

The New Geophysics: implications for hydrocarbon recovery and possible contamination of time-lapse seismics

Stuart Crampin*

Abstract

Recent theory and observations suggest that the fluid-saturated microcracks in hydrocarbon reservoirs (and most other *in situ* rocks) are so closely spaced that they are critical systems verging on failure by fracturing. As a result reservoirs are highly compliant and respond to small changes with 'butterfly wings' sensitivity. However, these phenomena cannot be imaged with conventional technology and the largest effects may be possible complications when recovering hydrocarbons. This critical behaviour leads to a New Geophysics, where the response to changes in fluid-saturated rock (during hydrocarbon production, for example) necessarily varies both spatially and temporally so that detailed measurements degrade with time from the moment they are made. This means that behaviour cannot be averaged. Consequently, many (perhaps most) standard oil-field procedures may not be wholly or strictly valid. The typical (and extraordinarily low) 30% recovery from most oil reservoirs is at least partly explained by the sensitivity of reservoirs and behaviour inexplicable in terms of conventional geophysics. The New Geophysics is the cause of at least some of the difficulties in standard oil-field procedures, but does offer enormous potential advantages that may be exploitable. This article discusses new ways of monitoring production, where the response of the reservoir to production procedures can be calculated, possibly predicted, and even potentially controlled by feed back.

Introduction

Stress-aligned shear-wave splitting (illustrated schematically in Figure 1) is observed in almost all rocks in the Earth's crust (including almost all hydrocarbon reservoirs) [1,2,3]. Principally caused by propagation through stress-aligned fluid-saturated microcracks, the percentage of observed shear-wave velocity anisotropy can be inverted for the crack distributions in Figure 2 [1,2,3]. Figure 2 suggests that, even in unfractured rocks (two left-hand diagrams), microcracks are so pervasive that most rocks are close to fracture-critical-

* Shear-Wave Analysis Group, School of GeoSciences, Edinburgh University, Grant Institute, West Mains Road, Edinburgh EH9 3JW, Scotland UK; also at Edinburgh Anisotropy Project, British Geological Survey, Edinburgh EH9 3LA. scrapin@ed.ac.uk; Reprints and preprints at <http://www.glg.ed.ac.uk/~scrapin/opinion/>.

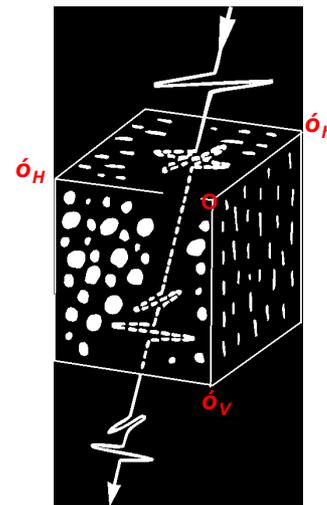


Figure 1 Schematic illustration of stress-aligned seismic shear-wave splitting [1]. Transversely polarised seismic shear-waves propagating near-vertically through distributions of vertical parallel fluid-saturated microcracks split into two orthogonal phases polarised parallel and perpendicular to the direction of maximum horizontal stress. Such stress-aligned shear-wave splitting is observed in almost all reservoirs and rocks in the Earth's crust. The microcracks tend to be aligned (like hydraulic fractures) normal to the direction of minimum horizontal stress, σ_h . Several features of the observations are remarkable.

- As crack density ϵ is approximately equal to one hundredth of the percentage of maximum shear-wave velocity anisotropy, it is easy to estimate crack density from observations of shear-wave splitting (in Figure 2). Crack density ϵ is equal to Na^3/v , where N is the number of cracks of radius a in volume v .
- Observations of 1.5% to 4.5% shear-wave velocity-anisotropy indicate a narrow range $0.015 \leq \epsilon \leq 0.045$ of the inferred crack density in ostensibly intact rock. This range is independent of geology (similar in sedimentary, igneous, and metamorphic rocks), porosity (similar in 1% porosity granites as in 30% porosity sandstones), and tectonic history, with only a few well-understood exceptions.
- Fracture criticality is associated with the percolation threshold which can be determined theoretically for a distribution of aligned cracks as $\epsilon = 0.055$ (5.5% shear-wave velocity anisotropy) [4].
- The limited range of crack density means that the cracks in all in situ rock are critical systems verging on criticality and failure (Figure 2).

STATIC EFFECTS		Ref.	Ref.
Field observations of SWVA [‡] (below 500 to 1000 m-depth)		(Obs.)	(APE)
1) SWVA in all rocks independent of porosity and geology.		[1]	[4]
2) Minimum SWVA in intact rock: observed $\approx 1.5\%$; APE-modelled $\approx 1.0\%$.		[1]	[4]
3) Maximum SWVA in intact rock: observed $\approx 4.5\%$; APE-modelled $\approx 5.5\%$.		[1]	[4]
4) Narrow range of crack density: $0.025 \leq \varepsilon \leq 0.045$.		[1]	[4]
5) Proximity of fracture-criticality (at percolation threshold) $\approx 5.5\%$.		[1]	[4]
Other field observations			
6) Fracture-criticality limit specifies crack distributions with a range of dimensions of about 9-orders of magnitude.		[7]	[8]
7) $\pi/2$ shear-wave polarisation changes (90°-flips) in overpressurised rocks, overpressurised reservoirs and seismically active fault planes.		[9,10,11]	[9,10,11]
DYNAMIC EFFECTS			
Temporal changes in SWVA during production procedures			
8) Changes before and after pumping tests.		[12]	£
9) Changes before and after high pressure CO ₂ -flood in carbonate reservoir		[10]	[10]
Temporal changes in SWTD [†] before earthquakes			
10) Variations of time-delays before earthquakes (with hindsight).		[13,14,15]	[4]
11) Successful forecast of time and magnitude of an $M=5$ earthquake in SW Iceland.		[14]	£
Temporal changes in SWTD before volcanic eruption			
12) Variations in SWTD for some 5 months before 30 th Sept., 1996, Vatnajökull eruption, Iceland, at distances of: 230 km WSW; 170 km SW; and 240 km, N.		[15]	£
Variations of shear waves in laboratory experiments			
13) Variations of SWVA and permeability in uniaxial stress cell.		[16]	[17]
14) Variations of (isotropic) shear-wave velocities to changes in confining pressure and pore-fluid pressure for oil-, water-, and gas- (dry) saturations in stress cells of sandstone cores.		[18]	[18]
15) Variations of velocity and attenuation from sonic (transducers) to seismic (resonant bar) frequencies.		[19]	[20]

*APE - anisotropic poro-elasticity; £Effects compatible with APE;
[‡]SWVA - shear-wave velocity-anisotropy; †SWTD - shear-wave time-delays;

Table 1. Match of APE*-modelling to observations [2] (updated).

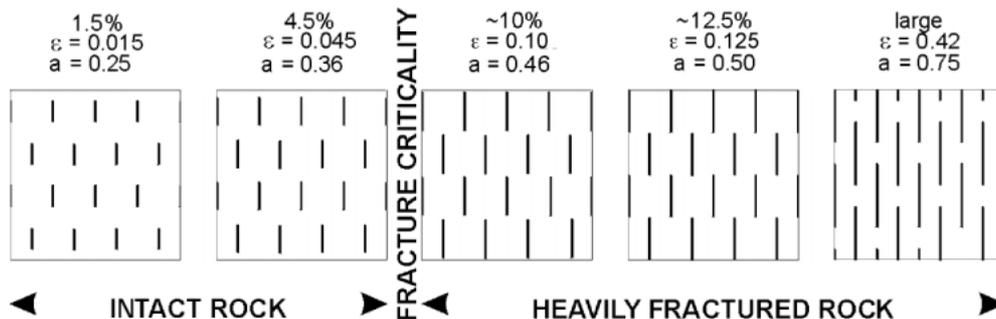


Figure 2 Schematic interpretation of observed percentage of shear-wave velocity anisotropy [1,2,3], where ε is crack density and a is crack radius. The narrow range of observed crack density in intact rock below fracture-criticality ($\varepsilon \approx 0.055$) demonstrates that all rocks are so heavily microcracked that they are critical systems verging on criticality and failure by fracturing.

ity and failure by fracturing. Just nudge a rock and it fractures, as witness the acoustic events heard whenever sensitive instruments record reservoirs during hydrocarbon recovery. The effects are much more than just a readiness to fracture. The microcracks make rock extraordinarily compliant and sensitive to small changes in stress and pressure [4]. It can be shown that seismic shear-wave splitting, also known as seismic birefringence, monitors the low-level deformation of the reservoir before fracturing takes place [4,5]. Theory suggests and observations confirm (see Figure 6, below) that crustal rock is so compliant and sensitive to changes of stress that it responds to minor disturbances at substantial distances [2,3]. The nature of the response may have serious consequences for conventional hydrocarbon recovery.

Our understanding of shear-wave splitting (Figure 1), the key observable, has advanced substantially in the past few years. There are several reviews of these advances [2,3]. Many recent research papers and a reference list can be found on the web site <<http://www.glg.ed.ac.uk/~scrampin/opinion/>>. Note that this paper is an updated and more fully referenced version of a paper published in the upstream journal *PetroMin*. [6].

The mechanism of rock deformation

Figure 3 shows how distributions of fluid-saturated microcracks respond to small changes of stress (or any other change in conditions) during hydrocarbon recovery. The driving mechanism for this mode of deformation, known as Anisotropic Poro-Elasticity or APE [2,4,5], is fluid movement along pressure-gradients between neighbouring grain-boundary cracks and pores at different orientations to the stress field [4]. This leads to the aligned cracks and shear-wave splitting illustrated in Figures 1 and 2. Figure 3 is a simplified (but quantitatively accurate) illustration of the effects of small changes in differential stress on an initially random distribution of fluid-saturated microcracks. APE is almost parameterless yet, assuming a critical-system of fluid-saturated cracks, matches the approximate behaviour of a huge range of different phenomena in geology and geophysics [2,3].

Note that testing (calibrating) APE in deep rocks is difficult because high temperatures, pressures, and toxic environments prevent direct measurements in undisturbed *in situ* rocks. Table 1 lists the many indirect demonstrations of APE modelling and associated rock mass and reservoir compliance and sensitivity. There is considerable use of stress directions derived from shear-wave polarisations by industry.

There are three relatively-direct demonstrations of APE-modelling and the compliance of the crack-critical rock mass.

1) The most accurate calibration is where APE-modelling matched the seismic response of both high-pressure and low-pressure CO₂-injections in a fractured carbonate reservoir in New Mexico [10]. Figure 4 shows three-component reflection surveys before and after the injection.

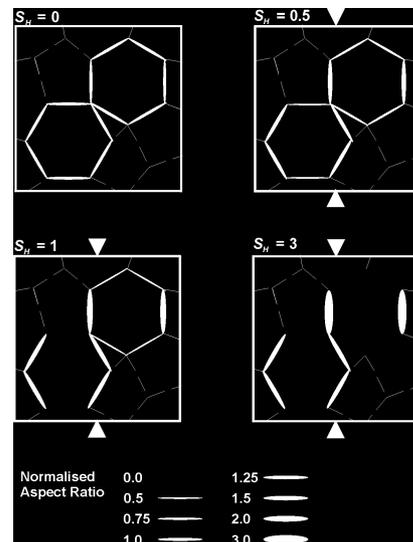


Figure 3 The Anisotropic Poro-Elastic (APE) model of rock deformation [2,3,4,5] calculates the response of cracked fluid-saturated rocks to small changes of stress. Stress-induced variations to microcrack geometry are driven by pore-fluid movement along pressure-gradients between neighbouring microcracks at different orientations to the stress field. The modelling is fully 3D, but the figure is a simple schematic (quantitatively accurate) 2D illustration of the effects of APE on a vertical distribution of cracks with a constant porosity of $\phi = 6\%$, where ϕ is percentage by volume.

- Top-left: a cross-section of a small selection of randomly oriented vertical cracks (hexagons are elastically isotropic). Under zero differential stress $s_H = s_b = 0$ and all cracks have equal aspect ratios (equal crack widths) and there is no shear-wave velocity anisotropy in the horizontal plane.
- Top-right: the effects of a small increase of differential stress, s_H . Some fluid adjusts to the change of stress by changing crack aspect-ratios but all cracks remain open and there is still no shear-wave velocity anisotropy.
- Bottom-left: the response when the critical stress s_H (normalised to one) is sufficient to close cracks normal to s_H . The shear-wave velocity anisotropy is about 1%, approximately the 1.5% minimum actually observed in the Earth (Figure 2).
- Bottom-right: as stress increases, cracks begin to line up with an average normal in the direction of minimum principal stress. Eventually at fracture-criticality (equivalent to the percolation threshold of through-going fractures), shear strength is lost and the rock fractures.

Theoretically this comparatively simple model is independent of porosity, and similar effects are observed in 1% porosity granites, as in 30% porosity sandstones.

The injection pressures inserted into APE simulated almost exactly the observed shear-wave response [10]. Since the compliant critical-system of fluid-saturated microcracked rocks is an essential feature for behaviour of APE, the success of APE-modelling directly confirms the critical-system of cracks in the crust.

- 2) APE suggests that increases of stress should cause changes in shear-wave splitting in specific stress-oriented directions [2,4,5]. Such changes have been recognised before some dozen earthquakes worldwide [13,15], and the time and magnitude of an $M=5$ earthquake in Iceland was successfully stress-forecast [14]. Note that shear-wave splitting carries no specific information about impending earthquake locations. However, if it is known that a large earthquake is approaching, other precursory phenomena may indicate the epicentre, as happened with the successful stress-forecast [14]. (Similar changes in shear-wave splitting are also seen before a volcanic eruption in several directions at up to 240 km [15].)
- 3) The most direct confirmation of rock mass sensitivity and compliance is from a seismic crosshole experiment. Figure 5a shows shear-wave polarisations at seismic stations in Iceland 1996 to 2000. Figure 5b shows earthquakes on transform faults of the Mid-Atlantic Ridge in northern Iceland. The crosshole experiment is sited on the coast near Station HED.

Figure 6 shows variations over 13 days of travel times of P -waves, SH - and SV -waves, and SV - SH anisotropy at 500 m depth between boreholes 315 m apart. The travel times show well-recorded variations of 6ms, 2ms, 2ms, and 0.2ms, respectively, correlating with a swarm of small earthquakes at 70 km NNW on an adjacent transform fault near Station GRI in Figure 5b [21]. The total energy release by the earthquakes is less than the energy of one $M=4$ earthquake. This is a comparatively small seismic disturbance and the observed sensitivity (in layered basalts in Iceland) at several hundred times the likely source dimensions is far beyond that expected in the conventional geophysics of a brittle-elastic crust.

These unique observations are recorded in a quiet environment below near-surface noise, and used the exceptionally repeatable down-hole orbital vibrator (DOV) source of Geospace Engineering Research International, Houston. The DOV was pulsed three or four times each minute allowing 100-fold stacks with accuracies of $\pm 0.02\text{ms}$ ($\pm 20 \mu\text{s}$) [21].

This extraordinary sensitivity displayed in Figure 6 is the

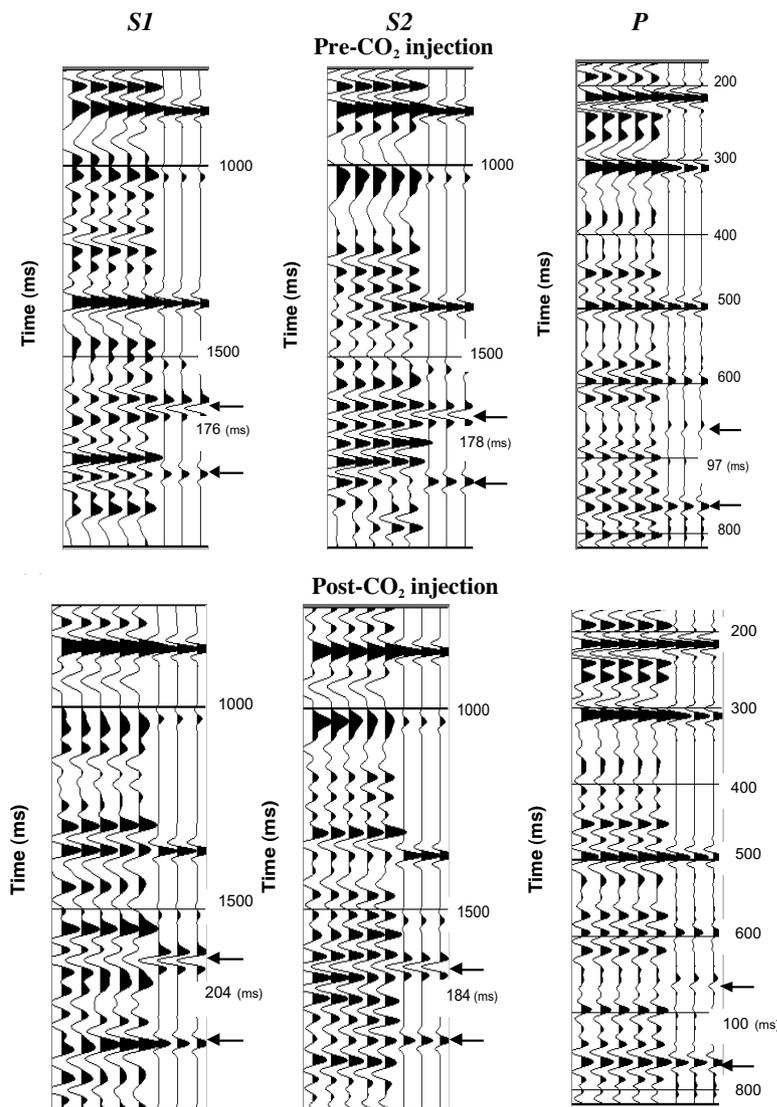


Figure 4 (a) Pre-injection waveforms of a multi-component nearly vertical reflection survey near the centre of the Vacuum Field, New Mexico, carbonate reservoir. $S1$, $S2$, and P are record sections with mutually orthogonal polarisations, where the horizontals $S1$, and $S2$, have been rotated into the split shear-wave arrivals parallel ($S1$) and perpendicular ($S2$) to the direction of maximum horizontal stress, respectively. The left-hand five traces are observed waveforms at neighbouring receivers 17 m apart, and the right-hand three traces are synthetic seismograms modelled by APE to match the shear-wave arrivals. Top and bottom of injection zone for shear waves (established by extensive analysis by students at Colorado School of Mines) are marked by arrows with time-delays in ms/km. (b) Post-injection waveforms after a high pressure CO_2 -injection. Again, the left-hand traces are observations and right-hand traces are synthetic seismograms modelled by APE with structure from (a) and an injection pressure of 17 MPa. Multiple arrivals are reverberations and are not modelled. (After [10])

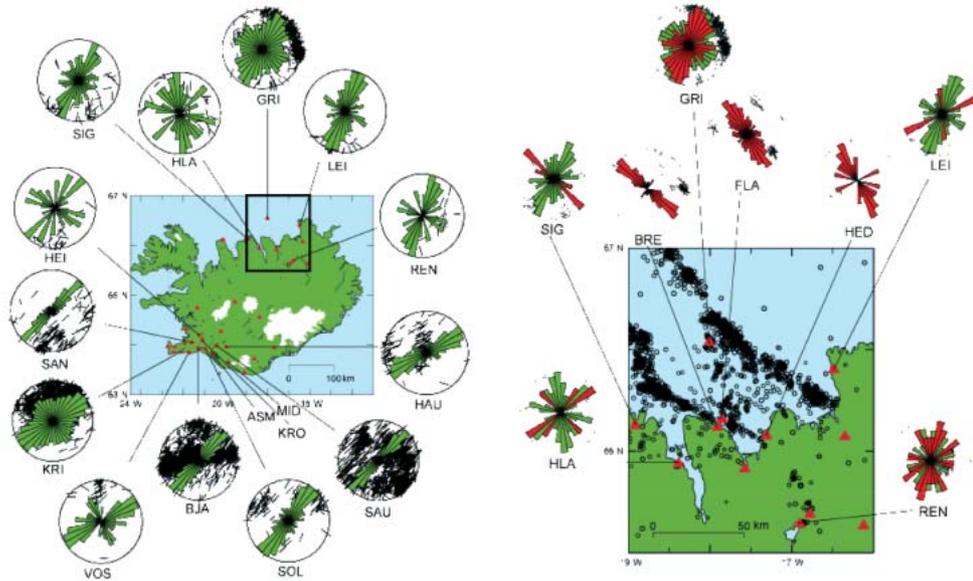


Figure 5 (a) Normalised equal-area rose diagrams superimposed on equal-area polar plots (out to 45°) of the polarisations of the faster split shear-wave observed above small earthquakes at the Iceland Seismic Network (red triangles) in years 1996 to 2000. Glaciers and ice caps shown in white. The rectangle refers to the area in (b). Rose diagrams and polar plots for the Tjörnes Fracture Zone outlined in (a). Green petals are polarisations for earthquakes in years 1996 to 2000, and red petals are polarisations in 2001, when stations BRE, FLA, and HED were installed. Earthquake locations are shown for 2000 and 2001. Note rose diagrams in (a) and (b) are normalised for each station, and green and red rose diagrams have different normalisations. (After [21])

response of a critical system of fluid-saturated microcracks to small disturbances. If the effects of a $M=4$ earthquake are visible at 70 km in relatively brittle basaltic rocks, the effects of larger $M=8$ earthquakes, releasing at least 10,000 times more energy, can probably be seen worldwide, particularly in more compliant reservoir rocks. The variations in Figure 6 are a direct demonstration that detailed seismic measurements, responding to changes in microcrack geometry, are sensitive to small disturbances at substantial distances. This confirms the compliant critical system of fluid-saturated stress-aligned cracks in rocks in the crust [1,2,3].

Properties of critical systems of cracks in the crust

Critical systems are one feature of the New Physics of complicated interactive phenomena which behave conventionally until they approach critical points. Near critical points, the behaviour is no longer controlled by the sub-critical physics but becomes extremely sensitive to small variations of the initial conditions (the ‘butterfly wing’ sensitivity), and at critical points the effects show deterministic chaos [2]. Distributions of closely spaced fluid-saturated microcracks make the Earth’s crust such a critical system, where the critical points are levels of fracture-criticality (Figures 2 and 3), and the chaotic behaviour is fracturing and earthquakes [2,3].

It has been shown that critical systems near criticality (such as microcracks in the crust in Figure 2) behave statisti-

cally more like other critical systems than the sub-critical physics [4,5]. This is the reason why the nearly parameterless APE modelling approximately matches behaviour of extremely complicated heterogeneous crustal rocks [2,3]. Practically, this means that the behaviour of the anomalies in Figure 6 may not be explicable or even understandable in terms of conventional sub-critical geophysics. Certainly, critical systems are known to have several remarkable properties [2,3,4,5].

Some of these properties have serious disadvantages for conventional oil-field geophysics and conventional oil-field operations.

- A1 The detailed behaviour of reservoirs is temporally and spatially unstable so that any given measurement may degrade in time, as in Figure 6, where measurements vary significantly with time (and place - not shown).
- A2 Many properties of reservoirs are self-similar and are temporally and spatially heterogeneous at all scale lengths, so any averaging may only be valid in particular limited circumstances.
- A3 There is the possibility of (i) long-range interactions between-, and (ii) long-term interactions within-, hydrocarbon reservoirs. The effects of A3ii have been observed in large mature oil fields [22].
- A4 Detailed behaviour (such as the behaviour in Figure 6) may not correspond to or be explicable by conventional geophysics.

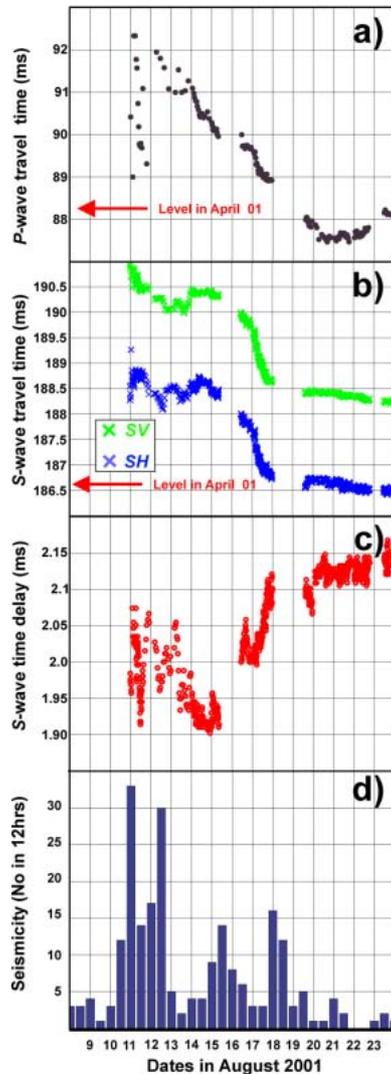


Figure 6 Anomalies in seismic travel times correlating with the burst of small-scale seismicity at 70 km NNW near Station GRI [21]. Seismic travel times variations (11 to 24 August, 2001) at 500 m depth between boreholes 315 m apart parallel to a Mid-Atlantic Ridge transform fault onshore in northern Iceland: (a) P-wave; (b) SV- and SH-waves; and (c) SV - SH delay times; coinciding with (d) number (12-hour) histogram of 106 small earthquakes ($M < 2.8$) at 70 km distance (total energy equivalent to one $M < 4$ event). The levels of the P- and shear-wave travel times from previous observations in April 2001 are indicated in (a) and (b). (After [21]).

Despite these complications and disadvantages, there are other properties which may have enormous potential benefits for hydrocarbon recovery.

- B1 Current configurations of crack geometry within the deep interior of the rock mass or reservoir can be monitored with shear-wave splitting and evaluated by APE [2,3,4].
- B2 Response of rock mass or reservoir to known changes can be calculated by APE [2,3,4].

B3 Response of rock mass or reservoir can be controlled by feedback by repeating items B1 and B2 [2,3,4]. If the response can be calculated and monitored by shear-wave splitting, in principle, the optimal response and optimal recovery can be controlled by adjusting input parameters with feedback.

- B4 An important additional constraint is that modelling by APE (items B1 and B2) will only apply to slowly driven systems, when stress relaxation processes and fluid percolation are allowed to evolve naturally [2]. Only when slowly driven can the response of a complicated heterogeneous reservoir to specific changes be calculated, or predicted, by APE, as happened in the CO_2 -injections reported in [10]. Stress-relaxation times are not known, and require further investigation. However, preliminary evidence from: i) CO_2 -injections [10]; ii) cross-well seismics in Figure 6 [21]; and iii) changes before earthquakes [4,13,14,15], suggests that the response is comparatively rapid, and that effects can be modelled by APE after only a day or two relaxation - this might be an acceptable delay in oil field procedures. The implications are that reservoirs forced by aggressive production strategies will create further heterogeneities, cannot be modelled by APE, and hence yield less oil.

The disadvantages and potential benefits open huge opportunities for exploitation, some of are briefly discussed here.

Main disadvantages and benefits for hydrocarbon production

Unquestionably, the biggest operational disadvantages are A1 and A2, and the implication of B4 that reservoirs will only behave predictably if slowly driven and stress is allowed to relax between processes.

Evidence for A1: *Temporal and spatial instability*, is demonstrated directly by the variations in Figure 6, where repeated measurements between fixed source and fixed receiver vary with time correlating with small distant seismic disturbances. Other evidence [2,13,14,15] suggests these variations could vary from weeks before small earthquakes within tens of km to years before the largest earthquakes and eruptions that could be visible worldwide. Other sources of disturbance could be production operations in neighbouring not necessarily adjacent oil fields [22], earth tides, and other phenomena. APE modelling implies that the Earth's crust is in a continual state of flux. Consequently, detailed seismic measurement of a reservoir may vary with time due to what are likely to be intangible unidentifiable phenomena. These variations are likely to be small but could well contaminate time-lapse (4D) seismic monitoring in production reservoirs.

A2: *Temporal and spatial heterogeneity*, is possibly even more serious. The principal heterogeneity is believed to be temporal and spatial variations in microcrack geometry, with variations in crack aspect ratio one of the major effects

New ways needed to monitor reservoirs

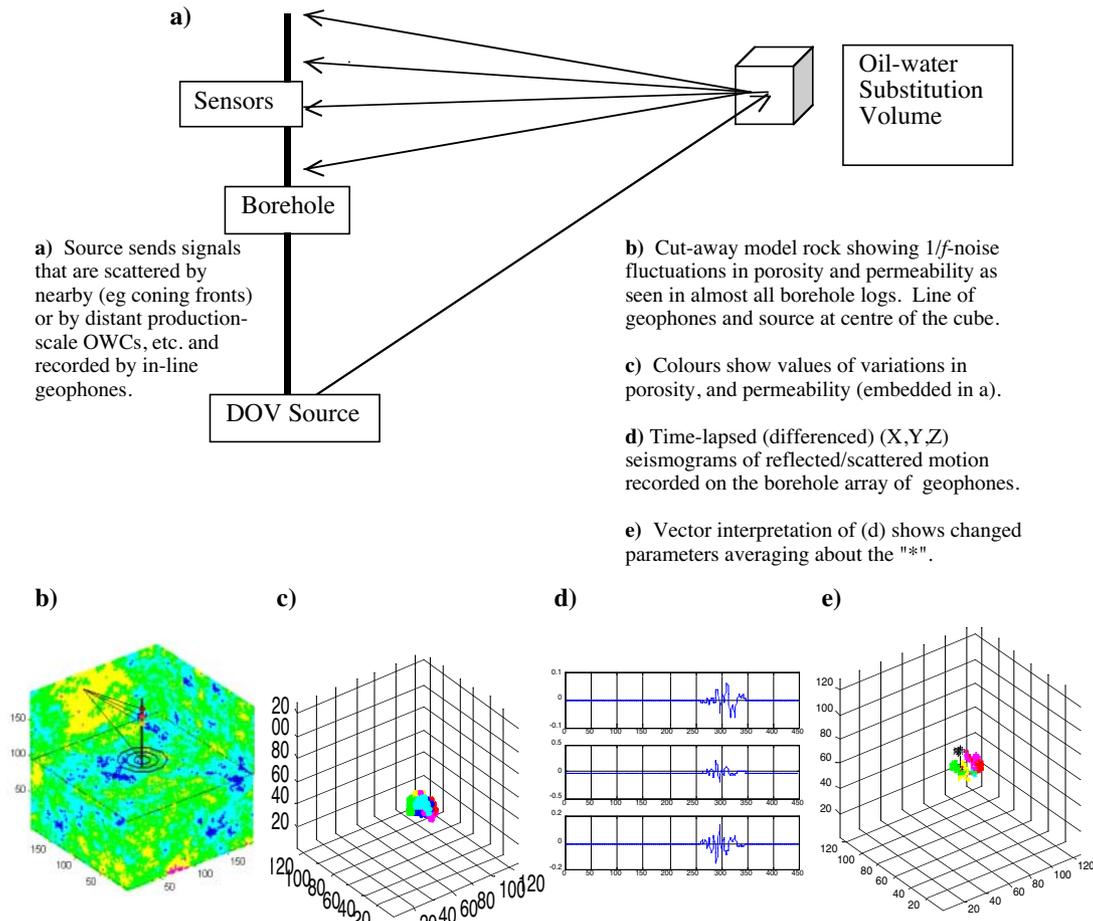


Figure 7 Modelled time-lapse single-well imaging of a cube having the observation-based 1/f-noise variations in porosity and permeability before and after small variations in one corner.

(Figure 3). This could lead to variations in (particularly directional) permeability. Since fluid percolation through porous rocks is the dominant mechanism in hydrocarbon production in many reservoirs, temporal variations in permeability could substantially modify flow rates. Such variations would be difficult to estimate, difficult to predict, and difficult to assign to a particular cause. The variation of permeability with direction in water-flood operations, for example, shows that aligned cracks have a large affect on hydrocarbon percolation. Thus variations of crack aspect-ratios (the most compliant crack parameter) could have major effects on directional permeability and hydrocarbon production rates.

These effects have been demonstrated in observations of shear-wave splitting above small earthquakes [1,13,14,15]. The enormous ($\pm 80\%$) scatter in time-delays above small earthquakes has been shown to be caused by minor variations in stress and pore-pressure after each earthquake causing variations in microcrack geometry that have substantial effects on seismic ray paths, travel times, and particularly shear-wave time-delays [23].

Taken together these mean that, in detail, rocks in the crust are critical systems of highly sensitive compliant fluid-saturated cracks which can only be imaged by shear-wave splitting. In particular:

- 1) Detailed seismic measurements are likely to vary with time.
- 2) The longer the seismic ray path, the larger the possible temporal and spatial variations in seismic measurements, because of temporal and spatial heterogeneities.
- 3) Comparatively minor variations in microcrack geometry could have major effects on porosity and permeability and hence have major effects on hydrocarbon production.

As a consequence conventional seismic observations, where source and/or receivers are surface-based, may suffer possibly severe anomalies in time and space that may not be explainable in terms of conventional geophysics. Meaningful measurements have to be taken at the time and place they are required and need to be recorded as close as possible to the production zone.

Time-lapse single-well imaging (SWI)

The most direct way of recording seismics within a producing reservoir is by time-lapse (4D) single-well imaging (SWI). SWI is where a borehole source (the DOV for example) is repeatedly pulsed, and scattered reflections and diffractions are recorded by three-component geophones in the same borehole as the source. Recordings of a single pulse may well be uninterpretable. However, if pulse is repeated before and after there has been some change in the reservoir, Figure 7 shows that time-lapse (differencing successive recordings) can in principle determine the direction and distance of the changing properties.

SWI is a new technique that has several advantages.

- 1) Time-lapse (4D) SWI can, in principle, locate the direction and distance of any change within the reservoir (the movement of oil-water contacts, for example). Majer *et al.* [24] recorded SWI changes in direct P-wave reflections, from a known fracture following air injection, recorded in a borehole a few metres from the fracture, and the source-receiver configuration was arranged so that direct reflections were recorded by the inline instruments. The recordings were made with hydrophones and no shear-waves were recorded.
- 2) The SWI location of changes (as in Figure 7) is largely independent of reservoir structure. This means that, in principle, SWI from a single well (ideally the production well) in a producing reservoir could: follow moving oil-water-contacts; anticipate water coning; locate by-passed oil (as volumes where there was no fluid movement); locate fractures by SWI location of small acoustic events (and in optimum geometry by direct seismic reflections, as in [24]); and otherwise provide immediate information for managing the reservoir. In principle, this could be without the need for expensive structural surveys.
- 3) Analysis (in principle) is simple, automatic, and largely independent of structure, thus almost real-time analysis is possible.
- 4) There are several significant advantages over alternatives for monitoring production:
 - 4.1 SWI would provide the basic parameters for initiating APE-modelling.
 - 4.2 SWI operation and processing is, in principle, automatic and fast (almost instantaneous).
 - 4.3 SWI is much cheaper ($\times \sim 1/100$) than 4D reflection surveys, particularly if geophones are located behind the casing when casing is first installed.

As a result, SWI opens up whole new areas where time-lapse seismics could be used for real-time monitoring of the producing reservoir with the possibility of making dynamic changes to optimise production processes during hydrocarbon recovery.

Conclusions

The crust of the Earth has been shown to be a critical system of closely spaced fluid-saturated microcracks responding with great sensitivity to small disturbances. Such extreme sensitivity verging on criticality is a feature that appears in many other phenomena, ranging from velocity glitches in pulsars to quantum electrodynamics, from weather forecasting to the behaviour of traffic on roads and the economics of the New York Stock Exchange. Critical systems are universally common features of complex interactive systems. Consequently, it is not surprising that the rocks in the Earth's crust, like many other Natural phenomena, are critical systems [2,3].

If observations of the reservoir are low-resolution, then the New Geophysics can probably be ignored (except for interpreting shear-wave splitting), but if more accurate measurements are attempted, measurements are likely to be less and less understandable as resolution is increased. This is because the behaviour near criticality is more like other critical systems than it is to the underlying sub-critical physics [2,3]. One cannot expect to understand this behaviour in terms of conventional sub-critical physics. It is often claimed that it is one of the miracles of nature that the behaviour of these complicated interactive systems is so orderly, controlled, and calculable. It is interesting that the practical engineers and managers, to whom this paper is primarily addressed, should have to consider this state-of-the-art physical advance for better appreciation of the behaviour of their reservoirs, and hopefully an increase in oil production.

A New Geophysics has been outlined, suggesting that for detailed understanding of reservoirs and increasing oil production, reservoirs need to be monitored by time-lapse SWI. SWI is a new, largely untried, technology. Figure 7 indicates that in principle time-lapse SWI works. The most important requirement now is to begin to process real data.

SWI today is in much the same position that reflection seismology was perhaps 70 years ago. There are many known and unknown problems to resolve, as there were with reflection seismology. With the massive advances projected in technology and processing, it is suggested that SWI could become a key oil field production tool for the 21st century.

Acknowledgements

This work was partially supported by European Commission Prepared Project, Contract Number EVG1-CT2002-00073.

References

- [1] Crampin, S. [1994] The fracture criticality of crustal rocks. *Geophysical Journal International* **118**, 428-438.
- [2] Crampin, S. and Chastin, S. [2003] A review of shear-wave splitting in the crack-critical crust. *Geophysical Journal International* **155**, 221-240. (Paper scsc03)*
- [3] Crampin, S. [2003] The New Geophysics: shear-wave splitting provides a window into the crack-critical rock mass. *The Leading Edge* **22**, 536-549. (sc03a)*

- [4] Crampin, S. and Zatsepin, S. V. [1997] Modelling the compliance of crustal rock: II - response to temporal changes before earthquakes. *Geophysical Journal International* **129**, 495-506.
- [5] Zatsepin, S. V. and Crampin, S. [1997] Modelling the compliance of crustal rock: I - response of shear-wave splitting to differential stress. *Geophysical Journal International* **129**, 477-494.
- [6] Crampin, S. [2004] The New Geophysics: implications for hydrocarbon production. *PetroMin*, **30**, in press.
- [7] Heffer, K. J. and Bevan, T. G. [1990] Scaling relationships in natural fractures. *Society of Petroleum Engineers*, SPE Paper 20981.
- [8] Crampin, S. [1997] Going APE: I - Modeling the inherent anisotropy of intact rock. 67th Annual International Meeting, Society of Exploration Geophysicists, Dallas, *Expanded Abstracts* **1**, 952-955; see also 956-959; 921-924.
- [9] Crampin, S., Zatsepin, S. V., Slater, C. and Brodov, L. Y. [1996] Abnormal shear-wave polarizations as indicators of pressures and over pressures. 58th Conference, European Association of Geoscientists and Engineers, Amsterdam, *Extended Abstracts*, O38.
- [10] Angerer, E., Crampin, S., Li, X.-Y. & Davis, T. L., [2002] Processing, modelling, and predicting time-lapse effects of overpressured fluid-injection in a fractured reservoir. *Geophysical Journal International* **149**, 267-280. (ea+02)*; Angerer, E., Crampin, S., Li, X.-Y. & Davis, T. L. [2000]; Time-lapse seismic changes in a CO₂ injection process in a fractured reservoir 70th Annual International Meeting, Society of Exploration Geophysicists, Calgary, *Expanded Abstracts* **2**, 1532-1535.
- [11] Crampin, S., Volti, T., Chastin, S., Gudmundsson, A. and Stefánsson, R. [2002] Indication of high pore-fluid pressures in a seismically-active fault zone. *Geophysical Journal International* **151**, F1-F5. (sc+02)*
- [12] Crampin, S. and Booth, D. C. [1989] Shear-wave splitting showing hydraulic dilatation of pre-existing joints in granite. *Scientific Drilling* **1**, 21-26.
- [13] Booth, D. C., Crampin, S., Lovell, J. H. and Chiu, J.-M. [1990] Temporal changes in shear wave splitting during an earthquake swarm in Arkansas. *Journal of Geophysical Research* **95**, 11,151-11,164; Crampin, S., Booth, D. C., Evans, R., Peacock, S. and Fletcher, J. B. [1990] Changes in shear wave splitting at Anza near the time of the North Palm Springs Earthquake. *Journal of Geophysical Research* **95**, 11,197-11,212; Crampin, S., Booth, D. C., Evans, R., Peacock, S. and Fletcher, J. B. [1991] Comment on "Quantitative measurements of shear wave polarizations at the Anza seismic network, southern California: implications for shear wave splitting and earthquake prediction." by Aster, R., Shearer, P.M. & Berger, J., *Journal of Geophysical Research* **96**, 6403-6414; Liu, Y., Crampin, S. and Main, I. [1997] Shear-wave anisotropy: spatial and temporal variations in time delays at Parkfield, Central California. *Geophysical Journal International* **130**, 771-785; Gao, Y., Wang, P., Zheng, S., Wang, M. & Chen, Y.-T., 1998. Temporal changes in shear-wave splitting at an isolated swarm of small earthquakes in 1992 near Dongfang, Hainan Island, Southern China. *Geophysical Journal International* **135**, 102-112.
- [14] Crampin, S., Volti, T. and Stefánsson, R. [1999] A successfully stress-forecast earthquake. *Geophysical Journal International* **138**, F1-F5. (sc+99)*
- [15] Volti, T. and Crampin, S. [2003] A four-year study of shear-wave splitting in Iceland: 1. Background and preliminary analysis. In New insights into structural interpretation and modelling, ed. Nieuwland, D. A., Geological Society, London, *Special Publication*, **212**, 117-133; Volti, T. and Crampin, S. [2003] A four-year study of shear-wave splitting in Iceland: 2. Temporal changes before earthquakes and volcanic eruptions. In New insights into structural interpretation and modelling, ed. Nieuwland, D. A., Geological Society, London, *Special Publication*, **212**, 135-149; Gao, Y. and Crampin, S. [2004] Observations of stress relaxation before earthquakes. *Geophysical Journal International*, in press. (gysc04c)*
- [16] King, M. S., Chaudhry, N. A. and Ahmed, S. [1994] Experimental ultrasonic velocities and permeability of sandstones with aligned cracks. 56th Conference, European Association of Geoscientists and Engineers, Vienna, *Extended Abstracts* P113.
- [17] Zatsepin, S. V. & Crampin, S., 1996. Stress-induced coupling between anisotropic permeability and shear-wave splitting. 58th Conference, European Association of Geoscientists and Engineers, Amsterdam, *Extended Abstracts* C030.
- [18] Crampin, S., Rowlands, H. J., Zatsepin, S. V., Smart, B. J., Edlmann, K. and Crawford, B. [1997] Predicting the response to effective stress of cores with different pore fluids. 59th Conf. EAGE, Geneva, *Extended Abstracts* **2**, CO22; Crampin, S., Zatsepin, S. V., Rowlands, H. J., Smart, B. J. and Somerville, J. M. [1999] APE-modelling of fluid/rock deformation of sandstone cores in laboratory stress-cells. 61th Conference, European Association of Geoscientists and Engineers, Helsinki, *Extended Abstracts* **1**, 2-08.
- [19] Sothcott, J., O'Hara, S. G., Khazanehdari, J. and McCann, C. [2000] From sonic to ultrasonic - the acoustic properties of reservoir sandstones. 62nd Conference, European Association of Geoscientists and Engineers, Amsterdam, Glasgow, *Extended Abstracts* D-39; Sothcott, J., McCann, C. and O'Hara, S. G. [2000] The influence of two different pore fluids on the acoustic properties of reservoir sandstones at sonic and ultrasonic frequencies. 70th Annual International Meeting, Society of Exploration Geophysicists, Calgary, *Expanded Abstracts* **2**, 1883-1886.
- [20] Chapman, M., Zatsepin, S. V. and Crampin, S. [1998] Anisotropic dispersion in stress-sensitive poroelasticity. 60th Conference, European Association of Geoscientists and Engineers, Leipzig, *Extended Abstracts* **1**, 10-10; Chapman, M., Zatsepin, S.V. and Crampin, S. [2000] Incorporating

stress-sensitivity into dynamic poro-elasticity. 70th Annual International Meeting, Society of Exploration Geophysicists, Calgary, *Expanded Abstracts 2*, 1536-1539.

[21] Crampin, S., Chastin, S. and Gao, Y. [2003] Shear-wave splitting in a critical crust: III - preliminary report of multi-variable measurements in active tectonics. *Journal of Applied Geophysics 54*, 265-277. (sc+03a)*

[22] Heffer, K. J., Fox, R. J., McGill, C. A. and Koutsabeloulis, N. C. [1995] Novel techniques show links between reservoir flow directionality, Earth stress, fault structure and geomechanical changes in mature waterfloods. *Society of Petroleum Engineers*, SPE Paper 30711.

[23] Crampin, S., Peacock, S., Gao, Y. and Chastin, S. [2004] The scatter of time-delays in shear-wave splitting above small earthquakes. *Geophysical Journal International 156*, 39-44. (sc+04a)*

[24] Majer, E. L., Peterson, J. E., Daley, T., Kaelin, B., Myer, L. R., Queen, J., D'Onfro, P. and Rizer, W. [1997] Fracture detection using crosswell and single well surveys. *Geophysics 62*, 495-504.

*Identification of papers available at website <<http://www.glg.ed.ac.uk/~scrampin/opinion/>>.



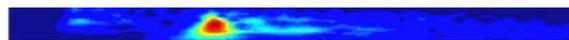
Magnitude

Microseismic Monitoring Services



“Smart monitoring”[®]

gas storage, waste injections,
hydraulic fracturing, water flooding,
EOR



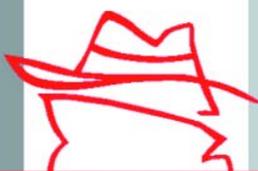
www.magnitude-geo.com



Main Office : phone: +31-53-4315155 e-mail: info@dgb-group.com
USA : phone: +1-281-2403939 e-mail: info.usa@dgb-group.com

OpendTect

Open Source
environment
+
commercial
plugins for
added
functionality



How much are you prepared to pay?

Multi-volume attributes (incl. math and logic)	0
Spectral decomposition NEW	0
Volume rendering and stereo viewing	0
Cross-platform distributed computing	0
Horizon & fault mapping Coming soon	0
Source code	0
Plugin architecture	0 +

Total price* \$ 0,00

* OpendTect is free for R&D and education. Commercial users pay a modest maintenance & support fee

www.OpendTect.org