Microcracks in the Earth’s crust
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The presence or absence of cracks within in situ crustal rocks is open to wide misunderstandings because of the inaccessibility of the material and the difficulty of reproducing in situ conditions in the laboratory. There is now evidence from a wide range of results that most crustal rocks are pervaded by aligned liquid-filled microcracks, where the liquid is usually water but may be oil in hydrocarbon reservoirs. The recognition that there are aligned liquid-filled microcracks deep within the crust ties together a number of previously contradictory phenomena.

Introduction
Liquid-filled cracks in the Earth’s crust, although generally recognised as being present (Brace 1972, 1980), are little understood and the implications of their behaviour have not been explored. This is partly because it is impossible to reproduce in laboratory conditions more than a few of the large range of independent phenomena controlling the existence and behaviour of cracks in rock in situ. The liquid in these cracks is usually a water solution but may be oil in hydrocarbon reservoirs.

The other major source of misunderstandings about cracks in the crust is that the principal technique for examining the properties of rocks at depth in the crust has been the analysis of travel times of seismic body-waves, and reflection and refraction experiments by the exploration industry yield consistent structural interpretations without any need to assume the existence of widespread cracking. We now recognise that this is because almost all seismic experiments in the past have used P-waves, and P-wave travel-times are very little affected by liquid-filled cracks with low aspect-ratios. In contrast, shear-wave splitting (shear-wave birefringence) is very sensitive to distributions of aligned cracks.

(Crampin 1978). Recent observations of shear-waves (Crampin et al. 1980; Crampin 1985a) suggest that parallel, vertical, water-filled microcracks pervade much of the brittle, upper 10–20 km of the crust.

We call such distributions of aligned fluid-filled cracks extensive dilatancy anisotropy (EDA) (Crampin, Evans and Atkinson 1984). EDA is a unifying concept that allows a variety of phenomena from geology, geophysics and the rock-mechanics laboratory to be correlated for the first time. The existence of such cracks has wide implications for all deformatory processes in the crust, and the ability to monitor crack geometry by shear-wave propagation has applications to many currently important activities ranging from determining preferred directions of flow in hydrocarbon reservoirs to earthquake prediction.

Cracks in the crust
There is certainly water within most crustal rocks (Fyfe, Price and Thompson 1978). Meteoric water has been incorporated into most sedimentary rocks at deposition, and this water will be retained under compression unless there are very unusual circumstances (it is very difficult to dry even small specimens in the laboratory). Initially randomly aligned (isotropic) pore space in sandstones, for example, takes on the characteristics of distributions of aligned cracks when subjected to deviatoric stresses in the laboratory similar to those expected in the crust. Similarly, since water is one of the by-products of most prograde metamorphic processes, water will be released within most igneous and metamorphic rocks. Such water would be released by each grain within the rock undergoing metamorphism, and the only mechanism for releasing water deep in an otherwise impermeable rock mass is by hydrofracture (Fyfe et al. 1978) into intra- and intergranular microcracks at higher pore pressures. Such microcracks will again be aligned relative to the prevailing stress. Some of the water in the cracks may be absorbed in retrograde processes but retrograde metamorphism is customarily much less complete than prograde metamorphism. In igneous rocks, these fluid-filled microcracks are dense distributions of isolated cracks in an otherwise impermeable rock-mass, often without paths of flow to adjacent microcracks. There may also be macrocracks in crustal rocks, but the cracks referred to here are primarily distributions of microcracks within the mass of otherwise competent rock. We are not specifically referring to fractured beds, fractured reservoirs, or to high fluid-conductivity shear zones.

Thus, there is strong evidence to suggest that there are liquids in distributions of aligned pores and cracks throughout, at least, the brittle, top 10–20 km of the crust. It is these open inclusions that we refer to as cracks. The effects of cracks on seismic waves are important since seismic experiments are one of the few geophysical techniques capable of examining the properties of rock in situ with any degree of resolution. The
behaviour of seismic shear-waves offer techniques for monitoring the presence and estimating some of the properties of aligned cracks \textit{in situ} which are crucial to any understanding of the detailed behaviour of crustal rocks (Crampin 1985a).

The existence of distributions of liquid-filled microcracks may be demonstrated most directly by appealing to hydrocarbon reservoirs. Every hydrocarbon field is a reservoir of fluid-filled cracks, using cracks in the wider sense, and every reservoir has some kind of impermeable cap preventing drainage and containing the fluid within the rock at high enough pore-fluid pressures to prevent the cracks closing or healing. There are productive wells below a depth of 8 km and the deepest levels that hydrocarbons have been found are below 10 km (Drilling, pp. 92–102, August 1981). Since the ratio of hydrocarbons to water in crustal rocks is small, and yet hydrocarbon reservoirs are comparatively common, it is clear that water-filled cracks and impermeable caps must be almost ubiquitous features of crustal rocks. The new evidence that aligned fluid-filled cracks are extremely common comes from the widespread observation of shear-wave splitting reported by Crampin (1985a) which is diagnostic of some form of effective anisotropy such as that resulting from EDA.

There are a few studies reporting the absence of cracks at depth in the crust. Such results usually need to be revised following recent advances in our understanding of the behaviour of cracks in \textit{in situ} rock—an example of such a study is discussed in the Appendix.

**The behaviour of cracks**

There are a wide variety of phenomena affecting the behaviour of cracks in the crust. Some of these factors are:

1. lithostatic or overburden pressure;
2. pore-fluid pressure;
3. deviatoric, non-lithostatic, or differential stress;
4. rate of strain (since comparatively stable stress conditions may persist in the crust, in some cases for many millions of years, processes with very large time constants may have important effects on the cracks);
5. crack distribution;
6. crack geometry (parallel, bi-planar, or multi-planar crack distributions);
7. crack orientation;
8. crack dimensions;
9. crack aspect-ratios;
10. presence of debris in the cracks;
11. likelihood of subcritical crack growth;
12. rate of crack healing;
13. amount of connection, or possibility of flow, between the cracks (EDA cracks do not imply high permeability, unless the deviatoric stresses are great enough to promote active crack growth);
14. temperature.

This list indicates the large number of phenomena affecting the behaviour of cracks in an otherwise impermeable rock-mass in the crust. However, the list is not exhaustive, the order is not significant, and some of the factors are partially interdependent or interrelated.

Despite the presence of fluid-filled cracks in crustal rocks having major, often dominating, effects on the elastic and deformatory behaviour of the rock, our knowledge of the behaviour and distribution of micro- (and macro-) cracks in the crust is, at present, almost complete speculation. No laboratory experiments to date have been in conditions wholly appropriate to cracks at depths of more than a few tens of metres beneath the surface. For example, almost all laboratory experiments have been made with connected cracks since access to the interior of the pore space is usually essential to monitor the behaviour of the cracks. These limitations mean that in order to estimate the behaviour of cracks at depth in the crust it is necessary to make multi-variable extrapolations from their behaviour in the very restricted conditions of a few field and laboratory experiments.

Even well-logs, which at first sight may appear to be examining conditions \textit{in situ}, are sampling material which has had the original stress-field modified and partially destressed by the passage of the bit and the presence of the well cavity. Since stress is one of the major phenomena directly controlling most of the factors listed above, well-logs will sample cracks in which many of the factors controlling their behaviour will have been seriously disturbed.

Despite these factors and their effects on each other being very imperfectly understood, some broad statements can be made. Since many of these statements appear to be unappreciated or neglected, the purpose of this paper is to suggest some fundamental principles which should guide our examination of cracks in the Earth's crust.

In the absence of pore fluids, comparatively modest lithostatic pressures of 100–200 MPa (3–6 km) are sufficient to immediately close most cracks, although the closure may not be uniform if there are asperities on the crack faces (Kranz 1983). When similar and greater pressures are sustained for geological periods of time, all cracks will close unless they are kept open by pore-fluids approximately equalising the lithostatic pressures. Similarly, isolated cracks with pore pressures higher than lithostatic will grow over geological periods until the increased pore space has reduced the pore-fluid pressure to the lithostatic pressure.

The most important observation is that, since water has low compressibility, isolated (unconnected) water-filled microcracks, such as those produced by prograde metamorphism, \textit{will not be closed merely by increasing lithostatic pressure}.
Causes of alignment
In the presence of deviatoric stresses, cracks will tend to deform by a variety of stress-controlled mechanisms. Cracks with large aspect ratios will tend to elongate by spalling by the same processes that cause drill holes to become elliptical (Zoback 1983) which will in time reduce the large aspect cracks to a distribution of small cracks. Small cracks will grow, or re-align, relative to the directions of stress by subcritical crack growth (Atkinson 1984), possibly extremely slowly (Crampin et al. 1984). The products of corrosion at the stress concentrations near the crack tip are transported by pore fluids and may be deposited at surfaces of low stress-intensity away from the crack tip. If the faces of the crack have small separation the gap between the faces will be filled by these corrosion products and the crack will be subdivided. As the strain continues, there will be a build-up of stress intensity at these healed dividers until eventually subcritical crack-growth re-opens the healed portion. (There are several ways in which this cycle of healing and re-opening can occur, but the results would be similar.) The cycle of healing and re-opening of microcracks will slowly lead to redistribution of the local stress field and is probably one of the key parameters controlling the behaviour of earthquake swarms, fore-shocks and possibly aftershocks. All such phenomena result in microcracks growing parallel to the axis of maximum compression if \( \sigma_1 \gg \sigma_2 = \sigma_3 \), or normal to the maximum tension if \( \sigma_1 > \sigma_2 > \sigma_3 \), and will result in distributions of cracks containing preferred directions of orientation. Such microcracks are a mobile phenomenon, which continually re-align themselves (perhaps very slowly) by subcritical crack growth with the stress acting on the rock mass. Such distributions of aligned cracks will be effectively anisotropic to the propagation of seismic waves (Crampin 1978, 1984).

These arguments suggest that all cracks at depth in the crust are likely to be closed by lithostatic stress to at most a few centimetres in length unless pore pressures are exceptionally high, and pore pressures much higher than the lithostatic stress are unlikely to be stable over long periods of time. Thus we infer that the cracks in EDA are micro- rather than macrocracks, and this seems to be confirmed geologically, as the relics of widespread distributions of macrocracks are not commonly observed in crustal rocks, whereas distributions of finely divided pore space in sedimentary rocks, and microcracks in igneous and metamorphic rocks (Simmons and Richter 1976) are universally present.

Causes of microcracking
It could be argued that whether cracks are open or closed at any depth in the crust is the result of a balance struck between the rate of crack growth and the rate of crack healing. Although this is of course broadly true, the healing process may be comparatively fast, within minutes in optimum laboratory conditions (but very dependent on the surrounding conditions), whereas sub-critical crack-growth may be extremely slow. A distinction should be made between sealing, when dissolved material is transported into connected cracks and subsequently precipitated, and the healing which may occur in isolated cracks. Microcrack healing proceeds by first reducing the pore space to a series of tubular bubbles, and then much more slowly to planar distributions of spherical bubbles (Smith and Evans 1984). To our knowledge, laboratory experiments in crack healing have not been made at high pore-fluid pressures, and we suggest that healing is unlikely to proceed in isolated microcracks once the pore-fluid pressure has been increased to the lithostatic pressure by the reduction in pore space. Microcrack healing fills the fluid-filled crack with a mobile solid (silica for microcracks in quartz) with the pore-fluid often concentrated into dense distributions of spherical or tubular bubbles in the erstwhile crack cavity. It seems likely that effects on seismic waves of scattering by these distributions of bubble planes will be similar to the effects of the original fluid-filled cracks with perhaps a reduction of the effective crack-density. However the balance between crack growth and crack healing is struck, the result is clear. Distributions of aligned fluid-filled microcracks are a common if not universal condition in the crust, at least in the top 10–20 km of cooler, brittle rock, and abundant fluid-filled microcracks pervade upper mantle rocks (Andersen, O'Reilly and Griffin 1984). The reason for the absence of sealing is that isolated microcracks are excluded from transported material, and the reason for the absence of healing is that high pore-fluid pressures keep the cracks open.

The major reason why there should be any controversy over fluid-filled cracks in the crust is that exploration seismology has been so extraordinarily successful in discovering hydrocarbon reserves by seismic reflection interpreted in terms of uncracked isotropic rock layers. This is because, until very recently, all analysis in exploration seismology in the West and almost all earthquake seismology has been confined to interpreting records from single component vertical instruments. This confines the analysis to interpreting P-wave arrivals and neither the mean velocity nor the velocity-anisotropy of P-wave propagation is very much affected either by aligned or random distributions of liquid-filled cracks (Crampin 1978, 1984).

Monitoring with shear waves
The polarisations of shear-wave are more affected by the presence of cracks, and the phenomenon of shear-wave splitting is very sensitive to the effective anisotropy of distributions of aligned liquid-filled cracks (Crampin 1984, 1985b). Shear waves have complicated interactions at the free surface which may disguise the effects of anisotropy except within the shear-wave window where the angle of incidence is less than critical (Evans...
Shear-wave splitting is observed within the shear-wave window above small earthquakes, and is now almost routinely observed in three-component VSPs—see the review by Crampin (1985a).

**Some problems resolved**

There are several fundamental difficulties in interpreting the physics of crustal rocks which are resolved by EDA. Some of the phenomena are:

1. All fault mechanisms, but particularly thrust faults, require pore-fluid pressure to reduce the effective normal stress across the fault sufficiently to allow sliding to occur at lower values of shear-stress (Fyfe et al. 1978). EDA provides such fluid as soon as local stresses are large enough to promote crack growth sufficiently to connect the microcracks and permit water to flow into regions of greater dilatancy near the eventual fracture.

2. The fracture strength of crustal rocks in situ, as estimated from earthquake movements, is far below that expected from laboratory studies of intact competent rock specimens. Observations of shear-wave splitting in the crust suggest that EDA cracks are widespread in earthquake zones and possibly elsewhere. This is another demonstration that small, competent, intact specimens in the laboratory do not model crustal rocks in situ. Rocks in the crust will be weaker than their laboratory counterparts because of the widespread occurrence of EDA cracks.

3. The theoretical attenuation, $1/Q_\nu$, caused by scattering of shear-waves propagating through liquid-filled cracks is greater than the attenuation of P-waves by a factor of about 3 (Crampin 1984). Thus the aligned liquid-filled cracks in EDA explain the larger shear-wave attenuation in the crust, and the variation with direction could help to explain some of the inconsistencies in observed measurements of $1/Q_\nu$. The marked difference in attenuation between Earth and lunar rocks may also be due to liquid-filled EDA cracks causing large attenuation in the Earth, whereas cracks in the Moon are dry due to the absence of evaporites and are closed by lithospheric pressure and result in low attenuation.

4. The presence of dense distributions of water-filled cracks would be expected to increase substantially the electrical conductivity of dry rocks. It is well known that conductivity at all levels in the crust is anomalously high by several orders of magnitude relative to dry rocks in the laboratory (Shankland and Ander 1983). This is true both at shallow depths, as measured in well logs, and at deeper depths (down to 20 km) from large-aperture long-period measurements at the surface.

5. EDA provides the common driving mechanism for the large range of geophysical precursors which are sometimes observed before earthquakes. Since EDA is anisotropic, the effects of each precursory phenomenon will vary widely with the orientation of the earthquake mechanism, the geological structure, and the position of the recording sites, so that the behaviour of precursors will occur very irregularly, as is observed in the Earth.

**Conclusions**

Most of what is said in this paper about the widespread distribution of microcracks in crustal rocks is well known and is stated or implied, for example, by Brace (1980), Fyfe et al. (1978), Jaeger and Cook (1979) and others, but the implications have not been understood. The only difference now is the recognition that the cracks are aligned (Crampin 1985a) so that the distribution of cracks can be monitored by shear-wave splitting. The contradiction that seismic recordings show little evidence of cracking is resolved. P-waves are insensitive to liquid-filled microcracks, but observations of shear-wave splitting (Crampin 1985a) suggest that distributions of stress-aligned water-filled microcracks are widely distributed throughout many parts of the Earth's crust.

We suggest that the presence of aligned cracks is widespread in hydrocarbon reservoirs and the ability to monitor some of their parameters by their effects on shear-wave propagation has important implications for the hydrocarbon extraction. In particular, the polarisations of shear waves may indicate the orientations of cracks in situ and the directions of the in situ stresses causing these alignments. Shear-waves are probably not going to be particularly important for discovering new reservoirs, but some of the most difficult decisions in the industry are the appraisal and evaluation of existing reservoirs, and planning the correct production strategies for primary, secondary and tertiary recovery. These decisions are presently based mainly on empirical techniques with little direct geophysical input. Seismological techniques for evaluating the internal structure and preferred directions of flow in reservoirs could be crucially important for extracting the maximum percentage of the hydrocarbon from the reservoirs.

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**References**


Appendix

Explanation of apparently contradictory results

A small number of papers have obtained results suggesting that rocks are not cracked at depth in the crust. Such results usually require modification in the light of our more recent understanding of the behaviour of cracks in in situ rock. An anonymous reviewer drew our attention to the paper by Wang and Simmons (1978), who deduce, principally as a result of Differential Strain Analysis on laboratory samples, that the gabbroic rock at 5 km depth in the Michigan Basin does not contain cracks.

Wang and Simmons did not consider the possibility of isolated water-filled microcracks in their samples. The presence of such cracks alters their analysis in two respects. Firstly, the attempt to dry samples in an evacuated chamber without heating fails because the low compressibility of water means that isolated water-filled microcracks will be largely unaffected by external pressure changes. Wang and Simmons dried their sample at room temperature because they recognised that heating would induce cracking (which we suggest would be caused by the exploding of isolated cracks by the increase in vapour pressure). Secondly, the low compressibility of water makes Differential Strain Analysis insensitive to isolated water-filled microcracks so that their presence cannot be recognised. Consequently, the conclusions of Wang and Simmons that there are no cracks at depth in their sample does not exclude the possibility of isolated water-filled cracks being present in their samples, as in most metamorphic rocks.