

Two species of microcracks*

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Abstract: We identify two interrelated but independent species of microcracks with different origins and different distributions. One species is the classic high-stress microcracks identified in laboratory stress-cells associated with acoustic emissions as microcracks open with increasing stress. The other species is the low-stress distributions of closely-spaced stress-aligned fluid-saturated microcracks that observations of shear-wave splitting (SWS) demonstrate pervade almost all in situ rocks in the upper crust, the lower crust, and the uppermost 400 km of the mantle. On some occasions these two sets of microcracks may be interrelated and similar (hence ‘species’) but they typically have fundamentally-different properties, different distributions, and different implications. The importance for hydrocarbon exploration and recovery is that SWS in hydrocarbon reservoirs monitors crack alignments and preferred directions of fluid-flow. The importance for earthquake seismology is that SWS above small earthquakes monitors the effects of increasing stress on the pervasive low-stress microcrack distributions so that stress-accumulation before, possibly distant, earthquakes can be recognised and impending earthquakes stress-forecast.

Keywords: crack-induced anisotropy, fluid-saturate microcracks, shear-wave splitting, stress-forecasting earthquakes, two species of microcracks

Introduction

In the past, most investigations of microcracks in rocks were confined to analysing thin sections of microcracked rock and interpreting laboratory stress-cells (Simmons and Richter, 1976; Kranz, 1983). This was because microcracks in rock are compliant and cannot be examined in situ without opening the rock matrix and hence modifying the microcrack geometry and distribution. In this paper, we show that shear-wave splitting (SWS), seismic birefringence, allows in situ microcrack geometry to be investigated remotely so

that the effects of stress on microcrack geometry can be monitored (Crampin, 1994, 1999; Crampin et al., 2008; Crampin and Gao, 2013).

This paper suggests there are two species of microcracks. The development of faults and shear fractures in laboratory stress-cells generates acoustic emissions (AE) over a broad range of stress, pressure, and temperature conditions in a variety of rock types. AE is the transient release of energy as microcracks open during rapid microcrack growth and coalescence (with the unproven implication/assumption that similar effects apply directly to opening microcracks in situ rocks). AE is an ubiquitous phenomenon associated with small-scale brittle fracture

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and has provided a wealth of information about the details of failure and fracture processes of rock in laboratory stress-cells. Lockner (1993) is a comprehensive review of a substantial number of studies of AE in rock specimens. At that time, the underlying hope was that monitoring AE might identify precursors for predicting fractures and earthquakes (Atkinson and Rawlings, 1981). This hope has not been fulfilled. Thirty years on, AE has led to an improved understanding of fracture growth and faulting in rock in laboratory specimens, but has largely disappeared from prediction studies. Overall AE is important, as it demonstrates that almost all deformation initially evolves from stress-induced manipulation of microcracks. We refer to this species of stress-induced ‘fracture and failure microcracks’ as FFM. FFM leave a permanent record in rock specimens which can be examined in thin sections (Simmons and Richter, 1976; Kranz, 1983).

The second species of microcracks are the fluid-saturated stress-aligned microcracks pervading almost all in situ rocks, which worldwide observations of shear-wave splitting (SWS) demonstrate are ubiquitous in most rocks and rock types (Crampin et al., 1984; Crampin, 1994, 2006; Crampin and Peacock, 2008; Crampin and Gao, 2013). Levels of SWS indicate that these microcrack distributions pervade the upper crust, the lower crust, and the uppermost 400 km of the mantle (the ‘microcracks’ in the mantle are likely to be intergranular films of hydrated melt, Crampin, 2003a). Observations of SWS show that these low-stress microcracks are so closely-spaced that they verge on failure and fracture (Crampin et al., 2003; Crampin and Gao, 2013). Phenomena verging on failure in this way are critical-systems in a New Physics (Davies, 1989), hence, SWS observations suggest a New Geophysics, indicating pervasive rock-mass criticality (Crampin, 2003b, 2004, 2006; Crampin and Gao, 2013). We refer to these low-stress cracks as ‘crack-critical microcracks’ (CCM). CCM are important for understanding and evaluating large-scale solid-Earth deformation in the New Geophysics, where all strain deformation necessarily evolves from existing distributions of compliant stress-aligned CCM microcracks. This deformation includes industrial applications: hydrocarbon extraction and production; hydraulic fracturing (aka fracking); CO₂-sequestration; mining; quarrying; and tunnelling; as well as almost all other examples of geophysical, geological, and tectonic deformation (Crampin, 2006) including the natural phenomena of earthquakes (Crampin et al., 1999, 2004b, 2008) and volcanic eruptions (Volti and Crampin, 2003b; Bianco et al., 2006).

The major difficulty in evaluating both FFM and CCM microcracks in in situ rock is that they cannot

be physically examined without opening the matrix surrounding the cracks, and hence modifying the defining microcrack distributions and geometry. Consequently, all in situ microcracks must be accessed remotely. If the volume of material to be examined is small (a sample in a laboratory stress-cell, say), AE can be used to study FFM microcracks as they open (Lockner, 1993). If the volume to be examined is large enough to be spanned by several seismic wavelengths (a volume of in situ rock, say), a range of seismic techniques can be applied. In particular, observations of SWS can be used to infer the density and alignment of existing CCM distributions, and monitor changes in stress, as in monitoring the stress-accumulation observed before earthquakes (Crampin et al., 1999, 2004b, 2008; Crampin and Gao, 2013).

There are a few intermediate examples: Cruts et al. (1995) transmitted 200 kHz signals across a 20 cm cube in a truly-triaxial stress cell, recorded anisotropic velocity variations as stress changes, and demonstrated SWS monitoring the changing geometry of stress-aligned (CCM) microcracks in in situ rock; Gao and Crampin (2003) used 20 MHz signals to measure changing velocities of SWS in CCM microcracks in a loaded stress-cell; and Teanby et al. (2004) recorded small earthquakes (analogous to AE in FFM microcracks, but with much larger amplitude) generated by subsidence in a producing hydrocarbon reservoir, where the small earthquakes displayed SWS arrival-times on borehole recorders.

Note that some authors use ‘triaxial stress’ to mean uniaxial stress in a confining pressure which leads to anisotropic symmetry with transverse-isotropy. If the maximum stress is vertical as it usually is in the Earth, uniaxial stress leads to a vertical symmetry axis (known as VTI-symmetry). Typically, the anisotropic symmetry seen in the Earth is transverse-isotropy with a horizontal axis of symmetry (HTI-symmetry) (Crampin and Peacock, 2008).

High-stress fracture and failure microcracks (FFM)

When rocks are subjected to increasing stress in instrumented stress-cells, AE are interpreted as transient elastic-waves generated by opening microcracks and by the propagation of fractures as microcracks coalesce (Lockner, 1993). A simplified physical interpretation is summarized in Figure 1 from Main et al. (1993) and Table 1 lists some of the properties of AE and the associated microcracks. Table 1 suggests that many AE events have similar behaviour to small earthquakes.

Table 1 Some of the properties of AE and associated microcracks (reviewed by Lockner, 1993)

- 1) AE occurs as microcracks open in rock samples as compressional stress is increased.
- 2) Not every opening microcrack emits AE: the ratio in some circumstances may be as small as 1:600: this implies that many opening microcracks are stress-induced manipulation of existing CCM microcracks.
- 3) AE first-arrivals indicate a variety of (earthquake) focal mechanisms, commonly: double-couple; sometimes purely compressional; occasionally purely dilatational; and sometimes more complex than double-couple.
- 4) The locations of AE microcracks generally concentrate about impending or propagating fractures in a rock sample.
- 5) The amplitudes of AE events obey the power-law frequency-magnitude relationship for earthquakes known as the Gutenberg-Richter relationship.

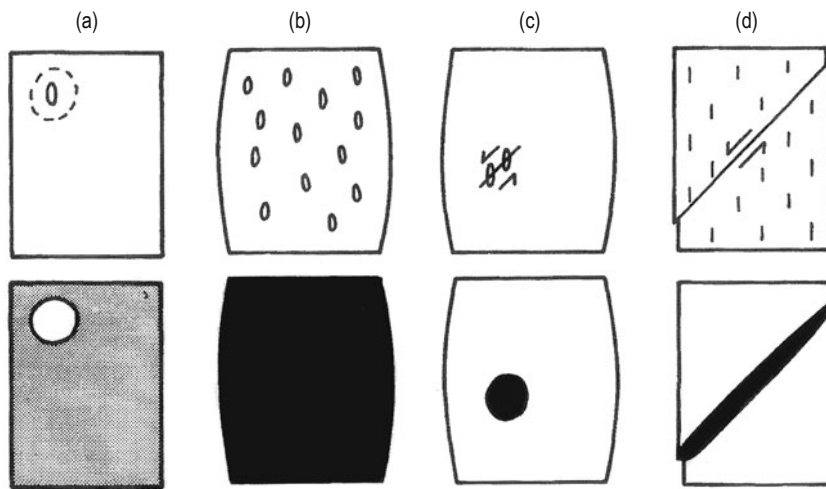


Fig.1 Idealized schematic illustration of the damage development in a heterogeneous solid under vertical compression leading to FFM cracks.

The upper panels of the Figure 1 shows crack distributions and the lower panels shows the local fracture probability. (a) The first crack opens in the weakest element, where the local probability of fracture (lower panels) is reduced in a domain around this crack but slightly enhanced elsewhere. Damage progresses with similar negative feedback until (b) the whole sample is pervaded by microcracks. (c) Two microcracks coalesce in an incipient shear fault leading to stress concentration and an increase in probability of fracture around a nucleating fault, which grows rapidly to form a through-going fault. In practice, the progress from (b) to (c) will be gradual and depend on structural details, but the general principal of progress from negative to positive feedback persists. (d) Slip on the fault closes dilatant microcracks, and further deformation is concentrated on and around the new fault (After Main et al., 1993).

We refer to these newly opened microcracks as high-stress fracture and failure microcracks (FFM). ‘High-stress’ because in cyclical stress histories, AE begin as levels of stress exceed previous cyclical values. Known as the Kaiser (1950) effect, this is a well known phenomenon in metallurgy, and other laboratory studies (J. Acoust. Emiss., 1982-2013). This implies that AE permanently damages the matrix, and in our case, typically leaves a record in the in situ rock which can be examined in thin slides. Note that the 31 volumes of the Journal of Acoustic Emission (1982 - 2013) contain papers about AE in metals and other solids but few (~ 2 %) about AE in rocks.

Low-stress crack-critical microcracks (CCM)

Since water-saturated microcracks are almost transparent to P-wave propagation (Crampin, 1993), shear-waves and SWS are the key observables for monitoring in situ microcrack distributions and geometries. Worldwide observations of SWS show that stress-aligned vertical fluid-saturated microcracks pervade almost all rocks throughout the Earth’s upper crust, lower crust, and uppermost ~400 km of the mantle (Crampin, 2003a; Crampin and Peacock, 2008). These

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pervasive microcrack distributions are low-stress CCM and are quite distinct from the high-stress FFM.

Azimuthally-varying stress-aligned SWS is almost universally observed and interpreted as the effects of stress-aligned fluid-saturated microcracks, which are so closely-spaced they verge on failure and fracture as earthquakes (Crampin, 1994, 2006; Gao et al., 1998; Crampin and Peacock, 2005, 2008; Gao and Crampin, 2004, 2008; Crampin and Gao, 2013). Low-stress CCM resulting in the almost universal observations of SWS were first suggested by Crampin et al. (1984), who

named the phenomenon extensive-dilatancy anisotropy (EDA) hence ‘EDA-cracks’. Figure 2 is a schematic but numerically accurate illustration of the evolution of EDA-cracks (i.e. CCM) under increasing horizontal stress, s_H , as formulated by the equations of anisotropic poro-elasticity (APE) (Crampin and Zatsepin, 1997; Crampin, 1999). CCM are the most compliant elements of in situ rock and evidence suggests that, unlike FFM, stress-induced manipulation of CCM microcracks does not permanently damage the rock matrix (Crampin, 1999; Xue et al., 2013).

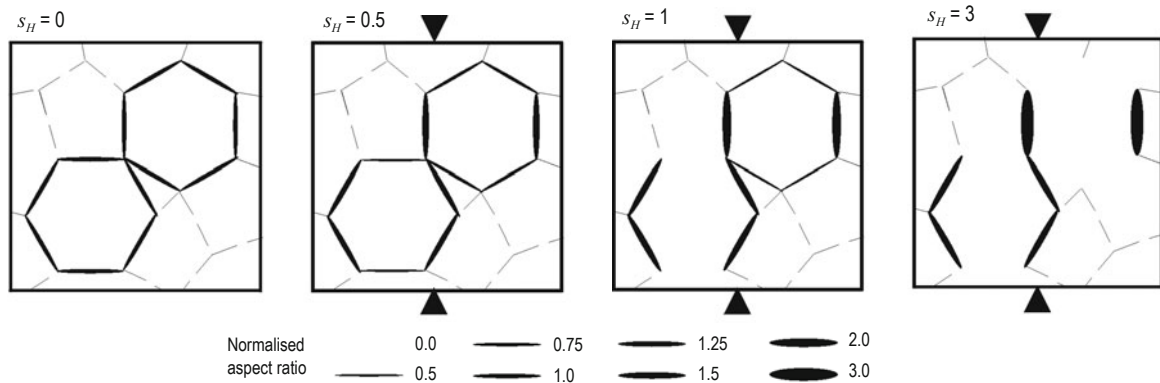


Fig.2 Schematic illustration of the evolution of microcrack aspect-ratios in an initially random distribution of vertical fluid-saturated CMM microcracks (solid lines) under increasing horizontal stress, s_H .

s_H is normalized to the critical value when cracks begin to close. Pore-fluid mass is preserved and aspect-ratios are correct for a porosity of $\phi = 5\%$. After Crampin (1999), who gives a more detailed description of the behaviour.

Neither FFM nor CCM microcracks can be directly examined. Their properties can only be inferred from indirect effects on other phenomena, particularly shear waves and SWS. This led to the classic presentation by Alford (1986), where three-component reflection

seismograms were rotated into preferred stress-aligned directions to display variations in shear-wave arrival-times consistent with parallel vertical stress-aligned cracks. Alford interpreted these cracks as the effects of large hydrocarbon-flow-enhancing macro-cracks. The

Table 2 Properties of New Geophysics of a critically-microcracked rock (Crampin and Gao, 2013)

Property	Effects	Ref.
1) Self-similarity:	Logarithmic plots of many properties are linear such as in the Gutenberg-Richter relationship.	[1,2]
2) Monitorability:	Behaviour can be monitored with SWS.	[3,4,5]
3) Uniformity:	Statistical behaviour is more like other critical systems than it is to the underlying sub-critical physics.	[4,5]
4) Calculability:	Behaviour is more uniform (universal) than sub-critical behaviour and can be modelled or calculated with the equations of Anisotropic Poro-Elasticity, APE.	[5,6,7]
5) Predictability:	If impending changes can be quantified, behaviour can be predicted by APE.	[5,6,7]
6) Controllability:	If conditions can be monitored (Item 2), calculated (Item 4), and modified by injection pressures [5 6], in principle the behaviour of the in situ rock mass can be controlled by feedback (optimizing flow-directions by fluid-injection say in hydrocarbon production, say).	
7) Universality:	Effects pervade all available space.	[8,9]
8) Sensitivity:	Butterfly-effect sensitivity to miniscule differences in initial conditions.	[8,9]

[1] Gutenberg and Richter (1956); [2] Gao and Crampin (2004); [3] Crampin (1999); [4] Crampin and Peacock (2005); [5] Crampin and Peacock (2008); [6] Angerer et al. (2002); [7] Crampin and Zatsepin (1997); [8] Volti and Crampin (2003a, 2003b); [9] Crampin and Gao (2012).

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ubiquitous nature of SWS in almost all rocks suggests that the splitting is generally caused by microcrack distributions, where the microcracks are so closely-spaced that almost all in situ rocks verge on failure in fracture and hence are critical-systems (Davies, 1989; Crampin et al., 2003). Larger cracks would tend to inhibit shear-wave propagation (Mueller, 1991), and this is not generally observed.

The New Geophysics

The percentage of observed shear-wave velocity anisotropy (SWVA) is approximately 1.5 % to 4.5 %, with equivalent crack densities of $\varepsilon = 0.015$ to $\varepsilon = 0.045$ (Crampin, 1994). Fracture-criticality when rocks loose their shear strength is identified with the percolation threshold at $\varepsilon \approx 0.055$ for parallel stress-aligned cracks (Crampin and Zatsepin, 1997; Crampin and Gao, 2013).

Thus the observed SWVA indicates that almost all rocks verge on failure and hence are critical-systems (Davis, 1989). Such critical-systems impose a range of fundamentally-new properties on conventional sub-critical geophysics, some of which are listed in Table 2 and referred to as the ‘New Geophysics’ (Crampin, 2006; Crampin and Gao, 2013). Although CCM microcracks are remote and inaccessible, there is a huge range of evidence (over millions of individual source-to-receiver ray paths), some of which are listed in Table 3, that confirms the presence of CCM microcracks and New Geophysics and demonstrates some of their behaviour and properties.

Since almost all complex heterogeneous interactive phenomena are critical-systems (Davies, 1989), it would be extraordinary if the Earth, an archetypal complex heterogeneous interactive phenomenon, was not a critical-system (Crampin et al., 2003). Nevertheless, for reasons listed in Table 4 New Geophysics remains controversial (Crampin, 2012; Crampin and Gao, 2013).

Table 3 Evidence for CCM microcracks throughout the crust (Crampin and Gao, 2013)

	Evidence inexplicable in terms of conventional sub-critical geophysics*.	Ref.
1)	Shear-wave splitting is observed in almost all in situ rocks in the crust and upper mantle.	[1,2,3]
2)	There is a minimum shear-wave velocity anisotropy (SWVA) of ~1.5% in almost all in situ rocks.	[1,2,3]
3)	There is a maximum SWVA of ~5.5% in ostensibly unfractured rock.	[1,2,3]
4)	Fracture-criticality limit of SWVA is ~5.5% in in situ rocks independent of rock-type, geology, tectonics and porosity, etc, where SWVA of ~5.5% is the percolation threshold for parallel cracks.	[1,2,3]
5)	High pore-fluid pressures induce 90°-flips in polarizations of the faster split shear-waves.	[4,5]
6)	Explains the large (“±80%”) scatter in shear-wave time-delays above small earthquakes.	[5,6]
7)	Effects of CO ₂ -injections on seismic reflection surveys modelled by APE.	[4,5,6]
8)	Stress-accumulation observed before earthquakes.	[7,8,9]
9)	Time magnitude and impending fault-break successfully stress-forecast in real time.	[8,9]
10)	Stress-relaxation (crack-coalescence) observed before earthquakes.	[2,10]
11)	Stress-accumulation observed before volcanic eruptions.	[2,7,8]
12)	Extreme sensitivity: stress-variations observed in Iceland two and a half years before the Sumatra-Andaman EQ at the width of the Eurasian Plate from Indonesia.	[11]
13)	Explains how a stressed rock differs from an unstressed rock.	[12]
14)	Explains how the enormous stress-energy before a large earthquake accumulates without inducing smaller earthquakes.	[12]
15)	Explains why initial stress drop at an earthquake is small (typically 2 to 4 MPa) and independent of earthquake magnitudes which may vary by over 10 orders of magnitude.	[12]
16)	Explains how irregular fault-planes slip when constrained by enormous lithostatic stress.	[12]
17)	Explains why we cannot deterministically predict but can stress-forecast the time magnitude and fault-break of impending earthquakes.	[12]
18)	Explains why the Gutenberg and Richter (1956) relationship between logarithms of cumulative frequencies of earthquakes and earthquake magnitudes is linear.	[12]
19)	Partly explains why despite huge investments average recovery is less than 40% of in-place oil.	[13]

* Without innumerable special cases.

[1] Crampin (1994, 1999); [2] Crampin and Peacock (2008); [3] Crampin and Zatsepin (1997); [4] Angerer et al. (2002); [5] Crampin et al. (2002); [6] Crampin et al. (2004a); [7] Volti and Crampin (2003b); [8] Crampin et al. (1999); [9] Crampin et al. (2008); [10] Gao and Crampin (2004); [11] Crampin and Gao (2012); [12] Crampin et al. (2013); [13] Crampin (2006).

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Table 4 Some of the reasons why New Geophysics is controversial (Crampin and Gao, 2013)

- 1) The major reason for controversy is that the vast majority of seismic recordings are currently of P-wave propagation. Since the effects of New Geophysics are controlled by shear waves and SWS and the manipulation of water-saturated microcracks, which are almost transparent to P-wave propagation (Crampin, 1993), New Geophysics is effectively invisible to many current seismic observations.
- 2) Shear-waves are expensive to record and process. Observations of shear-waves and SWS require three-component recording with very specific source-to-receiver geometry (Figure S1 in Crampin and Gao, 2013), consequently shear-waves and SWS typically at least treble recording and processing costs.
- 3) Because of recording and processing costs, experience of shear-waves is limited. Only groups in Edinburgh: the Edinburgh Anisotropy Project (EAP) oil-company funded consortium (www.eap.bgs.ac.uk), currently led by Xiang-Yang Li; and Crampin and associates (www.geos.ed.ac.uk/homes/scrampin/opinion) have extensive experience (over ~40 years and ~350 research papers) of the theory, calculation, observation, and interpretation of shear-waves and SWS in both exploration and earthquake seismology.
- 4) Stress-forecasting earthquakes* is a principal attribute of New Geophysics. To-date there has been only one successful real-time stress-forecast earthquake (Crampin et al., 1999, 2004b, 2008). However, characteristic effects have been seen before ~15 earthquakes retrospectively (Crampin and Peacock, 2008; Crampin and Gao, 2012), but due to failure to forecast earthquakes in the past, retrospection is suspect. Further real-time stress-forecasts are needed to confirm stress-forecasting earthquakes.
*The term ‘earthquake stress-forecast’ is used rather than ‘earthquake prediction’ or ‘earthquake forecast’ to emphasize the different methodology.
- 5) New Geophysics is a fundamental revision of conventional sub-critical geophysics and is slow to gain acceptance. Recognition of the New Geophysics of a critically microcracked Earth is currently at Schopenhauer* Stages 1 and 2 and is “ridiculed” and “violently opposed”.
*“All truth passes through three stages. First is ridicule. Second is violent opposition. Third is self-evident” (Schopenhauer 1788 – 1860).

Note that New Geophysics is based on the APE-deformation of a critically-microcracked rock mass with many fundamentally-new critical properties (Table 2). One cannot begin to understand the behaviour of the critical New Geophysics with experience based on conventional sub-critical geophysics (Crampin and Gao, 2013). A paradigm shift in understanding is required. Some geoscientists are unwilling to make this paradigm shift (Crampin, 2012) and New Geophysics remains controversial (Table 4).

Implications of two species of microcrack

Identification of the existence of two species of microcrack resolves the conundrum of how microcracks, marked by AE events, are opened in failure and fracture in the laboratory, and yet are also the stress-aligned fluid-saturated microcracks pervasive in almost all in situ rocks. Some of the attributes of New Geophysics that this new understanding has helped to resolve are several geophysical conundrums: specifically how a stressed rock differs from an unstressed rock; how rocks store the enormous stress-energy released by large earthquakes, without generating smaller events; why the initial stress

released by an earthquake source is uniformly small; and how rough and irregular fault surfaces slip when constrained by enormous lithostatic pressures (Crampin et al., 2013). We suggest that the properties of New Geophysics need to be taken into account for almost all investigations of solid-Earth geophysics in the future when the resolution of further conundrums may be expected (Crampin and Gao, 2013).

Conclusions

We identify for the first time the two distinct species of microcrack: high-stress fracture and failure microcracks (FFM), which are local and leave a record of cracks in the rock matrix; and low-stress crack-critical microcracks (CCM) throughout the rock mass, that are compliant and can heal and evolve without damaging the rock matrix. (Xue et al.(2013) reports an example of crack healing following the devastating 2008 M 7.9 Wenchuan Earthquake, China). Distributions of CCM exist in almost all in situ rocks where CCM evolution under low-level changes of stress can be modelled and monitored by the equations of anisotropic poro-elasticity. In contrast FFM are defined principally by acoustic emissions (AE), when they open during the application

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of relatively high-stress in laboratory stress-cells.

Analysis of FFM has yielded much information about the evolution of fractures and fracturing in small-scale experiments in the laboratory. Analysis of CCM has demonstrated the evolution of a compliant critically-microcracked rock that leads to a New Geophysics which explains the huge range of previously inexplicable phenomena in Table 3. We argue (Crampin and Gao, 2013) that the new properties of New Geophysics in Table 2 are the most fundamental advance in solid Earth geosciences for many decades. New Geophysics and the two species of microcracks modify much of our understanding of conventional sub-critical geophysics, including applications to hydrocarbon recovery (Crampin, 2006; Crampin and Gao, 2013).

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