УДК 550.31

STRESS-FORECASTING EARTHQUAKES IN A CRITICAL CRUST

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It is becoming increasing apparent that the crust of the Earth is a critical system, which specifically precludes the deterministic prediction of the magnitude, time, and place of future large earthquakes. A new understanding of the pre-fracturing deformation of crustal rock suggests an alternative approach. The progress towards *fracture-criticality*, when the cracking is so extensive that the percolation threshold is reached and earthquakes can occur, can be monitored by analyzing seismic shear-wave splitting. Assuming a reasonably constant input of stress, the time when the effects of increasing stress on the crack distributions in the crust reach levels of fracture-criticality can be estimated and the time and the magnitude, but not necessarily the location of a future large earthquake can be *stress-forecast*. The effects have been seen with hindsight on many occasions before both earthquakes and volcanic eruptions. Recently, the time and magnitude of an $m_b = 5$ earthquake in SW Iceland has been successfully stress-forecast, within a comparatively narrow error-defined time and magnitude window. Using small earthquakes as the source of shear-waves to monitor the rockmass as in SW Iceland requires a nearly continuous swarm of small earthquakes within the shear-wave window of seismic stations together with rapid location and analysis procedures. Such facilities are found probably uniquely in SW Iceland. Swarms of small earthquakes elsewhere are extremely uncommon and are not found when needed near earthquake-vulnerable cities. Stress-forecasting earthquakes on demand requires controlled source seismology, and the first Stress-Monitoring Site (SMS) is currently being set up in 1km-deep boreholes in the Tjörnes Fracture Zone at Húsavík in Northern Iceland. Such SMS could be set up at any cite the hazard of earthquakes or volcanic eruptions.

ПРОГНОЗ ЗЕМЛЕТРЯСЕНИЙ ПО НАПРЯЖЕНИЯМ В ЗЕМНОЙ КОРЕ, НАХОДЯЩЕЙСЯ В КРИТИЧЕСКОМ СОСТОЯНИИ

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В последнее время становится все очевиднее, что земная кора является критической системой, которая исключает детерминистский прогноз силы, времени и места сильных землетрясений. Альтернативный подход подсказывается новым пониманием предразрывного деформирования пород земной коры. Приближение к предразрывному критическому состоянию, когда трещинообразование становится столь интенсивным, что достигается порог перколяции и наступает возможность возникновения землетрясения, можно определять путем слежения за расщеплением сейсмических волн. В предположении достаточно постоянного во времени нарастания напряжения можно оценить момент времени, когда эффект возрастающего напряжения на распределение трещин в земной коре достигает уровня готовности к разрыву, и из данных о напряжениях определить время и магнитуду, но не обязательно место будущего землетрясения. Это влияние можно видеть ретроспективно во многих случаях как перед землетрясениями, так и перед извержениями вулканов. Недавно по данным о напряжениях был осуществлен успешный прогноз времени и магнитуды землетрясения с $m_b = 5$, произошедшего на юго-западе Исландии, в достаточно узком интервале времени и магнитуды, определенном ошибками наблюдений. Использование слабых землетрясений в качестве источника поперечных сейсмических волн для слежения за состоянием массива горных пород, как это было проделано для юго-запада Исландии, требует наличия почти непрерывного роя слабых землетрясений в окне регистрации поперечных волн сейсмическими станциями одновременно с быстрым определением параметров этих землетрясений и анализом полученных данных. Такие уникальные возможности, вероятно, существуют лишь на юго-западе Исландии. В других местах Земли рои слабых землетрясений чрезвычайно редки, в особенности, когда они

требуются для прогноза вблизи уязвимых городов. Прогноз землетрясений по напряжениям в нужном месте требует использования искусственных сейсмических источников. В настоящее время в Гусавике, на севере Исландии, в зоне разлома Тьорнес создается первый пункт слежения за напряжениями при помощи аппаратуры, установленной в скважинах на глубине 1 км. Такие пункты можно создать и в других местах, где существует опасность землетрясений или вулканических извержений.

Preface

Professor Keilis-Borok played a crucial role at the beginning of the work reported in this paper. I was spending some months in Moscow, 1979-1980, at his invitation, when my colleague (Russ Evans) running the Turkish-Dilatancy Project in Turkey, first telexed me that they were seeing seismic shear-wave splitting on almost all seismograms recorded above small earthquakes. The shear-wave splitting indicated distributions of fluid-saturated *stress-aligned* microcracks. This was the first time that such distributions had been suggested and I did not know whether this was a reasonable supposition. In the Institute of Physics of the Earth, who better to give answers to fundamental questions than Keilis-Borok. I asked Volodya, and he said the equivalent of ”go for it”, and I have been going for it ever since.

Those observations were the first reliably identified examples of anisotropy-induced azimuthally-aligned shear-wave splitting in the crust. They were the precursor to the observations of shear-wave splitting now made extensively in both exploration and earthquake seismology in almost all rocks of the Earth’s crust. The work reported in this paper is one of many developments.

New ideas are very fragile, and Volodya’s support was very important to me at that time. It is a pleasure to dedicate this paper to Professor V. I. Keilis-Borok on his 80th birthday - long may he continue to be so supportive of more junior scientists!

Introduction

Current scientific discussions suggest that, because of the self-similarity of earthquake occurrence and other phenomena, typified by the straight line of the Gutenberg-Richter relationship, reliable prediction of the time, place, and magnitude of future large earthquakes, specified within useful limits, is not possible (see for example Geller [1], Geller *et al.* [2], Leary [3], and Kagan [4], amongst many others). These papers argue that the Earth is a critical system, with clusters of heterogeneities at all scale lengths. Consequently, any small earthquake is equally likely to cascade into a large event and in principle such small events can occur almost anywhere and anytime. I broadly agree with most of their results and arguments and, taken in their context, concur with their conclusions. However, I suggest there is an alternative approach, which appears to be valid, and is supported by theory, observation, and practice. This approach would not predict the time, place, and magnitude of future large earthquakes, but would allow the time and magnitude, but not necessarily the location, of large earthquakes to be *stress-forecast.*

The principal assumption is that large earthquakes cannot occur until sufficient stress-energy has accumulated in the crust and/or upper mantle. Since rocks are comparatively weak to shear-stress, the stress-energy before a large earthquake necessarily accumulates over an enormous volume of rock, perhaps tens to hundreds of millions of cubic kilometers before the largest earthquakes. In principle, when such a volume is close to criticality, a small earthquake almost anywhere within the volume could trigger a large earthquake and hence display the unpredictability of Geller, Leary, Kagan *et al.* [1, 2, 3, 4].

In an after dinner speech at one of the Geophysical Theory and Computer Conferences in the early seventies, Keilis-Borok suggested, as remember it, that it was inconceivable for the Earth to store up sufficient energy for a large earthquake without some recognizable geophysical effect. This seemed to me obvious at the time but, perhaps surprisingly, nobody, not even Keilis-Borok, appears to have followed this up.

The difficulty is that, until recently, the effect of the accumulation of stress on the rock mass was not understood. It was not known how the difference between stressed and unstressed rock could be recognized. We now know that the immediate effect of the small changes of stress before earthquakes is to modify the geometry of the most compliant elements of the rockmass: the stress-aligned fluid-saturated grain-boundary cracks and low aspect-ratio pores that pervade almost all rocks in the crust [5, 6]. Such fluid-saturated microcracks are almost transparent to P-waves, and by far the most sensitive seismic diagnostic for monitoring the effects of the stress build-up before earthquakes is monitoring variations in the splitting of seismic shear-waves.

When conditions are appropriate, subtle temporal changes in shear-wave splitting are now seen almost routinely before earthquakes in the highly-seismic transform zone of the Mid-Atlantic Ridge onshore in SW Iceland. The time and magnitude of an $M = 5$ has been successfully *stress-forecast* [7]. Note that shear-wave splitting cannot indicate the location of the stress-forecast event, but when a larger earthquake is stress-forecast, other evidence can be interpreted correctly. Consequently, persistent small-scale seismic activity in Iceland allowed Ragnar Stefansson of the Icelandic Meteorological Office, to correctly identify the fault on which the stress-forecast event would occur [7]. So in this example, the time, magnitude, *and location* were correctly predicted before the event.

(Note that the magnitudes of Icelandic earthquakes, written as M, are magnitudes approximately equivalent to body-wave magnitudes m_b. Note also that relationships between magnitude scales may be complicated by varying depths, fault-lengths versus stress-drops, etc., so that the various scales are not directly comparable.)

I shall briefly discuss shear-wave splitting and stress-forecasting, review the new results, discuss the stress-monitoring site (SMS) currently being developed in Northern Iceland, and the criticality of the rock mass. SMSs use crosshole seismics to monitor shear-wave splitting along those particular ray paths, which analysis of shear-waves above small earthquakes suggests, and APE-modelling confirms, are sensitive to increasing stress. In principle, SMSs could be set up near any location vulnerable to seismic hazard independent of local seismicity. This would mean that changes of stress could be monitored and the time and magnitude of large earthquakes stress-forecast anywhere in the world. Thus, SMSs may be the key to eliminating some of the hazard of earthquakes.

1. Review of crack-induced shear-wave splitting

Shear-wave splitting (seismic birefringence) with stress-aligned azimuthal anisotropy is observed in almost all sedimentary, igneous, and metamorphic rocks in at least the uppermost half of the Earth's crust [5, 6, 8, 9]. (There are only a few well-understood exceptions, where rocks, such as shales, clays, and oolites, do not always display azimuthal anisotropy [6].) Observations of shear-wave splitting below the critical depth of 1km, say, where the vertical stress is greater than the maximum horizontal stress, show the leading (faster) split shear-wave approximately parallel (within ±15°) to the direction of maximum horizontal stress. Surprisingly, these observations show a *minimum* shear-wave velocity anisotropy of about 1.5%, and a *maximum* of about 4.5%, in all (ostensibly) intact rock independent of geology: igneous, metamorphic, and sedimentary rocks have similar characteristics, independent of porosity and independent of tectonic history. Similar velocity anisotropy is seen in 30% porosity sandstone in shear zones as in 2% porosity granites in continental shields. These results were inexplicable when first observed [5].

Such parallel polarizations are indicative of hexagonal isotropic symmetry with a horizontal axis of cylindrical symmetry, sometimes referred to as *TIH-anisotropy* (transverse isotropy with a horizontal axis of symmetry), or a minor perturbation thereof. The *only phenomenon* common to all rocks with such symmetry with a stress-aligned horizontal axis of cylindrical symmetry is parallel vertical cracks or microcracks, which tend to be aligned like hydraulic fractures, with crack-normals in the direction of minimum stress. Hence, the splitting can be reliably assigned to propagation through the distributions of stress-aligned fluid-saturated grain-boundary cracks and low aspect-ratio pores. Known as *extensive-dilatancy anisotropy*, or *EDA* [10], such distributions of microcracks pervade almost all *in situ* rocks. Since below the critical depth, the minimum stress is horizontal, throughout most of the crust EDA-cracks are oriented approximately vertical approximately parallel to the maximum horizontal stress. Fig. 1 shows a schematic illustration of crack-induced stress-aligned shear-wave splitting.

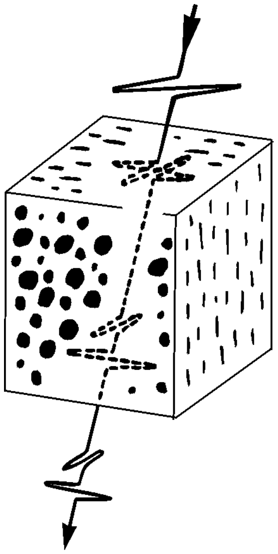

Fig. 1. Schematic illustration of shear-wave splitting in distributions of stress-aligned fluid-saturated cracks. Such parallel vertical orientations are found below a critical depth, usually between 500 m to 1 km

Since crack density, $\varepsilon = Na^3/\nu$, where N is the number of cracks of radius a in volume ν, can be shown to be approximately equal to one hundredth of the percentage of shear-wave velocity anisotropy [11], the observed range, 1.5% to 4.5% of velocity anisotropy, is approximately equivalent to crack densities in the range $\varepsilon = 0.015$ to $\varepsilon = 0.045$, respectively. This range is illustrated schematically in Fig. 2, as 2D sections of 3D dimensionless distributions of parallel equal-sized penny-shaped cracks [5]. Although it is not suggested that cracks are wholly parallel or uniformly distributed, each diagram shows the amount of alignment required to cause the observed amounts of shear-wave velocity anisotropy. Crampin [5] suggested a fracture-criticality limit ($0.045 < \varepsilon < 0.1$) separating ostensibly intact rock from rock that has no shear-strength and is disaggregating at the free-surface. The preliminary interpretations of Fig. 2 [5, 8, 9] were empirical. The evolution of such EDA cracks as stress changes or other conditions change has now been modelled by *anisotropic poro-elasticity*,

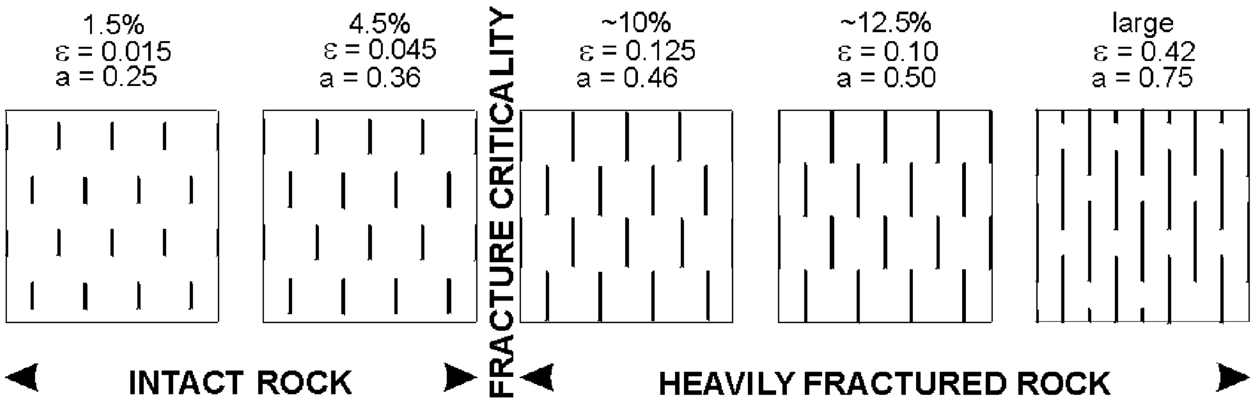

Fig. 2. Schematic interpretation of observed percentages of shear-wave velocity-anisotropy interpreted as uniform (dimensionless) distributions of equal-sized parallel penny-shaped cracks with the same percentage of shear-wave velocity-anisotropy, where ε is crack density (approximately equal to a hundredth of the percentage anisotropy) and a is crack radius. Crampin [5] suggested there is a *fracture-criticality* limit, $0.045 \le \varepsilon \le 0.1$, separating ostensibly intact rock ($\varepsilon \le 0.045$) from rock that is disaggregating at the free surface ($0.1 \le \varepsilon$). The fracture criticality limit in stressed fluid-saturated intact rock is now shown to be associated with the percolation threshold at about $\varepsilon \approx 0.055$ [15]. (After Crampin [5])

or *APE* [13]. APE models low levels of deformation before fracturing occurs (*pre-fracturing deformation*), where the driving mechanism is fluid movement by dispersion or flow along pressure gradients between neighboring grain-boundary cracks or low aspect-ratio pores at different orientations to the stress field. Fig. 3 shows a schematic but geometrically correct illustration of the effects of APE on distributions of initially randomly oriented fluid-saturated vertical cracks undergoing increasing differential horizontal stress [14, 15]. A detail description of the behavior of Fig. 3 is given in Appendix A. The three most notable features are: (1) there is a minimum shear-wave velocity anisotropy of about 1.5%; (2) the effect of increasing stress is to increase the *average* aspect ratio; and (3) fracture criticality can be associated with the percolation threshold of about 5.5% shear-wave velocity anisotropy [15, 6].

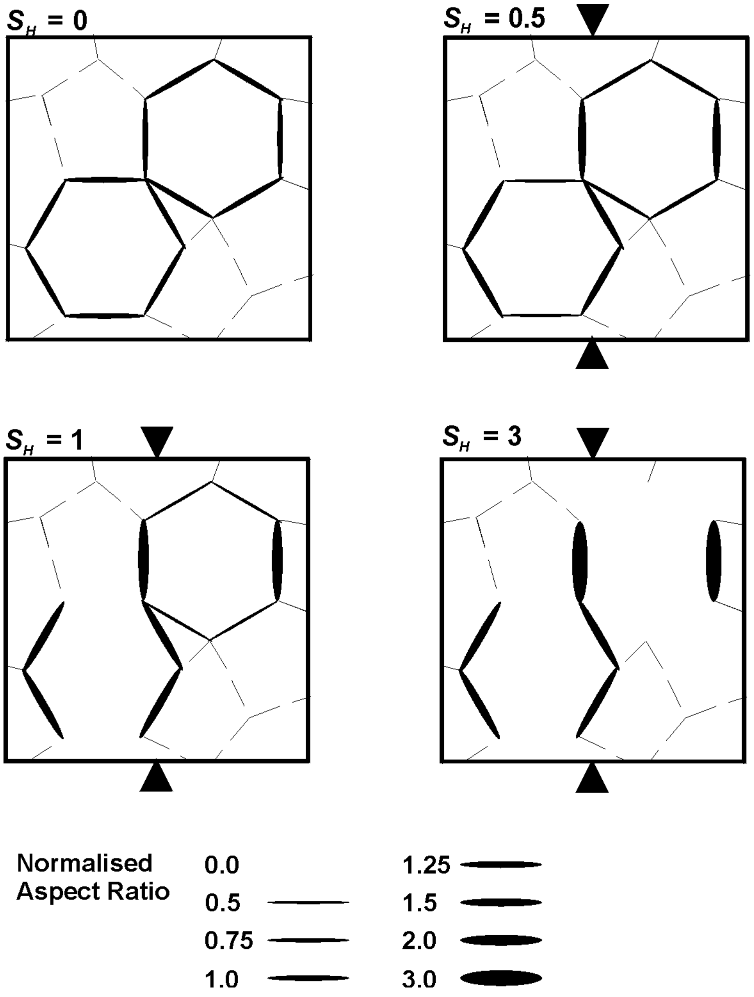

Fig. 3. Schematic illustration of the evolution of crack aspect-ratios of an initially random distribution of vertical cracks for four values of increasing maximum horizontal differential stress normalized to the critical value at which cracks first begin to close. Pore-fluid mass is preserved and aspect ratios are correct for a porosity of $\varphi = 5\%$. The detailed evolution is described in the Appendix A. (After Crampin and Zatsepin [14])

Confirmation of the relevance of APE is demonstrated by the good match of APE-modelling to observations. As well as explaining the minimum velocity anisotropy and the level of fracture-criticality, numerical modelling with APE also matches or is consistent with a large range of other observations. Some of these are listed in a Table, where observations and APE-modelled results are indicated. Table is updated from an earlier version in Crampin [6].

TABLE. Match of APE*-modelling to observations (Crampin [6], updated)

	STATIC EFFECTS	**Ref. (Obs.)**	**Ref. (APE)**
	Field observations of SWVA‡ (below 1km-depth)		
1	SWVA in all rocks independent of porosity and geology.	[5]	[15]
2	Minimum SWVA in intact rock: observed $\approx 1.5\%$; APE $\approx 1.0\%$.	[5]	[15]
3	Maximum SWVA in intact rock: observed $\approx 4.5\%$; APE $\approx 5.5\%$.	[5]	[15]
4	Narrow range of crack density: $0.025 \le \varepsilon \le 0.045$.	[5]	[15]
5	Proximity of fracture-criticality (percolation threshold) $\approx 5.5\%$.	[5]	[15]
	Other field observations		
6	Fracture-criticality limit specifies crack distributions with a range of dimensions of about 9 orders of magnitude.	[21]	[6,22,23]
7	#$\pi/2$ shear-wave polarization changes in over-pressurized reservoirs.	[19,20,18]	[19,20,18]
	DYNAMIC EFFECTS		
	Temporal changes in SWVA during production procedures		
8	Changes before and after pumping tests.	[24]	£
9	#Changes before and after high-pressure CO_2-flood in carbonate reservoir	[16,17,18]	[16,17]
	Temporal changes in SWTD† before earthquakes		
10	#Variations of time-delays before earthquakes (with hindsight).	[7,20,24,26,27]	[15]
11	#Successful forecast of time and magnitude of $M = 5$ earthquake in SW Iceland.	[7]	£
	Temporal changes in SWTD before volcanic eruption		
12	Variations in SWTD for some 5 months before 30th Sept., 1996, Vatnajökull eruption, Iceland, observed at distances of approximately: 240km and 200km WSW; 160km SW; and 240km, N.	[28]	£
	Variations of shear waves in laboratory experiments		
13	Variations of SWVA and permeability in uniaxial stress cell.	[29]	[30]
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.	[31,32]	[31,32]
15	#Variations of velocity and attenuation from sonic (transducers) to seismic (resonant bar) frequencies.	[33,34]	[35,36]

*APE anisotropic poro-elasticity; ‡SWVA shear-wave velocity-anisotropy; #Including recent examples;
£Effects compatible with APE; †SWTD shear-wave time-delays

It is difficult to calibrate APE accurately in *in situ* experiments in the deep crust as not enough is known about the interior for calibrations to be definitive. The best controlled *in situ* calibration to date is by Angerer *et al.* [16, 17] (Items 7 and 9, Table) in the match of modelled to observed seismograms of shear-wave splitting in a time-lapse experiment, where high-pressure CO_2 was injected into a reservoir in Vacuum Field, New Mexico [18]. The target zone was a fractured carbonate reservoir. The version of APE used by Angerer *et al.* [16, 17] assumes a microcrack distribution with a fixed alignment of large fractures. Synthetic seismograms matched the observed shear-wave splitting [16, 17] when the correct high-pressure CO_2 injection pressure of 170 bar with a 100 bar *in situ* pressure was specified in APE. It is interesting to note that the change in shear-wave splitting is caused principally by the change in crack aspect-ratios due to the increase of pressure rather than any change in pore-fluid properties.

Note that the injection pressure was an over-pressure and greater than the maximum horizontal stress. APE-modelling has previously shown [15] that in over-pressurized rocks, the polarization of the faster split shear-wave swings by 90° (the faster and slower split shear-waves exchange polarizations) as was demonstrated in the CO_2-injection [16, 17]. Such changes in shear-wave polarizations have also been observed in an over-pressured reservoir in the Caucasus [19], and in an over-pressured fault zone [20].

APE has also been calibrated in laboratory rock-physics experiments by the effects of stress on rock samples. Once the seismic *P*- and *S*-wave velocities have been matched, the effects on the velocities of increases of stress are predicted by APE [32]. APE also matches [35, 36] the 10% velocity and 100% attenuation dispersion between resonant bar (5kHz) [33, 34] and (more conventional) transmission (500kHz) experiments. Similar percentages of dispersion are observed between 20 MPa and 40 MPa confining pressures [35, 36]. These various results suggest that APE-modelling is a good first-approximation to the effects of changes of stress on the crack distributions in fluid-saturated microcracked rock.

2. Review of stress-forecasting earthquakes

APE-modelling shows that the immediate effect of an increase in horizontal stress is to increase the average aspect ratio (increase the thickness of the cracks) in distributions of EDA cracks where the cracks are aligned vertically parallel to the direction of maximum horizontal stress below about 1 km depth [15, 6]. Assuming cracks are approximately vertical and perpendicular to the direction of minimum (horizontal) stress as indicated by the parallel shear-wave polarizations, increasing aspect ratios modifies shear-wave splitting by increasing the average time delays in ray path directions making angles of ±(15° to 45°) to the crack plane. This double leafed solid angle is known as Band-1. The other band (Band-2) making angles of ±15° to the crack plane is sensitive principally to changes in crack density. These effects are reviewed by [6] and see also [26, 27].

The possibility of crack-induced changes in shear-wave splitting before earthquakes was recognized by Crampin [37] in 1978. However, the first observations of temporal changes in splitting were made by Peacock et al. [38] in 1988 and Crampin et al. [26, 27] before the 1986 $M_S = 6$ North Palm Springs earthquake near Anza in Southern California. These papers analyzed shear-wave splitting in the shear-wave window [53] above small earthquakes. Similar changes were observed, again with hindsight, before smaller earthquakes in Arkansas [25], again in Southern California [20], and in Hainan Island, South China Sea [39]. These are reviewed in [6]. All these variations were in Band-1 of the shear-wave window, but the interpretation that increasing stress would increase crack aspect ratios was empirical. It was only when APE was developed [15] that it could be shown theoretically that the immediate effect of small increases of horizontal stress was to increase average aspect ratios of stress-aligned microcracks. This would increase the average time delays in Band-1 of the shear-wave window as originally hypothesized [26, 27, 38].

Recognizing changes in shear-wave splitting before larger earthquakes, *using small earthquakes as the source of shear waves*, requires three conditions:

1) Nearly continuous small-scale swarms of seismic activity;
2) Seismic stations within the shear-wave of the small-scale seismicity;
3) A large earthquake nearby.

These requirements are severe (particularly the continuous small-scale swarms) and in almost ten years of searching worldwide [12], there were only the four examples noted above, where changes (in Band-1) before earthquakes have been (with hindsight) identified. However, it is perhaps worth noting that there have been no contradictory observations.

The breakthrough came when the European Commission PRENLAB Project for earthquake prediction research began routinely monitoring shear-wave splitting in Iceland [28]. A transform zone of the Mid-Atlantic Ridge is onshore in SW Iceland and provides nearly continuous small scale seismicity with the occasional larger event. The local SIL (South Iceland Lowland) seismic network [40] was enlarged in SW Iceland together with rapid earthquake parameter determination, and seismic waveform data transferred to a web site. As a consequence changes of shear wave time-delays in Band-1 of the shear-wave window are observed almost routinely before earthquakes and volcanic eruptions [28]). During 1997 and 1998, when there appeared to be no disturbances due to volcanic eruptions or the subsurface movement of magma (see next Section), consistent changes in shear-wave splitting before earthquakes were observed, particularly at Station BJA which was sited over a persistent swarm of small transform-zone earthquakes. Four larger earthquakes, with magnitudes $M = 3.8, 4.3, 3.5$, and 5.1, showed (with hindsight) precursory changes in shear-wave splitting indicative of stress-induced increases in crack aspect ratios.

Before each of these earthquakes in Fig. 4, time-delays in Band-1 increased and the earthquakes occurred when the time delays, normalized to ms km^{-1}, reached presumed levels of fracture-criticality at between about 11 and 14 ms km^{-1}. The magnitudes of the four earthquakes were approximately proportional to the duration of the increase in stress, or inversely proportional to the slope of the increase [28]. This can be interpreted in terms of an approximately constant rate of increasing stress from the movement of the Mid-Atlantic Ridge accumulating in a heterogeneous rockmass. If stress accumulation is concentrated in a small volume, the increase of stress is rapid but the final earthquake is smaller, whereas if stress accumulates over a large volume, the increase is slower but the final earthquake is larger. For the limited magnitude range $M = 3.5$ to $M = 5.1$, the relationship appears to be approximately linear [28].

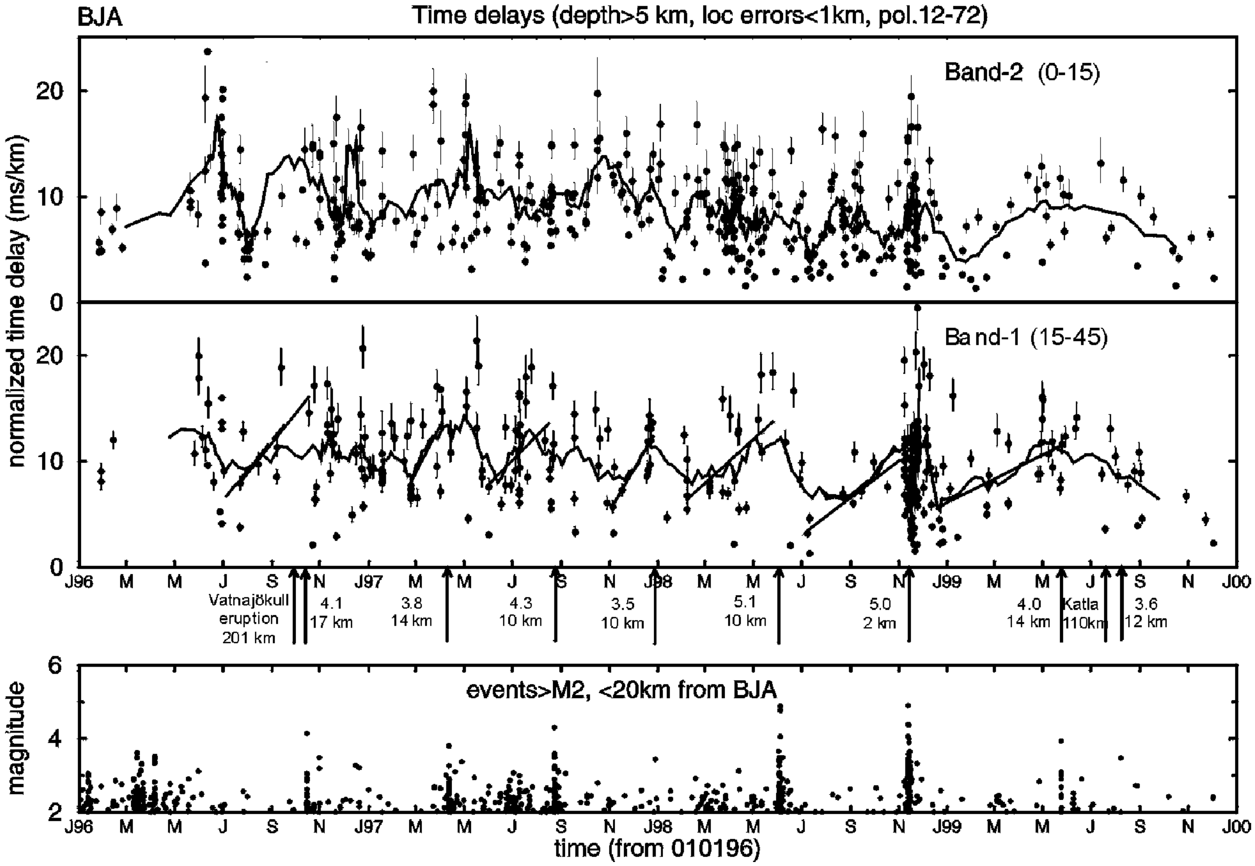

Fig. 4. Shear-wave splitting time delays for January 1, 1996 to December 31, 1999, at Station BJA. The middle and top diagrams show the variation of time delays with time for ray paths in Band-1, and Band-2, which are solid-angles ±(15° to 45°), and ±15° to the average crack plane, respectively. The time delays in ms are normalized to a 1km path length. The vertical lines through the time-delay points are (notional) error bars. The irregular lines are nine-point moving averages. The straight lines in Band-1 are least-square estimates beginning just before minima of nine-point average and ending when a larger earthquake or an eruption occurs. The arrows indicate the times of these larger events with magnitudes and epicentral distances indicated. The bottom diagrams show the magnitudes of earthquakes greater than $M = 2$ within 20 km of the recording station. (After Volti & Crampin [28])

Recognizing increasing time delays in Band-1 at BJA before the earthquake had occurred in October and November, 1998, the time and magnitude of an $M = 5$ earthquake on 13th November, 1998, was successfully stress-forecast in real time [7]. Table of Crampin et al. [7] lists the exchange of email messages between Edinburgh University and the Icelandic Meteorological Office between 27th October and 13th November, 1998. In summary, on 27th and 29th October, Edinburgh suggested that a significant event would happen "soon". On 28th October, Ragnar Stefansson of the Icelandic

Meteorological Office suggested that this might be associated with a small fault which had slipped in a previous $M = 5.1$ earthquake, where low-level seismicity was still continuing. In the final specific forecast of 10th November, 1998, Edinburgh suggested that "an event could occur any time between now", when it would be "($M \geq 5$), and end of February, when it would be ($M \geq 6$)". Three days later, on 13th November, the Meteorological Office reported that "there was a magnitude 5 earthquake … near to BJA … this morning at 10:38 GMT". This earthquake was on the fault line suggested by Stefansson on 28th October. Thus the time and magnitude were successfully stress-forecast, and local information correctly predicted the approximate location.

Note that many seismic networks do not bother to locate small earthquakes. The successful stress-forecast was based on the analysis of shear-wave splitting using small earthquakes as the source of shear-wave. The magnitudes of these earthquakes were mostly less than $M = 2$. This justifies the designed capability of the SIL seismic network in Iceland to locate small earthquakes with magnitudes less than $M = 2$ [40]. Without accurate locations of such small earthquakes, the rock mass would have insufficient sampling to identify temporal variations in shear-wave splitting, even in SW Iceland.

3. Changes in shear-wave splitting before volcanic eruptions

Changes in shear-wave splitting monitor the effect of changes of stress on EDA-crack distributions. The changes of stress may be caused by several phenomena. Temporal changes in shear-wave time delays in Iceland were first recognized before the Vatnajokull eruption of 1st October, 1996 [28], see for example Fig. 4. The increases in Band-1 were later seen for some five months (with hindsight) before the eruption at distances ranging from 240 km WSW at KRI, 200 km WSW at BJA, 160 km SW at SAU, and 240 km N at GRI. That is they were observed at all four stations in Iceland where there was sufficient small-scale seismicity within the shear-wave window beneath the station for temporal variations in Band-1 to be identified. Vatnajokull was a massive fissure eruption, presumably part of a spreading cycle of the Mid-Atlantic Ridge, and these distances of up to 240 km are by far the furthest distance that changes of shear-wave splitting have been observed. The five month increase in stress is assumed to be the time taken by the magma forcing itself through the Earth's crust.

Following earthquakes, the values of the time-delays in Band-1 immediately drop to about the value at the beginning of the increase (the individual measurements in Fig. 4 show the abrupt drop, but the nine-point moving averages tend to smooth over the drop). The abrupt drop is interpreted as the crack aspect ratios relaxing to thin cracks immediately following the release of stress by the earthquake. In contrast, *following the eruption* at Vatnajokull, the normalized time delays in both Band-1 and Band-2 do not show an abrupt decrease. They show a gradual decrease continuing for at least two years of about 2ms km^{-1} per annum. An eruption does not remove the source of the stress, the injection of magma into the crust. The two-year decrease can be interpreted as the time taken by the Mid-Atlantic Ridge to adjust to the input of stress from the Vatnajokull eruption above the Iceland plume [28]. The changes in shear-wave splitting reported in the previous section are superimposed on this gradual decrease in time delays.

Note that the $M = 4.1$ earthquake immediately after the Vatnajokull eruption in Fig. 4 is not thought to have significantly modified time delays. Although it might have influenced the time delays at Station BJA in Fig. 4, the modifications before the eruption were seen at stations up to 240 km distance, which is thought to be too far for the effects before a $M = 4$ earthquake to be visible. At the time of eruption there were a number of $M \geq 4$ events near the eruption fissure.

The effects before Vatnajokull show that changes in shear-wave splitting may also be observed in the course of stress changes during the subsurface movement of magma as well as before earthquakes. There have been minor eruptions in SW Iceland during 1999 and early in 2000. These have caused temporal changes in shear-wave splitting, which disrupt the comparatively regular changes before earthquakes observed during 1997 and 1998, and we have not been able to stress-forecast any earthquakes during 1999.

4. Developing stress-monitoring sites (SMSs)

Stress-forecasting the times and magnitudes of future large earthquakes by monitoring changes in shear-wave splitting as suggested above appears to be a way to provide reliable warnings of imminent earthquakes. As we have seen, stress-forecasting using small earthquakes as the source of shear waves to monitor the rockmass is severely limited by the need to find persistent small-scale seismic activity. Such persistent swarms are unreliable sources of shear-waves even in SW Iceland. To stress-forecast earthquakes near vulnerable locations without persistent seismicity requires some form of controlled source seismics. The characteristic stress-aligned shear-wave splitting is only observed in rocks below the severe scattering and attenuation in the uppermost layers of the crust [5] or at the surface of the Earth, when wavelengths and ray paths are so long that the surface irregularities have a small effect on the observations. Consequently, such controlled source monitoring requires some form of cross-well seismics below the critical depth where the vertical stress is greater than the maximum horizontal stresses.

Controlled source monitoring was first discussed by Crampin and Zatsepin [41] and Crampin [42]. At that time, there was no efficient borehole shear-wave source generally available, and Crampin and Zatsepin suggested using an airgun source. Since shear waves radiate at 45° to the well axis from an airgun source, using the airgun as a source of shear-waves required expensive deviated wells to provide the necessary ray paths.

Since then the highly efficient Downhole Orbital Vibrator or DOV (previously known as the Conoco Orbital Vibrator or COV [43]) has been developed commercially by Geospace Engineering Resources, Inc. The DOV has an eccentric cam, which is swept in clockwise and anti-clockwise directions, and exerts a radial force on the borehole wall. The radiated signal can be processed to simulate two orthogonally-polarized shear waves at any specified orientations. The DOV also generates minimal tube waves, which would be a serious problem with other borehole sources particularly for the required Band-1 or Band-2 ray paths. The DOV source allows shear-wave propagation along appropriate Band-1 ray paths by using conventional vertical wells in the Stress-Monitoring Site geometry suggested in Fig. 5. The receiver boreholes need to be at specific stress-related offsets and azimuths with respect to the source borehole in order to get observations within the solid angle of directions in Band-1 ray paths [44].

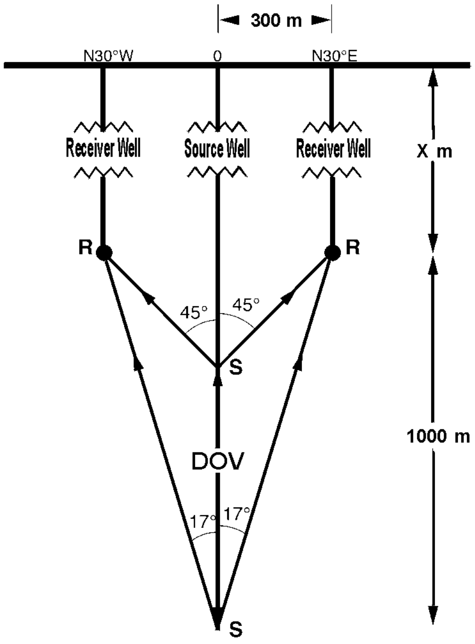

Fig. 5. Specifications for a stress-monitoring site* (SMS), where X m is a depth below which the minimum compressional stress is horizontal so that cracks tend to be aligned vertically. The DOV source operates from (X + 300) m- to (X + 1000) m-depth in the deeper well and receivers are at X m-depth in (at least two) vertical wells at 300 m-offset. The azimuths of the offsets should be within ±45° of the azimuthal direction of minimum horizontal stress, which for this example is taken to be North-South. (After Crampin [44]) *Protected by Patent Application No: PCT/GBOO/01137, filed 24th March, 2000

As this paper was being prepared, the first SMS is currently being developed in the SMSITES Project (Stress-Monitoring Sites Project) funded by the European Commission. It is located close to the Flatey-Husavik Fault of the Tjornes Fracture Zone of the Mid-Atlantic Ridge, where the fault runs onshore at the base of the Tjornes Peninsula in Northern Iceland. Many townships in Iceland drill boreholes for geothermal heat. By good fortune the township of Husavik has three boreholes in an appropriate stress-oriented geometry (compatible with Fig. 5) that are being made available for a stress-monitoring site, courtesy of Hreinn Hjartarson of Orkuveita Husavikur, the municipal water, heat and electrical company [45].

The SMSITES Project employs a state-of-the-art source in wholly new source-receiver geometry. To our knowledge, it will be the first time that the short-term temporal stability of shear-wave splitting will be examined. Whatever the outcome, SMSITES is likely to provide new constraints for interpreting shear-wave splitting, quite apart from monitoring changes before a possible large earthquake.

The European Commission is funding the development of the SMSITES Project at Husavik in order to develop techniques for stress-forecasting the times and magnitudes of impending large earthquakes wherever the need arises in Europe and worldwide [45]. If the Husavik SMS functions as expected, such SMSs could be installed near any earthquake- or eruption-vulnerable location anywhere worldwide. With such a SMS site, the stress changes before a large earthquake would be recognized, and would, at least, remove some of the uncertainty of earthquake hazard assessments.

There is a need for SMSs even in highly seismic SW Iceland. In 2000, there were a group of three $m_b > 5$ ($M_S > 6$) earthquakes in SW Iceland, which were not stress-forecast [28]. With hindsight the reason is clear. There was a gap in local seismicity within the shear-wave window of the nearest station. There were no reliable shear-wave source signals for about seven weeks at the beginning of the build up of stress, see figure in [28]. This meant that the increase in time delays was not recognized in time and could not be interpreted correctly and the $m_b > 5$ earthquakes were not stress-forecast [28].

5. Critical systems

The underlying reason why the crust is so compliant and calculable [6] is that the stress-aligned fluid-saturated EDA-cracks are a critical system [46, 47]. It is clear from Fig. 2 that the internal crack structure of most igneous, metamorphic, and sedimentary rocks in at least the uppermost 15km to 20km of the crust is comparatively close to fracture-criticality. Fracture-criticality has been shown to be associated with the percolation threshold of distributions of stress-aligned fluid-saturated cracks [15]. Anisotropic poro-elasticity, APE [15], is a mean field theory [48] based on an assumed critical system of cracks in crustal rock.

There are several other common phenomena equally inexplicable by conventional geophysics [47]:

1) The self-similar fractal distributions associated with fluid-rock interactions of cracks and fractures in *in situ* rocks typified by the Gutenberg-Richter frequency-magnitude relationship of earthquakes [6].

2) The self-similarity with $1/f$-noise (flicker noise) typically observed in power spectra of almost all well-logs [49,50,51]. The underlying cause of the almost ubiquitous $1/f$-noise is not understood, although it has been suggested [52] that $1/f$-noise is associated with self-organized criticality.

3) The occurrence of earthquakes which, avoiding issues of criticality, are usually explained by (highly-contrived) one-off explanations in terms of conventional physics and geophysics.

The large range of phenomena in Table, together with three phenomena, above, which are modelled, sometimes extremely accurately, by APE also strongly suggest that the distribution of cracks in crustal rock is a critical system.

Critical systems are dynamic interactive non-linear distributions that below criticality perturb only locally, whereas at criticality all members of the system influence the behavior of all other members so that any perturbation may be global [48]. Bak and Tang [54] suggested that the self-similarity of the Gutenberg-Richter relationship implied that the Earth was in a state of meta-stability known as self-organized criticality. When criticality is reached, an earthquake occurs, stress is released, and the system relaxes to sub-criticality and meta-stability to await the approach of criticality again. The selfsimilar relationships indicate that the time, place, and magnitude of larger earthquakes cannot be predicted because there is no scale or location implied.

Note that the mathematics and physical understanding of critical systems, mean field theories, and self-organized criticality are not wholly defined or refined. Bak and Tang [54], Geller [1], Geller et al. [2], Leary [3], and Kagan [4] based their ideas on the self-similarity of Gutenberg-Richter and similar relationships. They did not identify the sub-critical physics. They would probably claim that the behavior was wholly defined by the criticality and the sub-critical physics was irrelevant. I suggest however, that the success of the APE mean-field theory in modelling the evolution of stress-aligned fluid-saturated cracks in the crust (as listed in Table), is due to the correct identification of the sub-critical physics of pre-fracturing deformation (fluid movement by flow or dispersion along pressure gradients between neighboring cracks at different orientations to the stress-field).

Discussion and conclusions

It has been suggested that because the distribution of fluid-saturated stress-aligned cracks in the crust are a critical system, analysis of shear-wave splitting directly monitors changes in crack geometry in the crust. The parameters that control stress-induced modifications to crack geometry are exactly those that control shear-wave splitting [15]. Since fluid-saturated cracks are the most compliant elements of the rockmass and immediately display the effects of *any change in stress*, analysis of shear-wave splitting directly monitors the pre-fracturing deformation of the in situ rockmass. Since the rate of approach to fracture criticality, and the level of fracture-criticality, can both be assessed, the time when the rockmass reaches fracture criticality and the earthquake occurs can be stress-forecast. There has been one successful stress-forecast to date [7]. In that particular case, local seismicity correctly predicted the most likely location.

There are five basic assumptions for stress-forecasting.

1) The crack structure of the crust is a critical system [5,6,13,15,46,47].

2) Shear-wave splitting directly monitors the geometry of the distributions of the stress-aligned fluid-saturated EDA-cracks pervading most rocks in the crust [5,6,13,15] (Table), and the parameters that control shear-wave splitting are exactly those that control pre-fracturing deformation [13, 15].

3) Changes of stress modify the aspect ratio of distributions of nearly-parallel nearly vertical fluid saturated cracks [6,13,15,26,27] (Table).

4) As stress increases, aspect ratios increase until the level of fracture criticality is reached at the percolation threshold, when shear strength is lost and fracturing and earthquakes can occur. This is confirmed both by theory [13,15] and observations [7,20,25,26,27,28,38,39] (Table).

5) The principal underlying assumption is that fluid-saturated *in situ* rock is quite close to fracture criticality and shear failure, so that stress before a large earthquake necessarily accumulates and may be observed over an enormous volume of rock surrounding the eventual source zone [5,6,13,15].

The behavior of the critical crack system in the crust, or of critical systems in general [48], is not fully understood, and the mathematics is not yet fully resolved. Nevertheless, the amount of evidence for shear-wave splitting monitoring stress changes in the crust, as indicated in Table and in support of the five assumptions, above, is sufficient to show that APE must be, at least, a good first approximation to the behavior of crustal rock.

Hopefully, the crosswell SMSITES Project will provide confirmation of some of these ideas. SMSITES may be considered as a test of the stress-forecasting methodology. However, the principal difficulty in Iceland is that shear-wave splitting monitors increasing stress and stress changes can occur before sub-surface movements of magma as well before earthquakes, where the effects can extend over the whole island [28]. This would not matter in many earthquake-vulnerable locations. Beijing, Istanbul, Los Angeles, San Francisco, and many others, are at considerable distance from volcanic activity so changes in shear-wave splitting can be confidently assigned to earthquake related phenomena.

It is hoped that the SMSITES Project will be successful in monitoring the increase of stress before earthquakes, but it is only one site and may be anomalous for unexpected or inexplicable reasons. In particular, there may not be a large earthquake near the site for many years. The more SMS locations there are, the greater the chance of stress-forecasting a large earthquake, and we seek other locations for SMS installations elsewhere at earthquake- and eruption-vulnerable locations. Consequently, we are actively seeking collaboration with other groups to install other SMSs around the world to stress-forecast the magnitude and time (and possibly the location) of their next large earthquake.

Appendix A

Evolution of fluid-saturated cracks in Fig. 3

Each quadrant of Fig. 3 shows schematically a horizontal section of a distribution of vertical cracks with equalized pore-fluid pressure (no pressure gradients) with the same volume of pore fluid in throughout. Hexagons are elastically isotropic with transversely isotropic (TIV) symmetry, top left, where the solid lines have the same aspect ratio (same thickness) are an isotropic, effectively randomly-oriented, distribution of vertical cracks under zero *differential* horizontal stress. (*TIV-anisotropy* is transverse isotropy with a vertical axis of symmetry.) When the maximum horizontal stress increases to $s_H = 0.5$, top right, cracks perpendicular to s_H have greater pressure normal to the crack face than cracks parallel to s_H, and fluid migrates by fluid flow or fluid diffusion along the pressures across crack faces is equalized. The distributions of crack aspect ratios are modified as in the figure. Depending on their orientation, some cracks become thinner, and some swell and become fatter, but for low levels of differential stress, there are *no significant overall elastic changes and no significant anisotropy.*

Note that APE models a distribution of initially truly randomly oriented cracks. The random distribution of *vertical* cracks in Fig. 3 (top-left) is chosen for convenience and simplicity of illustration. The image of the initial random distribution of cracks at zero differential stress in Fig. 3 (top-left) is very similar to skeletons of porous rocks with similar porosities, $\varphi = 5\%$. (Skeletons of rock are made by filling the pore-space with a fluid that sets into a resistant solid, and the rock matrix dissolved by treatment with acid to leave an upstanding skeleton.) It is suggested that similar distributions are present in almost all rocks independent of porosity, although skeletons can only be produced for a comparatively narrow range of porosities. At lower porosity, skeletons are too weak to be self-supporting, and at higher porosities, skeletons are too opaque to be visually distinguishable.

As differential stress increases, bottom left, s_H reaches a critical level, s^c (normalized to $s^c = s_H = 1$), when cracks normal to s_H first begin to close. It can be shown that the shear wave velocity anisotropy immediately jumps to about 1.0% [15], close to the $\sim 1.5\%$ lower limit observed in the crust in what is normally thought of as intact rock [5]: compare Fig. 3, bottom left, with the first diagram in Fig. 2. As s_H continues to increase, bottom right, the anisotropy also increases. At a level of about 5.5% shear wave velocity anisotropy, the percolation threshold is reached for fluid-saturated distributions of stress-aligned cracks [14, 15]. Fracture criticality can be identified with the percolation threshold.

Note also that the percolation threshold is when there is a statistical likelihood that through-going fractures exist. Originally, percolation theory was a purely geometrical concept of random distributions of cracks, without stress, and without pore-fluid. Fracture criticality, $> 4.5\%$, can be viewed as the dynamic equivalent of the percolation threshold in *in situ* rock, when the elasticity of stressed fluid-saturated microcracked rock is taken into account. It is the level of cracking at which microcracks begin to coalesce into through-going fractures and seismic events are triggered.

Since stress-aligned shear-wave splitting is seen in almost all rocks in the crust below about 1 km, the differential horizontal stress s_H at depth must always be greater than the critical stress s^c even in stable areas of the crust. This suggests that:

1) the critical stress is small, perhaps a few bars, and is typically exceeded by differential horizontal stress below some critical depth ($\sim$ 1km) almost everywhere in the crust;

2) shear-wave splitting is sensitive to comparatively minor changes of stress and minor changes of *in situ* conditions;

3) all rocks are comparatively close to fracture criticality, so that the whole of the cracked crust is close to a critical system.

This work was partially supported by the European Commission in the SMSITES Project, Contract No. EVR1-CT1999-40002. The various ideas in this paper have developed over many years in many discussions with many persons too numerous to mention individually. However, I should like to acknowledge Vladimir Keilis-Borok, Ragnar Stefansson, and my immediate colleagues, Peter Leary, Sergei Zatsepin, David Taylor, Theodora Volti, and Sebastien Chastin for the invaluable part they have played in the development of these ideas.

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