modulus C is then of the form

$$C/C_0 = \frac{1}{1 + A - BP} \quad P \leq P_{cm}; A, B \text{ constants} \quad (3)$$

$$C/C_0 = 1 \quad P > P_{cm} \quad (4)$$

where C_0 is the "intrinsic" value of the modulus at high pressures.

$$\frac{d \log C}{d \log P} = \frac{BP}{1 + A - BP} \quad P \leq P_{cm}$$

A plot of $\log C$ versus $\log P$ is essentially flat at low pressures and becomes increasingly concave upward for pressures near, but less than, P_{cm} . Above P_{cm} the curve is flat.

Such a population of simple cracks generates a crack spectrum of the form shown in Figure 10a. The spectrum for a superposition of two such populations is shown in Figure 10b. If at $P \geq P_c$ the roughness of the cracks controls the remaining pore closure, then the bulk strains may be of the form of a power law $(P/P_c)^r$, where $P_c' > P_c$ and $r < 1$ ($r = 2/3$ for Hertzian contacts). The corresponding "crack spectrum" (Figure 10c generated is of the form

$$Pd^2\epsilon/dP^2 \sim P^{r-1} \quad (5)$$

Model Crack Spectra

Fig. 10

Schematic of crack spectra $v(P_c)$ for model crack populations.

Finally, if a simple population is defined by assuming all cracks have essentially equal widths at zero pressure, linear closure laws, and a flat distribution in lengths between $A_{\min}$ and $A_{\max}$, then the crack spectrum is of the form shown in Figure 10d.

To first order the spectrum for sample 335.0 shows a narrow crack length distribution and has a shape reasonably approximating the spectrum for a superposition of two simple crack populations (compare Figures 6 and 10b). At low pressures the spectra for 610.2 and 502.3 (Figure 6) are similar to that in Figure 10a. Therefore, parts of spectra may be interpreted in terms of fairly simple model crack populations.

Hysteresis

It is well-known that the mechanical moduli-pressure curve for a given sample can be dependent on whether the measurements were made under increasing or decreasing pressure (Walsh, 1965). This behavior may be due to inelastic deformation or to friction between crack faces in contact or to a combination of both, depending on the sample's geologic history and composition. Hysteresis between up-run and down-run measurements can be seen in some of the crack spectra for the LASL samples (e.g., Marble and Westerly Granite, Figs. 11 & 12). It manifests itself in the down run spectra as a displacement to lower closing pressures of specific spectral features whose original shape is essentially maintained or perhaps slightly broadened. Friction between closed crack faces such as that modelled by Holcomb and Stevens (1980) may be responsible for this effect. It is possible, though, that this effect is the result of some systematic bias in the operator's acoustic velocity measurements. At the present time we cannot absolutely rule this out. However, the existence of this observation of feature displacement is significant for two reasons:

- 1) Whether there is a real hysteresis offset or no, the same features are being observed in both the up and down runs.
- 2) The act of generating a crack spectra (i.e., approximately the differentiation of the compressibility data once) amplifies features in the original data, making phenomena such as hysteresis much more apparent and more easily quantifiable.

We are looking into the problem of systematic bias in the data between the up and down runs and we are planning to quantify the observation of real hysteresis data in order to obtain better constraints on possible models.

Fig. 11

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