Limits to Crack Density: The State of Fractures in Crustal Rocks

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SUMMARY

Shear-wave splitting in sedimentary basins and above small earthquakes in a wide range of geological and tectonic domains typically displays evidence for azimuthal shear-wave velocity anisotropy of between 1% and 5%. Interpreted as the effects of parallel vertical fractures, microcracks, and preferentially oriented pore-space, these percentages of anisotropy are equivalent to crack densities of \( e = 0.01 \) and 0.05 with normalized mean crack diameters of 0.43 and 0.74, respectively. The only exceptions are percentages of anisotropy exceeding 10% (\( e > 0.1 \)) observed in near-surface rocks where there is pronounced jointing.

It is suggested that the density of cracks in subsurface rocks is limited to shear-wave anisotropy of about 5% (\( e \sim 0.05 \)) because at a larger value of crack density, somewhere between \( e = 0.05 \) and 0.10, which we call fracture-criticality, the rockmass is so thoroughly pervaded by cracks that the rock can no longer be considered as elastically intact. Any externally- or internally-induced deformation would tend to produce through-going fractures in the critically fractured rockmass so that pore fluids would tend to disperse and the fractures collapse to a lower crack density. The range of normalized crack diameters, equivalent to the range from the smallest observed anisotropy (1%) to the largest (5%) is small, differs by a factor less than two. This means that the cracks within most rocks are comparatively close to the limit when the rock fragments. The implications of this critical state of fractures in crustal rocks are discussed.

INTRODUCTION

Shear-wave splitting in crustal rocks implying some form of azimuthal anisotropy was first identified above small earthquakes by Crampin et al. (1980a) and in sedimentary basins by Alford (1986) and Crampin et al. (1986). Since then, shear-wave splitting has been observed in a wide range of sedimentary, igneous, and metamorphic rocks on almost all occasions when shear-waves have been recorded on appropriate three-component instrumentation. Such shear-wave splitting typically displays differential shear-wave anisotropy of between 1% and 5% (Crampin and Lovell, 1991). Absence of azimuthal shear-wave anisotropy has not been reported.

Shear-wave splitting in the crust implying azimuthal anisotropy is interpreted as the result of propagation through distributions of aligned cracks, microcracks, and preferentially oriented pore-space (Crampin and Lovell, 1991). Crack density is defined as \( \varepsilon = N a^3/v \), where \( N \) is the number of cracks of radius \( a \) in volume \( v \). The radius \( a \) is much smaller than seismic wavelengths so that the long-wavelength approximation applies. It is convenient to put \( N = 1 \) and refer to \( \varepsilon = a^3 \) as the normalized crack density where \( a \) is the radius of one crack in a unit cube. Figure 1 shows the numerical relationship between the normalized crack density and crack radius per unit cube. The relationship is reasonably well-behaved for values of crack density less than about \( e = 0.05 \), radius \( a = 0.37 \), but larger values the crack density are very sensitive to small changes in radius.

Crampin (1993) shows that the crack density is approximately the percentage of shear-wave anisotropy divided by 100 when the Poisson’s ratio of the uncracked rock is 0.25. Percentages of anisotropy of 1% to 5% are thus approximately equivalent to crack densities of \( e = 0.01 \) and 0.05. Table 1 shows the relationship between normalized crack density and crack radius for a few specific values. The box in Figure 1 outlines the values of shear-wave anisotropy that are commonly observed in subsurface rocks. Note that the lower limit is real in the sense that, although absence of azimuthal shear-wave anisotropy is sometimes claimed, there are no published examples of well-authentic cases of subsurface rock with much less than 1% shear-wave anisotropy. However, measures of anisotropy are usually averages over at least several tens of metres and small thicknesses of isotropic rock cannot be excluded.

The behaviour of fluid-filled voids is controlled by stress so that neither cores nor well logs can necessarily provide much direct information about the state of in situ microfractures. The rock in both cores and logs has been partially or wholly de-stressed, and some 20 direct or indirect stress-controlled phenomena (Crampin and Lovell, 1991) are likely to have modified the core, and the rock in the immediate vicinity of the well, in ways which may not be easy to estimate.]

Such 1% to 5% values of shear-wave anisotropy have been found in km-length raypaths in a wide variety of sedimentary, metamorphic, and igneous rocks, and in mixed geological domains. This similarity of the observed anisotropy in a large range of rock types is remarkable. The only exceptions appear to be that occasionally large values of shear-wave anisotropy, implying large crack densities, have been found in the very near-surface, where they frequently indicate systems of bi-planar cracks. Crampin et al. (1980b) found P-wave anisotropy in a jointed limestone pavement equivalent to a bi-planar crack...
LARGE AND SMALL FRACTURES

The various formulations for determining elastic wave propagation through distributions of small cracks are long-wavelength approximations and are sensitive to the crack density, but not to the actual dimensions of the cracks. Differential shear-wave attenuation is probably the most sensitive parameter for quantifying crack size, but appropriate situ observations do not yet appear to have been made. Note that crack density and crack dimensions are two largely independent parameters so that, although they may be associated in practice, neither one directly specifies the other.

There appear to be two distinct classes of aligned fractures that can cause shear-wave splitting in the crust. The first is distributions of large fractures with dimensions of possibly metres or greater, but still much less than most seismic wavelengths, so that effective media and long wavelength concepts still apply. These large fractures are often originally induced by shear stress and are relatively immobile and do not respond significantly to small changes in stress [or small stresses] in most other phenomena acting on the rockmass. These large fractures occur in fractal distributions (Leary, 1991). Such large fractures have been identified seismically in hydrocarbon reservoirs both directly (Mueller, 1991; Li et al., 1991) and indirectly (Lewis et al., 1991; Cliet et al., 1991). These large fractures occur in fractal distributions (Leary, 1991). Such large fractures have been identified seismically in hydrocarbon reservoirs both directly (Mueller, 1991; Li et al., 1991) and indirectly (Lewis et al., 1991; Cliet et al., 1991).

The other class of fractures in the rockmass are distributions of small cracks or voids with dimensions of cms or less which are expected to be relatively compliant both direct and indirect stress-induced changes and other changes to the rockmass. Distributions of such stress-sensitive voids are known as extensive-dilatancy amlostropy or EDA, and the individual elements are known as EDA-cracks (Crampin and Lovell, 1991). The fractal nature of these fluid-filled compliant, EDA-cracks, with comparatively well-defined limits to crack dimensions from a few microns to at most a few cms, is not established. These distributions of small EDA-cracks appear to be the principal cause of the shear-wave splitting observed almost universally in crustal rocks. The shear-wave splitting suggests that the EDA-cracks are aligned (like hydraulic fractures) perpendicular to the local direction of minimum compressional stress, which may or may not be coincident with the more regional stress-field (Crampin and Lovell, 1991).

PHYSICAL REPRESENTATION OF CRACK DENSITIES

Figure 2 gives a schematic illustration of the physical relationship between crack size and crack density for the values marked by solid circles in Figure 1. There is a significant difference between distributions with small and large crack densities. For weak crack densities less than or equal to \( \varepsilon = 0.05 \) (differential shear-wave anisotropy up to about 5%), as in Figures 2a and 2b, the rock is predominately intact without substantial fracturing. Whereas for distributions with crack densities greater than \( \varepsilon = 0.05 \), as in Figures 2c and 2d, the rock is pervasively cracked, with one or more cracks within an average crack radius of almost every point in the rockmass.

Thus, we suggest that at some crack density between \( \varepsilon = 0.05 \) and 0.10, which we call fracture-criticality, the rock is so substantially weakened that it can no longer be considered as elastically intact. Any even small deformation, either as a result of externally- or internally-induced disturbances, is likely to connect individual cracks together so that the rock fragments. The reason why such high crack densities are seldom observed becomes clear. Large crack densities imply that the rock is essentially fragmented and such fragmentation is likely to be an unstable phenomenon. Pore fluids will more easily disperse in such fragmented rock so that, without being propped open by pore-pressure, the fractures would collapse to lower effective crack densities. The only exceptions are in the very near-surface where confining pressures are insufficient, and perhaps in over-pressurized hydraulic compartments (Powley, 1990) where the pore fluids may not easily disperse.

Clearly, we do not suggest that the schematic illustrations in Figure 2 represent pictures of real rock. Most rock, particularly sedimentary reservoir rocks, will have much associated porosity, and a large proportion of the EDA-cracks in such rock will be associated with preferential orientations of the pore space, rather than what are usually thought of as cracks. Nevertheless, because EDA-cracks are so small and most seismic wavelengths are so long, there is extraordinarily good statistical sampling, and synthetic seismograms can be modelled successfully with distributions of small penny-shaped cracks. Whatever, the real "crack" situation in rock is like, the crack densities in Figure 2c and 2d must represent conditions of pervasive cracking, and the arguments of this paper still apply.
Implications for reservoirs

The narrow separation of observed crack density from the density at which the rock fragments means that microfractures and possibly fractures in most reservoirs are customarily close to fracture-criticality. This makes the EDA-crack geometry likely to be particularly sensitive to changes in external and internal conditions. Comparatively minor variations of almost any phenomena acting on the rockmass are likely to vary the internal structure of stress-aligned fluid-filled cracks throughout the rockmass in ways that should be recognizable by careful monitoring of shear wave propagation.

Examples of the sensitivity of the reservoirs to changing conditions are the changes in the response of reservoirs to $P$-wave propagation recognized in several thermal EOR operations (Greaves and Fulp, 1987; De Buyl, 1989, etc.). Shear-waves are much more sensitive to seismic anisotropy than $P$-waves since their vector polarizations carry much more information than the merely radial (scalar) polarizations of $P$-waves. At present, there are no published reports of using shear waves to monitor EOR operations.

We have suggested that the critical crack density for fragmentation to occur is somewhere between $\varepsilon = 0.05$ and $0.10$ (shear-wave anisotropies of 5% and 10%, respectively) which represents a change in normalized crack diameter from $d = 0.74$ to $d = 0.93$. Since the minimum crack density in most rocks is observed to be about $\varepsilon = 0.01$ ($d = 0.43$), only small changes in linear crack dimensions are needed to bring rock from what appears to be the minimum crack density to fracture-criticality. The change in crack length is perhaps a factor of about two. In permeable sedimentary rocks, where pore-pressure changes are likely to be pervasive throughout the reservoir, this means that large volumes of rock may reach fracture-criticality simultaneously. This sensitivity provides a mechanism for the repeated sequences of hydraulic fracturing recognized by Powley (1990) as essential to the evolution of pressurized hydraulic compartments.

There are three aspects of fracture-criticality that may be important for the hydrocarbon industry.

1) It is suggested that pore fluids more easily disperse at fracture-criticality. If such levels of crack density could be recognized in a reservoir, by analysis of shear-wave splitting for example, it is likely that the reservoir would be in an optimum condition for hydrocarbon exploitation. One of the indicators of this condition may well be conditions of substantial overpressures, and it would be interesting to test this hypothesis by detailed measurements of shear-wave anisotropy in overpressurized reservoirs.

2) During hydrocarbon production it is expected that overpressures would decrease, and crack density decrease until the reservoir was no longer subject to fracture-criticality with pore fluids less easily dispersed. Consequently, it may well be desirable to maintain overpressures by hydraulic pumping, so as to maintain fracture-criticality throughout the production history of the reservoir.

3) It may be possible to recognize changes in crack density by monitoring shear-wave splitting. If this were possible, then, the evolution of reservoirs could be monitored during production processes including enhanced oil recovery operations.

What is needed to test these ideas is detailed monitoring with advanced instrumentation in Borehole Test Facilities in producing reservoirs, particularly over-pressurized reservoirs, before, during, and after production processes have passed through the BTG sites, as discussed in another paper at this meeting (Cramin et al., 1993).

Implications for igneous and metamorphic rocks

There are several possible causes of seismic anisotropy in igneous and metamorphic rocks: aligned crystals; aligned lithology; and other aligned fabric. However, the almost universal parallelism of observed shear-wave polarizations with the direction of maximum horizontal stress, and the typical range of shear-wave anisotropies from 1% to 5% are indirect confirmation that the anisotropy is caused, as in sedimentary rocks, by aligned cracks.

Possible causes of changes in crack density are changes in stress, changes in pore-fluid pressure, and changes in temperature, and confining pressure. The recognition of the proximity of most rocks to fracture-criticality accentuates the role that fluids play in the behaviour of all rocks, and we suggest that fluid-pressure is one of the most important parameters controlling the behaviour of all rock. The near fracture-criticality of micro-fracturing is one of the reasons in situ rock has so little strength under tension and why the stress-drop during earthquakes is so small. We suggest that one major cause of the differences in behaviour between permeable sedimentary rocks and relatively impermeable igneous and metamorphic rocks is the behaviour near fracture-criticality. Whereas in permeable rock, pressure changes tend to be pervasive throughout the rockmass, the generally low permeability of most igneous and metamorphic rocks suggests that fracture-criticality will not be, or will seldom be, achieved throughout large volumes of rock simultaneously. In relatively impermeable rocks any change in conditions is likely to be localized, possibly to volumes which are hydraulically connected, along shear-zones associated with fault zones, for example, which would be one of the reasons that earthquakes re-occur along previous fault zones.

Implications of fracture criticality

There are several reasons why fracture-criticality of less than about 10% shear-wave anisotropy (effective crack density $\varepsilon < 0.1$) is convenient for Earth scientists:

1) Mathematical formulations, such as those of Hudson (1980, 1981) for weak distributions of thin penny shaped cracks begin to diverge for values of crack density greater than about $\varepsilon = 0.1$. Fracture-criticality indicates that existing formulations are generally applicable.

2) Uniform distributions of penny-shaped cracks of small aspect ratio containing fluid of some effective viscosity and acoustic ($P$-wave) velocity may well be a reasonable long-wavelength approximation for elastic-wave propagation of small displacement when crack densities and cracks are small, as in Figure 2a and 2b. Once crack densities are large, as in

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Figure 2c, the complexity of the behaviour of multiple cracking in real rock increases significantly and the long-wavelength approximation of simple penny-shaped cracks is clearly inadequate.

3) Fracture-criticality between 5% and 10% means that observations of subsurface shear-wave anisotropy are typically between 1% and 5%. This can be observed with appropriate, if expensive, technology.

4) The near fracture-criticality of igneous and metamorphic rocks means that there are prospects of monitoring stress changes, before earthquakes for example, by analyzing changes in the behaviour of shear-wave splitting.

There are three possible implications for hydrocarbon production:

5) Fracture-criticality is likely to be associated with over-pressurized reservoirs and this condition may be identifiable by the high levels of shear-wave splitting throughout the reservoir.

6) Fracture-criticality of a reservoir is likely to lead to enhanced production. It may be desirable to maintain such fracture-criticality during production, by hydraulic pumping for example.

7) Near fracture-criticality, changes of crack density are likely during production, and EOR-type operations, and these may be monitored by analyzing shear-wave splitting.

What is needed to test these hypotheses are advanced borehole test facilities in producing reservoirs, as suggested by Crampin (1993).

REFERENCES


