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A quarter century of International Workshops on Seismic Anisotropy (0IWSA – 12IWSA): a historical review of anisotropy in the crust

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A quarter century of International Workshops on Seismic Anisotropy (0IWSA-12IWSA): a historical review of anisotropy in the crust

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Abstract

We report an independent series of 12 International Workshops on Seismic Anisotropy (IWSA) over 25 years that have captured most advances in seismic anisotropy in both exploration and earthquake seismology. These IWSA meetings have assisted the rapid progress of anisotropy and shear-wave splitting from an initially little understood occasional observation to the almost universal acceptance that most rocks are pervaded by fluid-saturated cracks, and the recognition that changes in shear-wave splitting monitor the low-level deformation of the rock mass.

1 Introduction

The first International Workshop on Seismic Anisotropy (1IWSA) was held in Suzdal, USSR, in 1982. The next, 2IWSA in 1986 in Moscow, was the first of twenty years of biennial meetings leading to 11IWSA, 2004, in St Johns, Newfoundland, Canada, and 12IWSA projected for Beijing in 2006. The proceedings of this quarter of a century of IWSA meetings have captured most of the significant markers spanning our understanding of seismic azimuthal anisotropy. Nowadays, stress-aligned seismic anisotropy is widely recognised in almost all rocks in the crust and upper mantle, so that international meetings, in both earthquake and particularly exploration seismology, frequently have sessions on seismic anisotropy. Here we review the past quarter of a century of research into seismic azimuthal anisotropy and shear-wave splitting as marked by IWSA meetings. This review is timely, as it is now argued that the crack-critical crust, as revealed by shear-wave splitting, leads to a fundamental revision of solid earth geoscience.

The first two International Workshops on Seismic Anisotropy were 1IWSA in Suzdal, USSR, 1982, and 2IWSA in Moscow, 1986. The continuing series of biennial IWSA have been in various countries, organised by various people, and sponsored by various organisations. Details are listed in Table 1, and the Appendix records how IWSA workshops began.

The first ten IWSAs, and a direct precursory meeting '*0IWSA*' had proceedings (11IWSA had abstracts) published in a variety of international research journals (Table 1). These proceedings contain many papers crucial to the development of the theory, observation, and interpretation of seismic anisotropy, and outline the overall development of particularly azimuthal anisotropy in both earthquake and exploration seismology. Initially, IWSA meetings were almost entirely about earthquake seismology. After 3IWSA, oil company sponsorship led to the almost complete dominance of exploration seismology at IWSA workshops. The reduction in earthquake studies is probably an overall loss to seismic anisotropy as we need to gain information about inaccessible subsurface rocks from as many sources as possible. The difference in pore-fluids between hydrocarbons and water-based salt solutions probably makes little difference to the structure or behaviour of fluid-saturated cracks, except during production procedures.

Here, we review the series of IWSA meetings and identify papers, both at IWSA meetings and elsewhere, that have had a significant effect on the development of seismic azimuthal anisotropy in the crust. Almost all the important papers in azimuthal anisotropy have appeared in IWSA Proceedings. The two principal exceptions being Thomsen (1986) defining the *Thomsen parameters* convenient for describing reflection surveys in transverse isotropy of sedimentary sequences in seismic exploration. Thomsen (1986) is the most highly-cited paper in *Geophysics*. The other exception is the equally highly-cited Crampin (1981), an early review of wave propagation in cracked and anisotropic rocks.

For convenience, entries from each workshop will be listed in order of (not mutually exclusive) theory, observation, and interpretation. Citations and references of papers published in the various proceedings are listed in **bold-face** type.

2 International workshops on seismic anisotropy

2.0 0IWSA, 1975, Paris, France: Proceedings in Geophys. J. R. Astron. Soc., 49, 1977.

In 1975, the IASPEI Commission for Controlled Source Seismology held a meeting in Paris, organised by David Bamford, at the Institut de Physique du Globe, Université Paris, on *Seismic Anisotropy and its Implications*. This meeting, 0IWSA (Table 1), was a direct precursor to the first IWSA. 0IWSA was the first meeting at which there had been a session, let alone a whole meeting (albeit only one day) on seismic anisotropy. At that time, azimuthal anisotropy in the Earth's crust had not been confirmed. In 1975, observations of seismic anisotropy in the Earth were confined to a comparatively thin layer at the top of the upper mantle, identified by two phenomena. *Pn*-waves propagating in oceanic basins showing azimuthal velocity anisotropy, where the velocity perpendicular to the spreading axis was typically 5% greater than in directions parallel to the axis. This was first recognised by Hess (1964), Raitt *et al.* (1969), and others. The second phenomenon was higher-mode surface-wave particle motions showing anisotropic coupling between higher-mode Love- and Rayleigh-waves which are controlled by anisotropy in the uppermost few km of the mantle (Crampin 1966). There were several earlier tentative reports of possible shear-wave splitting in the crust, but these were isolated examples and unconfirmed - see the introduction to 0IWSA: *Seismic anisotropy - state of the art*. **(Bamford and Crampin, 1977).**

Theory: Three papers by **Keith and Crampin (1977a, 1977b, 1977c)** calculated synthetic seismograms of (plane-wave) body-wave propagation in multi-layered azimuthally anisotropic media. This was the first time that shear-wave splitting had been demonstrated in synthetic seismograms. Today, shear-wave splitting is the most diagnostic and widespread observation of azimuthal anisotropy in the both the crust and upper mantle, but at that time (1975), anisotropy-induced shear-wave splitting was not a recognised phenomenon. The term *shear-wave splitting* for the differencing of shear-wave velocities in anisotropic media was first used (specifically *S-wave splitting*) by Crampin (1978) who first calculated synthetic seismograms and polarisation diagrams (hodograms) of propagation through aligned cracks.

Observation and interpretation: **Bamford (1977)** reported the first observations in the continental upper mantle of *Pn*-wave azimuthal velocity anisotropy from explosion refraction studies. These had similar characteristics to the previous examples of *Pn*-wave velocity anisotropy in oceanic basins from *Pn* refraction studies first identified by Hess (1964), Raitt *et al.* (1969), and others, which indicate a possibly thin layer of azimuthal anisotropy at the top of the upper mantle under oceanic basins.

Crampin and King (1977), using the techniques of Crampin and Taylor (1971), calculated for the first time the dispersion of surface waves in multi-layered anisotropic media, modelling previous observations of coupling between higher-mode Love and Rayleigh surface-waves (Crampin 1966). **Crampin and King (1977)** showed that, because a large proportion of higher-mode energy propagates in the top few km of the upper mantle, the observed coupling could be the result of as little as a 4km-thickness of 4% shear-wave velocity-anisotropy at the top of the upper mantle. **Fuchs (1977)** discussed the possible causes of *P*-wave azimuthal anisotropy in the upper mantle in terms of dynamical processes.

Schlue and Knopoff (1977) inferred anisotropy in the upper mantle from the inability of isotropic inversion to yield consistent structures from both Love and Rayleigh surface-wave phase velocity dispersion across the Pacific Basin. This phenomenon, known as *Rayleigh-Love polarisation anisotropy*, was first suggested by McEvilly (1964) and was later used extensively to suggest upper-mantle anisotropy.

2.1 1IWSA, Suzdal, USSR, 1982: Proceedings in Geophys. J. R. Astron. Soc., 76, 1984.

The first International Workshop on Seismic Anisotropy, 1IWSA, was held in Suzdal, USSR (Table 1). Again a *state-of-the-art* paper summarised the current position (**Crampin *et al*., 1984a)**. The first positive observations of seismic azimuthal anisotropy by stress-aligned shear-wave splitting had now been made in 1980 in the crust and mantle by Crampin *et al.* (1980) and Ando *et al.* (1980), respectively.

Theory: **Crampin (1984a)** surveyed wave propagation in cracked and anisotropic media in a summary of Crampin (1981) - a comprehensive review, which had just been published. A significant advance in calculating anisotropy was to rotate elastic tensors so that the horizontal projection of wave propagation was always in the *x*-direction, with *z* vertical. This meant that analytical expressions and computer programs in multi-layered models could be written in concise general forms by making use of the summation convention for repeated suffices. This procedure is well adapted for computer manipulation, and is one of the key features permitting the numerical developments in Crampin (1981), and most other theoretical calculations.

Cervený and Firbas (1984) and **Petrashen and Kashtan (1984)** presented theory for body wave propagation in inhomogeneous anisotropic media, but did not calculate synthetic seismograms. **Martynov and Mikhailenko (1984)** presented theory for wave propagation in inhomogeneous anisotropic media and used a finite-difference technique to calculate synthetic seismograms in transversely isotropic unlayered models with a vertical axis of symmetry.

Evans (1984) was the first to recognise that the restriction of Nuttli (1961) to surface observations of teleseismic shear-wave arrivals also applied to higher-frequency shear-wave arrivals from crustal earthquakes. This restriction limits useful shear-wave arrivals at a free surface to angles of incidence less than $\sin^{-1}Vs/Vp$ (~ 35°, for a Poisson's ratio of 0.25). Later called the *shear-wave window* (Booth and Crampin, 1985), shear waves arriving outside the window are severely distorted by *S*-to-*P* conversions. Note that refraction through near-surface low-velocity layers frequently means that the effective shear-wave window above small earthquakes can often be extended to an effective shear-wave window of 45° to 50° (Booth and Crampin, 1985).

Crampin (1984b) was the first to use the equations of Hudson (1980, 1981) to derive anisotropic elastic constants for both liquid- and gas-filled stress-aligned cracks - a problem first suggested by Crampin (Hudson, 1981). The effectiveness of these developments for the calculation of seismic propagation through cracked structures has been confirmed in many publications and Hudson (1981) is now a standard references. Crampin (1978) had originally calculated anisotropic elastic constants through cracked media using Garbin and Knopoff (1973, 1975a, 1975b), which lead to results compatible with Hudson (1981).

Using cracks to specify seismic anisotropy was an important advance for at least two reasons. Distributions of stress-aligned cracks are the accepted source of the shear-wave splitting observed in the exploration surveys by the oil industry (see Sections 2.4, 4IWSA, and 2.5, 5IWSA, below), and above small earthquakes (Crampin, 1994). However, the anisotropy of cracks also meant anisotropic elastic constants could be easily modified in meaningful ways in terms of crack density, crack aspect-ratio, and crack orientation, so that shear-wave splitting could be directly related to stress, porosity, and other physical parameters. Since the elastic constants of crystals are rather inflexible, specifying cracks meant that shear-wave splitting became a flexible investigative tool.

Observation - field: The proceedings contained eleven further papers on various observations of *P*-wave velocity anisotropy and shear-wave splitting in the crust and upper mantle, and Rayleigh-Love polarisation anisotropy in the upper mantle.

Observation - laboratory: Several authors discussed velocity anisotropy in laboratory tests of crystalline rocks. **Christensen (1984)** made comprehensive analysis of anisotropy in ultra-mafic upper-mantle rocks, and suggested that shear-wave splitting will provide much information about the mineral orientation and composition of the upper mantle, as indeed has been the case. **Babuška (1984)** examined *P*-wave anisotropy of other crystalline rocks, and **Babuška and Pros (1984)** examined the closure of microcracks at increasing lithostatic pressures and concluded that *P*-wave anisotropy is only observed at low lithostatic pressures. Note however that these experiments were in drained specimens where fluids could escape. Cracks in undrained specimens do not close completely and shear-wave splitting due to stress-aligned cracks is now observed throughout the crust.

Interpretation - aligned cracks: **Crampin *et al.* (1984b)** suggested that observations of shear-wave splitting indicated that rocks in stressed fault zones are pervaded by fluid-saturated microcracks (named as *extensive-dilatancy anisotropy* or *EDA*). Stress-aligned shear-wave splitting is now seen in almost all rocks of the crust, see particularly **Crampin (1993a**, 1994**)**. It is now generally, although not universally, accepted by both exploration and earthquake seismologists, that the shear-wave splitting observed in almost all rocks is caused be stress-aligned fluid-saturated microcracks. (See *Theory* in Section 2.5, below, for discussion of the effects of larger cracks.) Clearly, EDA-cracks would be highly compliant and **Crampin *et al.* (1984b)** stimulated the search for temporal variations in shear-wave splitting before earthquakes. This led to the first observations of temporal variations before earthquakes by Peacock *et al.* (1988), **Crampin *et al.* (1990,** 1991), **Booth *et al.* (1990)**, and others, and the first successfully stress-forecast earthquake (Crampin *et al.*, 1999), as well as variations in hydrocarbon reservoirs caused by fluid injection (Angerer *et al.*, 2002).

2.2 2IWSA, 1986, Moscow, USSR: Proceedings in Geophys. J. R. Astron. Soc., 91, 1987.

The second International Workshop was in Moscow in 1986 (Table 1). As was anticipated in the *state-of-the-art* paper for 1IWSA **(Crampin *et al.*, 1984a)**, increasing interest in anisotropy meant that the whole field could no longer be reviewed in a few pages, and state-of-the-art papers were discontinued. As an example of the rapidly increasing interest, there was one report of shear-wave splitting in the crust in 1980, three in 1985, and about 30 in 1986 **(Booth *et al.*, 1987)**.

Theory: Several papers discussed various techniques for calculating synthetic seismograms in anisotropic structures including double-contour integration by **Taylor (1987)**, and a ray algorithm for 3-D laterally inhomogeneous anisotropic layers by **Gajewski and Pšencík (1987)**, both of which were part of continuing developments.

Observation - Turkish Dilatancy Projects: **Evans *et al.* (1987)** reported the results of the Turkish Dilatancy Project, TDP3. The Turkish Dilatancy Projects were three deployments of radio-linked seismic networks spanning the North-Anatolian Fault east of the Marmara Sea (TDP1 in 1979, TDP2 in 1980, and TDP3 in 1984). These experiments were designed to search for shear-wave splitting above a persistent swarm of small earthquakes some 10km SE of Izmit (the TDP networks happened to span the epicentre, some 20 years later, of the devastating 1999, *M*7.5, Izmit earthquake). Shear-wave splitting was confirmed in the crust for the first time (Crampin *et al.*, 1980), and five papers following Crampin *et al.* (1985) reporting TDP1 and TDP2, set many of the parameters for observations of shear-wave splitting above small earthquakes. **Evans *et al.* (1987)** confirmed and enhanced previous results of TDP1 and TDP2.

TDP3 also deployed magneto-telluric (MT) stations **(Evans *et al.*, 1987)**. These MT sites showed regional contributions to the geoelectric-strike azimuths approximate parallel to the shear-wave polarisations, and local contributions to the geoelectric-strike azimuths were *exactly* along the maxima of shear-wave polarisations, except at one station where there was the severe topographic irregularity of a ~200m-deep gorge, nearby. (The effects of the shear-wave window makes shear-wave splitting extremely sensitive to near-station topography.) This was the first time that anomalies in electromagnetic signals associated with earthquakes had been directly correlated with stress-aligned microcracks.

Chen *et al.* (1987), aware of inhouse results of Peacock *et al.* (1988), also searched for temporal variations in the TDP records. In the five-month deployment of TDP3, they found an overall increase in time-delays between split shear-waves in time-delays in Band-1 directions within the shear-wave window normalised to ms/km. Band-1 is the double-leafed solid angle 15º to 45º to the plane of the inferred parallel cracks (Crampin, 1999). Increases in average time-delays in this solid angle indicate increasing stress as in the accumulation of stress before earthquakes. The Band-1 time-delays show an increase at five out of seven seismic stations, suggesting stress accumulation before an impending earthquake. This is likely to be associated with stress accumulation before an *M* 4.8 earthquake, some 45km SW of the centre of the network, on 28th October, 1984, four days after the monitoring had ended. At that time, the possible association was not identified, as the great sensitivity of fluid-rock deformation for comparatively small stress changes at substantial distances had not yet been recognised.

Observation: **Leary *et al.* (1987)** and **Li *et al.* (1987)** present observations and modelling of seismic propagation in the vicinity of the seismically active Oroville Fault in California, which provided information about the aligned fractures surrounding the fault.

Three papers reported various observations of anisotropic effects in Russia, including very detailed multi-azimuth reflection surveys and vertical seismic profiles (VSPs) in transverse isotropy by **Galperina and Galperin (1987).**

Young and Hutchins (1987) describe a potentially powerful technique for determining the elastic constants of samples of anisotropic rocks by using pulsed laser generation of ultrasonic waves.

Interpretation: **Crampin (1987)** speculated on how changes in shear-wave splitting could forecast earthquakes (first suggested by Crampin, 1978, and **Crampin *et al.*, 1984b**). These ideas eventually led to observations of temporal changes (with hindsight) in Band-1 time-delays before many earthquakes (there are two reports at the next IWSA), and one successful stress-forecast of an *M* 5 earthquake in Iceland (Crampin *et al.*, 1999).

Note that in 1986, Thomsen (1986) published an important paper identifying appropriate parameters for exploration processing of weakly anisotropic media with transverse-isotropy with a vertical axis of symmetry (*TIV-anisotropy*). The Thomsen parameters are one of the major factors that opened up seismic anisotropy to exploration seismologists in 4IWSA (1990) and beyond.

2.3 3IWSA, 1988, Berkeley CA, USA: Proceedings in J. Geophys. Res., 95, 1990.

The Third International Workshop was in the Berkeley Campus of the University of California, USA (Table 1). The reports at this meeting were almost exclusively on laboratory and field observations of fracture and particularly microcrack anisotropy **(Leary *et al.*, 1990)**.

Theory: Several papers calculated synthetic seismograms including: **Gajewski and Pšencík (1990)** extending previous work in dynamic ray tracing (**Gajewski and Pšencík, 1987)** to calculate synthetic seismograms in multi-layered anisotropic substrates. **Tsvankin**

and Chesnokov (1990) used double contour integrals to calculate synthetic seismograms in orthorhombic media.

Liu and Crampin (1990) showed that just as there is a shear-wave window limiting observations of shear waves at the surface, there are also internal shear-wave windows limiting observations at each interface due again to the difference in behaviour of *SV*- and *SH*-waves at horizontal interfaces. In some cases, the behaviour can suggest anisotropy-induced shear-wave splitting at isotropic-to-isotropic internal interfaces.

Observation: **Shih and Meyer (1990)** used the first automatic cross-correlation technique (Shih *et al.,* 1989) to measure shear-wave splitting in Long Valley Caldera, California. They found anomalies associated with faults, and larger time-delays above the resurgent dome. Larger time-delays are now recognised as being associated with rocks with high heat-flow (Volti and Crampin, 2003a, 2003b). **Savage *et al.* (1990)** also examined shear-wave splitting in Long Valley Caldera by visual techniques and obtained similar conclusions, but attributed the scatter in time-delays to near-receiver anisotropy. The large scatter above small earthquakes is now attributed to 90°-flips in shear-wave polarisations caused by the high pore-fluid pressures associated with all seismically-active faults (Crampin *et al.*, 2004). **Li *et al.* (1990)** modelled observations of VSPs in the Mohave Desert, California, with synthetic seismograms and found shear-wave splitting consistent with interpretations in terms of sub-parallel sub-vertical cracks in other studies (for example **Evans *et al.*, 1987**).

Kaneshima (1990) reviewed shear-wave splitting at some forty seismic stations in Japan. Shear-wave splitting was observed over a wide range of source zones and azimuths and **Kaneshima** concludes that shear-wave splitting may be limited to the uppermost 15-25km of the crust.

Interpretation: **Shepherd (1990)** gave a comprehensive geological analysis of microcracks, fluid inclusions, and stress which generally support the interpretation of shear-wave splitting in terms of propagation through sub-parallel sub-vertical fluid-saturated microcracks.

In an integrated study, **Queen and Rizer (1990)** found that the orientations of pressure-cracked core samples matched the orientations of shear-wave splitting at the Conoco Borehole Test Facility in Oklahoma. This was the first direct correlation of shear-wave splitting with microcrack lithology and suggested that shear-wave splitting was directly related to overall fracture orientations and densities, where shear-wave polarisations indicate directions of preferred fluid flow. This has now been widely established in production reservoirs and elsewhere.

Crampin *et al.* (1990) showed that, when more data became available, the statistically-significant increase of Band-1 time-delays identified by Peacock *et al.* (1988) at Station KNW of the Anza Seismic Network, Southern California, was immediately followed by the *M* 6 North Palm Springs of 8th July, 1986, ~30km-distant from KNW. (The aftershocks of the earthquake had previously overloaded the location program in California.) This was first time that temporal changes in Band-1 time-delays monitoring the accumulation of stress before earthquakes had been observed (with hindsight) before earthquakes as suggested by **Crampin** (1978, **1987**) and **Crampin *et al.* (1984b)**. Similar increases were also seen (with hindsight) in Band-1 time-delays before an *M* 3.8 swarm earthquake in Enola, Arkansas **Booth *et al.* (1990)**.

Note that the interpretation of Peacock *et al.* (1988) and **Crampin *et al.* (1990)** was challenged by Aster *et al.* (1990), who used an automatic measurement technique to infer that there were no temporal changes. Crampin *et al.* (1991) (reply, Aster *et al.*, 1991) showed that visual inspection of rotated seismograms indicated that the comments of Aster *et al.* (1990) could be discounted as their automatic measurements could be errors of up to 200%. Note that shear-wave splitting above small earthquakes is extremely difficult to measure automatically on typical seismograms, Crampin and Gao 2005). No wholly successful technique has yet been established, unless there is rigorous selection of seismograms and rejection of well over 50% of the records. Except for vigorous aftershocks sequences, there are seldom enough earthquakes within the shear-wave window to make this useful.)

2.4 4IWSA, 1990, Edinburgh, UK: Proceedings in Geophysical Journal International, 107, 1991.

The Fourth International Workshop on Seismic Anisotropy, 4IWSA, was held in Edinburgh (Table 1). Previous IWSAs had been principally concerned with earthquake seismology. However, shear-wave splitting had now been observed in the oil reservoirs. The 1986 Annual International SEG Meeting had 15 abstracts on crack-induced shear-wave splitting - see for example, Alford (1986) and Lynn and Thomsen (1986). Recognising this advance, in 1988, Crampin founded the Edinburgh Anisotropy Project (EAP) at the British Geological Survey. Sponsored by ~15 oil companies, EAP still continues, directed by Xiang-Yang Li. As a result of this change of emphasis, 4IWSA in Edinburgh had well over 50% of the proceedings related to exploration seismology, and all succeeding IWSA have been entirely dominated by exploration seismology, as oil companies provided increasing sponsorship (Table 1).

The first paper, **Crampin and Lovell (1991)**, reviewed the first decade of observations of shear-wave splitting in the Earth (essentially expanding this point in this review). **Crampin and Lovell** listed seven then unexplained features of shear-wave splitting ranging from, the coincidence of the degree of stress-aligned shear-wave velocity anisotropy in virtually all rock types, to the huge scatter in shear-wave time-delays and polarisations above small earthquakes. It is a mark of the progress in understanding shear-wave splitting that these seven unexplained features in 1991 have all been largely resolved, principally as a result of the recognition that the fluid-saturated microcracks are so closely spaced that the are critical systems with all the behaviour that this *New Geophysics* implies (**Crampin, 1998,** 2003; **Crampin and Chastin, 2001;** Crampin and Peacock, 2005; **Crampin *et al.*, 2003**).

Theory: **Hudson (1991)** reviewed the background and overall progress and conditions for modelling cracks in heterogeneous media begun ten years earlier by Hudson (1980, 1981).

Li and Crampin (1991a, 1991b) developed the linear-transform technique, LTT, to analyse vectorially-polarised shear-wave data by writing the two horizontal components as complex numbers, and successfully applied it to four very different case studies. This was the first time that a comprehensive analysis technique had been developed to analyse shear-wave splitting, and was important as demonstrating that this and, eventually, other fundamentally new techniques were possible.

Lou and Crampin (1991) calculated for the first time synthetic seismograms and dispersion of interface waves propagating along thin anisotropic wave guides. Such guided waves in cross-hole seismics have been used to test continuity of wave guides in hydrocarbon reservoirs.

Theory and observations - shear-wave singularities: **Wild and Crampin (1991)** demonstrated the theoretical effects of materials with combinations of transverse isotropy with a vertical axis of symmetry (*PTL-anisotropy*) and azimuthal *anisotropy (EDA-anisotropy*) believed to be common in hydrocarbon reservoirs. PTL-anisotropy is the transverse isotropy of periodic thin layers and the lithology of shales and mudstones with a vertical axis of symmetry. EDA-anisotropy is the azimuthal anisotropy of parallel vertical microcracks **(Crampin *et al.*, 1984b)**. One of the principal effects of a combination of PTL- and EDA-anisotropy is to yield orthorhombic anisotropic symmetry with numerous (theoretically up to 27) point singularities (Crampin and Yedlin, 1981). Point singularities, where the faster and slower shear-wave sheets touch, can cause severe disturbances to shear-wave ray paths passing within a several degrees of the singularity, depending on the various strengths of PTL- and EDA-anisotropy. **Crampin (1991)** used ANISEIS **(Taylor, 1987**, 1990**)** to calculate exact full-wave synthetic seismograms demonstrating the pronounced disturbances to shear-wave polarisations (90º-flips) and time-delays caused by point singularities, including abrupt reversals of sign without passing through zero. Note that both radial and azimuthal integration were used and the full-wave seismograms are exact without approximations. **Bush and Crampin (1991)** confirmed the effects of point singularities in observations of a multi-offset VSP in the Paris Basin.

Observation: The Proceedings of 4IWSA had some ten papers on observations of *P*-wave velocity anisotropy and shear-wave splitting in hydrocarbon reservoirs. There were also several examples of inverting both field and laboratory data for elastic parameters **(Artemieva and Chesnokov, 1991; Brodov *et al.*, 1991; Brown *et al.*, 1991; de Parscau, 1991; MacBeth, 1991a, 1991b)**.

Interpretation: In a classic paper, **Mueller (1991**) showed that the laterally variability of observed shear-wave splitting could be used to guide horizontal drilling into aligned fissures for enhanced oil recovery at depth in the Austin Chalk, Texas. This is one of the first published demonstrations of the direct value of shear-wave splitting to the hydrocarbon industry.

Leary (1991) showed for the first time that both sonic and electrical resistivity well-logs showed fractal distributions for over three-orders of magnitude of crack dimensions. Referred to as 1/*f*-noise, such effects have now been established as routinely present in virtually all well-logs worldwide, and are an important demonstration of the critical nature of cracks in the crust **(Crampin, 1998; Crampin and Chastin, 2001;** Crampin, 2003; **Crampin *et al.*, 2003)**.

Liu *et al.* (1991), continuing the investigations of **Queen and Rizer (1990)**, showed the effects of aligned fractures on shear-wave splitting in shallow VSPs at the Conoco Borehole Test Facility.

2.5 5IWSA, 1992, Banff, Canada: Proceedings in Can. J. Expl. Soc., 29, 1993.

The Fifth International Workshop on Seismic Anisotropy was held in 1992 in Banff, Alberta, Canada (Table 1), with again the majority of papers in exploration seismics, this time with a significant number of case studies. The small number of earthquake studies included the first papers from mainland China. Note that in ten years of IWSAs, many of the original discoveries of seismic anisotropy have been made. This means that as time progresses there are smaller numbers of significant papers and it is more difficult to identify those papers which will be important for the future. The proceedings of 5IWSA contain 10 papers calculating synthetic seismograms (four of which directly model observed shear-wave splitting), and it is difficult to identify which of these papers is most significant for future developments.

Theory: **Crampin (1993a)** presented the arguments for distributions of microcracks (EDA-cracks) rather than large cracks or fractures as the source of the nearly ubiquitous stress-aligned shear-wave splitting seen in almost all rocks. The overwhelming evidence for microcracks is that very similar phenomena are seen at all crustal-depths in almost all rocks whose only common feature is the presence of stress-aligned fluid-saturated grain-boundary cracks, thin pores, and pore-throats. Although larger cracks clearly exist, propagation through distributions of larger cracks is likely to severely attenuate second split shear-waves, as demonstrated by **Mueller (1991),** and cause reflections and refractions but not ubiquitous shear-wave splitting. The overall conclusion is that most shear-wave splitting is caused by micro- rather than macro-cracks.

Crampin (1993b) gave a theoretical review of the effects of crack parameters on wave propagation through cracked solids. Note that there is no simple relationship between the degree of velocity anisotropy and crack density. Almost counter intuitively, the degree of velocity anisotropy and behaviour of both *P*-waves and shear-waves is *heavily dependent* on crack aspect ratios, pore-fluid velocities, and *Vs*/*Vp* ratios (Poisson's ratio), as well as crack density. This means that unique inversions for crack parameters from observations of shear-wave splitting may be difficult if not impossible without very extensive data, which is seldom, if ever, available. There were several other papers about various anisotropic phenomena, including a number of papers about preferred techniques for observing or processing appropriate record sections.

Theory - synthetic seismograms: Many 5IWSA papers calculated synthetic seismograms in cracked media with TIV-anisotropy. **Guest and Kendall (1993)** use Maslov ray theory to calculate synthetic seismograms in anisotropic and inhomogeneous structures. **Igel *et al.* (1993)** present a finite-difference grid technique which avoids problems with reflectivity (restriction to plane-layered models), ray techniques (limited heterogeneity), and finite-difference (errors in phase and group velocities). They present satisfactorily small relative errors, but do not present synthetic seismograms. **Leary *et al.* (1993)** use finite-difference calculations of synthetic trapped-wave propagation in fractured low-velocity layers.

Wild *et al.* (1993) used the ANISEIS to display instantaneous amplitude and polarisation attributes of synthetic VSPs in layered anisotropic structures (see note on ANISEIS in Section 2.4). **Yao and Xiong (1993a, 1993b)** used the reflectivity technique of Booth and Crampin (1983) to model with synthetic seismograms, respectively, radiation from an anisotropic point source, and shear-wave splitting above local earthquakes. **Zhang *et al.* (1993)** use finite-difference modelling for synthetic seismograms in TIV.

Synthetic seismograms were also used to model observed shear-wave splitting. **Gledhill (1993)** uses the reflectivity technique of Booth and Crampin (1983) through cracked structures (Hudson, 1980, 1981) to match synthetic to observed shear-wave splitting in Wellington Peninsula, New Zealand. **Liu *et al.* (1993a)** used the ANISEIS software (Taylor, 1990) to successfully match synthetic seismograms in a multi-azimuth reverse VSP in the fractured Conoco Borehole Test Facility. **Niitsuma *et al.* (1993)** used wavelet transforms to model observed shear-wave splitting in the Kakkonda geothermal area in Japan. **Slater *et al.* (1993)** used ANISEIS to successfully model the first confirmed observations of anisotropic cusps in strongly anisotropic transversely-isotropic clay.

Observation and interpretation: There were several unique observations confirming various anisotropic phenomena. **Holmes *et al.* (1993)** monitored shear-wave splitting in a nearly complete solid angle of directions in a granite batholith at an underground research laboratory. (Continuing analysis showed that excavation damage probably extended to at least three diameters from a 3m-diameter tunnel, Holmes *et al.*, 2000).

Li *et al.* (1993) continuing the analysis of **Mueller (1991)** showed that hydrocarbon production rates across the Austin Chalk, Texas, approximately correlated with degree of shear-wave splitting in reservoirs at two producing and one non-producing reservoir. This was the first direct confirmation that varying degrees of shear-wave splitting are directly correlated with variations in production.

Liu *et al.* (1993a), see above, successfully matched synthetic seismograms in a multi-azimuth reverse VSP in fractured rock, confirming the association of shear-wave splitting to both micro- and macro-fracturing.

Liu *et al.* (1993b) monitored shear-wave splitting showing temporal variations before a *M* 4 earthquake at Parkfield on the San Andrea Fault similar to those variations reported previously (Peacock *et al.*, 1988; **Crampin *et al.*, 1990**; **Booth *et al.*, 1990).** This was the fourth example of a now frequently observed phenomenon. The third example was by Gao *et al.* 1998 on Hainan Island, China.) Note that other papers at 5IWSA also sought temporal changes in shear-wave splitting above small earthquakes.

Graham and Crampin (1993) examined regional earthquakes recorded by the TDP experiments in Turkey **(Evans *et al.*, 1987)**, and showed that shear-wave splitting in *Sn*-waves, refracted along the Moho, indicate substantial crack-induced anisotropy in the lower crust with similar orientation as the upper crust but with time-delays up to 1sec.

Observation - anisotropic cusps: **Slater *et al.* (1993)**, see above, successfully modelled synthetic seismograms using ANISEIS software (Taylor, 1990) in walkaway VSPs, an oil field in the Caucasus Basin, matching the first confirmed field observations of anisotropic cusps.

2.6 6IWSA, 1994, Trondheim, Norway: Proceedings on Seismic Anisotropy, Soc. Expl. Geophys., 1996.

The Sixth International Workshop on Seismic Anisotropy, 6IWSA, was in Trondheim, Norway (Table 1). The first paper was a *geophysicist's view on seismic anisotropy* by **Lynn (1996).** The original earthquake stimulation for IWSA has now almost completely disappeared and Lynn makes no mention of earthquake seismology. The next paper was by **Helbig (1996)** who, at several of the following IWSAs, presents papers outlining the historical background to seismic anisotropy. On this occasion, it was the contribution of William Thomson, later Lord Kelvin (1824-1907), to strain and stress tensors.

There were 20 other papers. Many of these are theoretical modifications of well-known phenomena, whose overall significance is difficult to assess. They include four papers on the theoretical modelling of anisotropic matrices, seven papers modelling wave propagation through material containing aligned cracks, several papers on various record-section processing techniques, and several on rock mechanics experiments.

Theory: **Rasolofossaon and Yin (1996)** set up the equations for non-linearity (NL) in anisotropic elastic media and present rock mechanics results that suggest that the sensitivity of the NL response to changing parameters may be far greater than that of the linear parameters such as wave speeds and moduli. This sensitivity was later to be confirmed in several papers (Angerer *et al.*, 2002; **Crampin *et al.*, 2003;** Volti and Crampin, 2003b).

Observation and interpretation: There were a small number of case studies. **Horne *et al.* (1996)** devise a successful genetic algorithm (GA) technique for inverting for elastic constants for a 620m-deep VSP at the Conoco Borehole Test Facility, whose shallow structure was modelled by **Liu *et al.* (1991, 1993a)**. **Kebaili *et al.* (1996)** presented a new slant stack processing technique and successfully applied it to a shallow VSP in Alberta. **Stawicki and Lynn (1996)** investigated the effects of complex tectonic strain on multi-azimuth VSPs in the Lower Indus Basin, Pakistan. **Mjelde (1996)** interprets two air-gun reflection surveys recorded on three-component ocean bottom seismographs at Lofoten, Norway. **Mjelde** interpreted shear-wave velocities in the lower crust in terms of 14% shear-wave velocity anisotropy. This is one of the few examples, together with **Graham and Crampin (1993)** and **Kaneshima (1990)**, of estimations of lower-crustal shear-wave velocity anisotropy.

2.7 7IWSA, 1996, Miami FL, USA: Proceedings in Advances in Anisotropy, Soc. Expl. Geophys., 2001.

The Seventh International Workshop on Seismic Anisotropy was held in Miami, Florida, USA (Table 1). The meeting was typical in that there were significant contributions on a wide range of topics that are too many to mention individually.

Theory - frequency dependent anisotropy: **Hornby (2001)** finds systematic differences between 'intrinsic' anisotropy of shales at ultrasonic frequency in cores with seismic scale anisotropy in walkaway VSPs. The conclusion was that the effects of fine layering anisotropy on the seismic scale are underestimated in sonic logs from Dipole Shear Sonic Indicator (DSI) borehole sonic tool.

Observation - laboratory: **Skjærstein and Fjær (2001)** measure attenuation in the model of open fluid-saturated cracks of Rathore *et al.* (1995) which had been used to compare various theoretical models of cracks. They confirmed the theoretical result that shear waves with polarisations perpendicular to parallel cracks are more attenuated than shear waves with polarisations parallel to the crack face.

Theory - temporal changes: **Bokelmann (2001)** presents a method for resolving small temporal variations between clusters of doublets (earthquakes with similar seismograms, and hence similar source). The results show that small temporal variations are common but **Bokelmann** offers no explanation. We now know that the sensitivity of critical-systems of fluid-saturated microcracks is a probable explanation (see entries for the next three IWSAs).

Observation and interpretation: Two papers examine the effects of dipping TIV structures. **Kühnel and Li (2001)** develop a algorithm for separating anisotropy and structure from the ranking of: a first order isotropic dip term; two second-order residual terms, isotropic dip, dip-independent anisotropy; and one third-order dip- and anisotropy-dependent residual. The algorithm is usually effective except for particular orientations of the anisotropy of the matrix material, when the technique is no longer applicable. **Leslie and Lawton (2001)** propagate *P*-wave signals through an anisotropic laboratory model with structure simulating a dipping sequence of shales. Comparatively severe distortion can be interpreted in terms of anisotropic and dip parameters as long as the degree of anisotropy is not too great.

2.8 8IWSA, 1998, Boussens, France: Proceedings in Spec. Issue, Rev. Inst. Franc. Pet., 53, 1998.

The Eighth International Workshop on Seismic Anisotropy was held in Boussens, France (Table 1). Approximately half the papers were on various aspects of theory and half on processing techniques with very few case studies.

Theory: Three papers calculated synthetic seismograms including: **Caddick *et al.* (1998)**, who compared Asymptotic- with Maslov-ray theory, which give different behaviour near shear-wave singularities (note that **Crampin, 1991** gave exact full-wave behaviour near singularities); and **Chichinina and Oblentseva (1998)**, who compared waveforms in anisotropic and gyrotropic media, Gyrotropy was not specifically defined, but seems to refer to media with a continuous rotation of preferred shear-wave polarisations. Such properties have not yet been demonstrated in *in situ* rocks.

There were a number of papers presenting variations on standard procedures whose overall significance is difficult to judge. **Helbig (1998)** presents a formalism for the non-linearity suggested by **Rasolofosaon and Yin (1996)**, and **Chesnokov *et al.* (1998)** developed a diagrammatic technique for the calculation of the dynamic properties, including the frequency response, of propagation through randomly distributed cracks and pores.

Observation: **Berthet *et al.* (1998)** showed that imaging dipping structures was improved by anisotropic rather than isotropic post-stack processing. They demonstrated the improvement in a record section from offshore Africa.

Interpretation: **Raymer and Kendall (1998)** showed synthetic seismograms through models containing salt, with anisotropic properties determined from laboratory texture analysis. They demonstrated that the anisotropy of salt produced substantial travel-time variations and significant shear-wave splitting that could be diagnostic of *in situ* salt.

Li (1998), assuming fracture-induced anisotropy, showed that near-vertically propagating converted *PS*-waves can indicate the orientation and intensity of *in situ* fractures. These effects were demonstrated with synthetic (ANISEIS) seismograms showing phase changes and variations in time-delays.

Interpretation - critical-systems: **Crampin (1998)** first suggests that the match of anisotropic poro-elasticity (APE) modelling (Zatsepin and Crampin, 1997; Crampin and

Zatsepin 1997) to observed shear-wave splitting implies that the fluid-saturated stress-aligned microcracks in most rocks in the crust are so closely-spaced that they are critical systems. This is supported by a large variety of observations relating to cracks, stress, and shear-wave splitting.

2.9 9IWSA, 2000, Camp Allen TX, USA: Proceedings in Anisotropy 2000, Soc. Expl. Geophys., 2001.

The Ninth International Workshop on Seismic Anisotropy was held in Camp Allen, Houston, Texas (Table 1). There was a historical review of the contribution of Maurice P. Rudzki (1862-1916) to seismic anisotropy, and a translation of Rudzki's paper on Fermat's Principle.

Theory: **Rommel and Tsvankin (2001)** develop a simple analytical approach for group- and phase-velocity relationships for rays of *P*-waves in TIV and orthorhombic media, based on the notation of Tsvankin (1996) for the Thomsen (1986) parameters applied to orthorhombic media. **Helbig and Rasolofosaon (2001),** continuing the ideas of **Rasolofosaon and Yin (1996),** develop a formalism for incorporating non-linearity and hysteresis into a "unifying theory". **Garmany (2001)** shows that phase shifts (90°-flips) in shear-wave polarisations occur whenever a ray touches a caustic surface (or passes near a shear-wave singularity as demonstrated with synthetic seismograms by **Crampin, 1991**).

Theory - AVOs and fractures: There eight papers dealing with various aspects of processing Amplitude Variations with Offset (AVOs) of models with anisotropic layered structure containing fractures. All seem useful, but space restrictions will limit comments to three papers. **Ikelle and Amundsen (2001)** present preliminary techniques for interpreting *P-P*, *P-SV*, and *P-SH* data with the ambiguity of TIV-anisotropy and heterogeneity. Since anisotropy and heterogeneity may always be present in AVOs, these techniques could be important discriminants**.** **Liu *et al.* (2001)** present techniques for extracting information about crack compliance and pore-fluid parameters from AVO analysis. Using synthetic seismograms **Liu *et al.* (2001)** show that the combined use of *P-P* and *P-SV* AVOs offers advantages in determining fractures and fluid saturations.

Observation - case studies: There were two case studies. **Granger *et al.* (2001)** use the shear-wave splitting of *P*-to-*S*-converted waves (*C*-waves) recorded on 3D-4C ocean bottom geophones to make a preliminary evaluation of azimuthal anisotropy of the North-Sea Valhall Field. Results show that principal directions coincide with fault systems at two levels, from this feasibility demonstration, but the authors do not attempt any interpretive conclusions. **Berthet *et al.* (2001)** apply anisotropic prestack depth migration to offshore data in West Africa. The technique shows sufficient sensitivity that it can be used as a lithology-discriminant to detect isotropic sands of a few wavelengths thickness.

Interpretation - processing TIV media: Five papers described various techniques for processing TIV media. **Williamson and Maocec (2001)** estimated local anisotropy using polarisations and travel times from the Oseberg 3D VSP. They achieve better determination of anisotropy by inverting polarisations than by standard slowness inversion.

Interpretation - critical-systems: **Crampin and Chastin (2001)** claim that three recent results support the arguments of **Crampin (1998)** that the stress-aligned fluid-saturated microcracks in almost all rocks are so closely spaced that they are critical systems. These results are modelling the response of a reservoir to a high-pressure fluid-injection (published later in Angerer *et al.,* 2002), modelling frequency dispersion in laboratory experiments (published later in Chapman *et al.,* 2002); and a successfully stress-forecast earthquake (Crampin *et al.,* 1999). It is suggested that critical-systems of stress-aligned fluid-saturated microcracks are the physical reality underlying the well-known self-organised criticality of the Gutenberg and Richter relationship and have a profound effect on a wide range of solid earth geoscience including carbon production and earthquake science.

2.10 10IWSA, 2002, Tutzing, Germany: Proceedings in Spec. Issue, J. Appl. Geophys., 54, 2003.

The Tenth International Workshop on Seismic Anisotropy, 10IWSA, 2002, was in Tutzing, Germany (Table 1). There were two further translations of papers by Rudzki on seismic anisotropy. There were too many useful papers at this meeting to refer to each individually.

Theory - shear-wave triplication: **Thomsen and Dellinger (2003)** discuss analytically the occurrence of cusps and shear-wave triplications and suggest that *P*-wave kinematics suggest that cusps in the *SV*-wave sheet in TIV-anisotropy are common. Although such triplications have been observed in a wide-angle VSP **(Slater *et al.*, 1993)**, the angles of incidence at which cusps would be seen are further from the vertical than *P*-to-*S* converted waves (*C*-waves) would typically sample in surface seismic surveys.

Theory and observation - frequency-dependent anisotropy: **Gurevich (2003**) developed the mathematics for the elastic properties of saturated porous rock with aligned cracks. Wave-induced fluid-flow between pores and cracks in rock with parallel cracks is shown to alter the elastic behaviour for low-frequency waves. **Chapman *et al.* (2003)** showed that the movement of fluids between cracks and pore-space strongly alters the anisotropic behaviour, where a simplified model matched laboratory data. In particular, the analysis showed the effects are frequency dependent. **Li and Yuan (2003)** derive improved equations for calculating the moveout and conversion points of the non-hyperbolic *C*-waves. Comparison of analysis with real data shows that the technique is sufficiently accurate to yield reliable structures. **Liu *et al.* (2003)** observed and interpreted frequency-dependent anisotropy in terms of variations of time-delays with depth in different frequency pass-bands. The anisotropy diminished from 2.8% at 10Hz to 2% at 25Hz.

Observation and interpretation: **Gao and Crampin (2003)** reported the temporal variations of shear-wave splitting in field and laboratory studies in China, which show changes of shear-wave splitting with increasing pressure. The laboratory experiments show an abrupt decrease in time-delays immediately before fracturing occurs. This stress-relaxation is also observed before earthquakes (Gao and Crampin, 2004), where is now interpreted as the effects of crack coalescence as the impending fracture is identified.

Observation and interpretation - critical system sensitivity: **Crampin *et al.* (2003)** (see also Crampin, 2004) reported preliminary results from a prototype borehole Stress-Monitoring Site (SMS) adjacent to the Húsavík-Flatey Transform Fault in northern Iceland. Well-recorded anomalies (accurate to ±0.02ms) in *P*-, *SH*-, *SV*-travel times, and shear-wave splitting (*SV – SH* travel times) correlated with low-level seismicity (equivalent energy to one *mb* = 3.5 earthquake) at 70km-distance. This exceptional sensitivity (in layered-basalts), at hundreds of times the likely source dimensions, confirms the criticality of the fluid-saturated microcracks in the crust advocated by **Crampin (1998)** and **Crampin and Chastin (2001)**. **Crampin *et al.* (2003)** also reported 90°-flips in shear-wave polarisations caused by critically-high pore-fluid pressures on all seismically-active faults (Crampin *et al.* 2002). These 90°-flips are the cause of the large (±80%) scatter in shear-wave splitting time-delays (Crampin *et al.*, 2004) always observed above small earthquakes **(Crampin *et al.*, 1990; Booth *et al.*, 1990)**.

2.11 11IWSA, 2004, St. Johns, Newfoundland, Canada: No published Proceedings, but Abstracts in Geophysics, in press, 2005.

The Eleventh International Workshop on Seismic Anisotropy, 11IWSA, was in St John’s, Newfoundland, Canada (Table 1). The historical paper was about George Green (1793-1841) who defined Green’s theorem.

The majority of the abstracts at 11IWSA were theoretical and appear to modifications of well-known phenomena. At this time, it is difficult to judge their future relevance.

Theory - frequency dependent anisotropy: **Vikhorev *et al.* (2005)** suggest that different scales of inhomogeneities can cause differences between the values of anisotropy in ‘sonic-waves’ (~20kHz) and ‘seismic-waves’ (5-10Hz).

Theory - wave propagation in viscoelastic media: **Cervený and Pšencík (2005a)** investigate the properties of plane waves in viscoelastic anisotropic media by specifying the attenuation by complex values of the slowness vector. Note that the use of complex quantities for modelling attenuation was first suggested by Crampin (1981), and ANISEIS routinely uses complex quantities to model full-wave synthetic seismograms in multi-layered attenuating media (**Taylor, 1990**). In some ways, complex constants may be a more natural way to specify attenuating media, as the one complex specification avoids the complications of the complex slowness of **Cervený and Pšencík (2005a,** 2005b**).**

Theory - wave propagation in penny-shaped cracks - a necessary correction: **Grechka (2005)** uses finite element modelling to determine Thomsen parameters for media with parallel cracks and shows results that are diverge from those of Hudson (1980), particularly for crack densities greater than 0.05. **Grechka** attributes the divergence to the first-order theory of Hudson (1980, 1981) not treating crack-to-crack interactions. This is not surprising. Hudson (1980, 1981) *is a* first-order theory. The second-order theory of Hudson (1986) correctly models crack-to-crack interactions. **Grechka** also claims that “conventional wisdom” suggests Hudson’s “first-order results are correct up to crack densities ˜ 0.1”. Crack densities in stable rock are limited to *less than* the fracture criticality of ~0.05 (Crampin, 1994, 1999). (The exact vary may vary slightly with different matrix Poisson’s ratios). This is not a question of formula derivation or mathematical modelling. The physical reality of crack densities of aligned cracks higher than ~0.05 is that the rock is so heavily fractured that it is without shear-strength and is physically unstable. Hudson’s (1980, 1981, 1986) formula are valid for parallel cracks with crack-to-crack interactions in stable rock for crack densities less than the physical limitation of ~0.05.

Observation - CO_2-injections: **Jenner (2005)** investigates the effects of injecting high-pressure CO_2 at 10-14MPa on the anisotropic behaviour of *P*-waves in a reservoir at the Weyburn Field, Saskatchewan, Canada and finds that there is no “seismically discernible change in anisotropy”. Note that Angerer *et al.* (2002), who found substantial changes in shear-wave anisotropy for similar high-pressure CO_2-injections, also found negligible changes in *P*-wave signals. Theory and observations suggest that the principle effect of changing pressures is to modify crack aspect-ratios (Crampin 1999), which modify shear-wave splitting. Nearly vertically-propagating *P*-waves are not very sensitive to aspect-ratios of nearly vertically-aligned cracks. This confirms that shear-wave splitting is the most sensitive phenomenon for time-lapse monitoring of small changes in conditions.

Interpretation - GEMS, the opportunity for a global network of borehole stress-monitoring sites to forecast all damaging earthquakes worldwide. **Crampin *et al.* (2005)** suggest that the sensitivity of the prototype borehole stress-monitor site (**Crampin *et al.*, 2003)** indicates that a global network of (both onshore and offshore) borehole SMSs, on a 400km-grid in seismic areas and a 1000km-grid elsewhere, would be able to forecast all damaging (M = 5) worldwide.

3 Discussion

There have been some 250 papers published in the proceedings of the IWSAs. This review cites papers which are believed to be significant for the continuing development of shear-wave splitting and seismic anisotropy, usually because they were first observations, first analyses, or part of continuing developments. With ten or more years' hindsight, one can recognise the significant papers. Recent papers tend to be smaller advances over broader fronts, whose significance is more difficult to assess. Consequently, this review is necessarily a rather subjective selection, and there are many excellent papers in the proceedings that are too numerous to cite individually, and we beg forgiveness of those authors whose papers have been omitted.

The significant advances are summarised in Table 2. Each IWSA tends to be unique with the principle subject matter changing from one workshop to the next. Almost all significant developments in shear-wave splitting have appeared in IWSA proceedings, and most of the few omitted papers have been cited in this review. One of the principle benefits of IWSA workshops has been that all the major research workers in anisotropy have known (and trusted) each other. Consequently, workshops have been comparatively open, so that most impending developments have been immediately known to the whole research community of '*anisotropists*'. This has meant that frequently, without prior consultation, several, sometimes many, people work on similar topics, so that IWSA meetings often have a dominating topic of research. This has no doubt contributed to the comparatively rapid advance, which has taken anisotropy, particularly shear-wave splitting, from the first occasional observations in the crust, to observations worldwide, to an understanding of fluid-rock deformation in a critical system of closely-spaced fluid-saturated microcracks in almost all rocks in the crust.

Note that the Society of Exploration Geophysicists has promoted much of the research in seismic anisotropy and shear-wave splitting. Its own annual meetings have had many sessions on anisotropy. It has sponsored several IWSAs, and has published proceedings or abstracts of several IWSAs (Table 1). SEG awarded Virgil Kauffman Gold Medals for research in anisotropy (Stuart Crampin, 1988; Rusty Alford, 1990; and Ilya Tsvankin, 1996). Leon Thomsen (2002) presented a Distinguished Short Course on anisotropy, and Heloise B. Lynn (2004) was Distinguished Lecturer on anisotropy.

Note also that Joe Dellinger, of BP maintains an Internet email address where information can be posted on an Anisotropists Digest list. This greatly aids communication between 'anisotropists'. One registers at <anisotropists-request@freeusp.org>.

4 Conclusions on shear-wave splitting

IWSAs have reported observations of, particularly shear-wave splitting, with very similar characteristics over an enormous range of frequencies from the upper mantle (0.1-2.0Hz), above crustal earthquakes (2-20Hz), reflection seismology (10-80Hz), VSPs (10-200Hz), sonic logs (kHz), and laboratory measurements (mHz). Since such universality and calculability are all characteristics of critical systems (Bruce and Wallace, 1989), these are direct evidence for the critical systems of fluid-saturated cracks as extensive all-embracing phenomena (Crampin and Chastin, 2001; Crampin *et al.*, 2003).

As **Vikhorev *et al.* (2005)** suggested, this clearly covers an enormous range of lineament dimensions, and indeed, as Heffer and Bevan (1990) observed, the frequency and lengths of microcracks, cracks, fractures, faults, and lineaments are self-similar over some ten orders-of-magnitude. This is related to the other outstanding self-similar distribution in geophysics, the Gutenberg-Richter relationship between frequency and magnitude of earthquakes, over some eight orders-of-magnitude. For the first time we can recognise that the deformation of fluid-saturated cracks is the physical reality underlying the Gutenberg-Richter relationship.

In the earth there is a continuum of all scales of ordered heterogeneities, from 0.001mm of microcracks to 100s of km plate boundaries in critical systems. The implications of critical systems are that low-level deformation before fracturing takes place: can be *monitored* with shear-wave splitting, future behaviour *calculated* by APE, even *predicted* if changing conditions are known, as in Angerer *et al.* 2002), and in some circumstances future behaviour potentially *controlled* by feedback (Crampin and Chastin, 2001). If correct, and the series of IWSAs reported in this review suggests overwhelming supporting evidence, this is a fundamental advance in understanding fluid-rock (pre-fracturing) deformation in solid Earth geoscience.

A large proportion of papers by exploration seismologists presented at IWSAs have been about observing, processing and calculating the effects of anisotropy and shear-wave splitting, with much of the emphasis how anisotropy effects conventional isotropic processing: how conventional processing for structure and stratigraphy is affected by anisotropy. We suggest that the *implications* of shear-wave anisotropy for fluid-rock interaction are important for hydrocarbon production, as well as almost all solid earth geoscience, by they affect fluid-rock deformation.

Appendix: *How IWSAs began*

Evgeni Chesnokov and Stuart Crampin, in a casual conversation over a vodka-fuelled dinner during a three-months' collaboration in Moscow in the winter of 1979-1980, speculated on the need for an international workshop on seismic anisotropy to discuss and publicise our ideas. In those days, anisotropy needed encouragement. Several well-known geophysicists (who shall be nameless) poured scorn on the very idea of widespread stress-aligned anisotropy in the Earth. We needed to gather support to show we were not wasting our time. One of us (EMC) happened to mention this idle speculation to Academician V. A. Magnitsky, who immediately lent his authority to the idea, and the first workshop was on its way. Organised by Chesnokov, Crampin, and Magnitsky, the first IWSA was in 1982 in the beautiful ancient city of Suzdal, USSR.

The workshop happened to be in the right place at the right time. Shear-wave splitting had just been reported in the crust and upper mantle (both as it happens in the same 1980 volume of *Nature*), and there was more general interest in anisotropy in USSR than elsewhere at that time.

1IWSA set the pattern for future IWSAs. IWSAs tend to be comparatively small (less than 100 participants) and single session; tend to be in interesting and memorable places; and tend, after 2IWSA, to alternate across the Atlantic (and in the future the Pacific). IWSAs are from Monday to Friday, with Wednesday set aside for the usually-cultural excursions. These excursions are important, since many of the most productive ideas, as with the original idea for IWSA, come from casual exchanges away from lecture rooms.

The first IWSA, in 1982, was a resounding success and seemed worth continuing, so the next meeting was arranged four years hence in Moscow, 1986. This gap set another pattern. After 2IWA, biennial meetings were established. IWSAs are not repeated unless there is sufficient enthusiasm amongst participants at one meeting to organise the next in two years time. Thus IWSA meetings have an in-built quality assurance. When enthusiasm flags, IWSAs will immediately fold, which will be a right and proper finale to what has been a very productive and rewarding series of meetings.

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(Papers from proceedings of IWSA workshops have authors and years in **bold** type face.)

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Table 1. The International Workshops on Seismic Anisotropy.

ID	Year	Place	Organisers	Sponsors	Proceedings	No. of papers	No. of pages	Editors
0IWSA	1975	Paris	Bamford, D.	IFP, IASPEI	1977 *Geophys. J. R. Astron. Soc.*, 49, 1-243.	14	243	Bamford, D.
1IWSA	1982	Suzdal, USSR	Magnitsky, V.A., Chesnokov, E.M., and Crampin, S.	Acad. Sci. USSR, IASPEI,, and UNESCO	1984. *Geophys. J. R. Astron. Soc.*, 76, 1-272.	28	272	Crampin, S., Hipkin, R.G.,, and Chesnokov, E.M.
2IWSA	1986	Moscow, USSR	Magnitsky, V.A., Chesnokov, E.M., and Crampin, S.	Acad. Sci. USSR, Amoco, IASPEI,, and UNESCO	1987. *Geophys. J. R. Astron. Soc.*, 78, 261-554.	30	293	Booth, D.C., Crampin, S., and Chesnokov, E.M.
3IWSA	1988	Berkeley, CA, USA	Leary, P.C., Crampin, S., and McEvilly, T.V.	AGU, Amoco, Arco, Chapman Conference, Exxon, SEG, Shell, Unocal,, andWestern Atlas	1990. *Journal of Geophysical Research,* 95, 11,105-11,358.	30	253	Leary, P.C., Crampin, S., and McEvilly, T.V.
4IWSA	1990	Edinburgh, UK	Crampin, S., and Lovell, J.H.	Amoco, Arco, BGS, CGG, Conoco, EAP, Exxon, PSTI, Schlumberger, Western Atlas	1991. *Geophysical Journal International,* 107, 385-714.	30	329	Crampin, S., and Lovell, J.H.
5IWSA	1992	Banff, Canada	Brown, R.J., and Lawton, D.C.	Amoco, Arco, Chevron, Conoco, CREWES, CSPG, Gulf, NSERC, Schlumberger, Shell, Western Atlas	1993. *Can. J. Expl. Geophys.*, 29, 1-390.	35	390	Brown, R.J., and Lawton, D.C.
6IWSA	1994	Trondheim, Norway	Fjær, E., Holt, R.M., and Rathore, J.S.	Amoco, Elf, Norsk Hydro, Saga, Statoil,	1996. *Seismic Anisotropy, Soc. Expl. Geophys.*, 1-763.	22	763	Fjær, E., Holt, R.M., and Rathore, J.S.
7IWSA	1996	Miami, FL, USA	Berge, P., Cheng, A.H, Hood, J.A., Lynn, H.B., Schoenberg, M.	Amoco, Chevron, Conoco, Schlumberger, Western Atlas	2001. *Advances in Anisotropy: Selected Theory, Modeling, and Case Studies, Soc. Expl. Geophys., Open File Publ. 5,* 1-322.	18	322	Hood, J.A.
8IWSA	1998	Boussens, France	Arnaud, J., Helbig, K., Rasolofosaon, P., and Thomsen, L.	Amoco, Arco, CGG, Chevron, Elf, Geco-Prakla, IFP	1998. *Spec. Issue, Rev. Inst. Franc. Pet.*, 53, 539-763.	26	224	Rasolofosaon, P.
9IWSA	2000	Camp Allen, Houston, TX, USA	Arnaud, J., Dellinger, J., Ikelle, L., Lynn, H., MacBeth, C., Thomsen L. and Tsvankin, I.	BP, Sclumberger, Texas AandM University, Total-Elf	2001. *Anisotropy 2000: Fractures, Converted Waves, and Case Studies, Soc. Expl. Geophys., Open File Publ. 6,* 1-425.	25	425	Ikelle, L.T., and Gangi, A.
10IWSA	2002	Tutzing, Germany	Gajewski, D., Vannelle, C., anc Pšencík, I.	BP, EAGE, IASPEI, PGS, RWE-DEA, Statoil, TotalFinaElf, Veritas, WIT	2003. *Spec. Issue, J. Appl. Geophys.*, 54, 161-454.	23	293	Gajewski, D., Vanelle, C.,, and Pšencík, I.
11IWSA	2004	St John’s, Newfoundland, Canada	Bona, A., Brown, R. J., Harris, J. J. Helbig, K., Kendall, R., Pšencík, I., Slawinski, M., and Tsvankin, I.	BP, Input/Output, Veritas	2005 Abstracts in *Geophysics*, in press.	Abstracts 43	in press	Grechka, V., Helbig, K., and Pšencík, I.
12WSA	2006	Beijing, China	See: http://www.eap.bgs.ac.uk/12IWSA					

Table 2. Summary of significant advances in seismic anisotropy at IWSA meetings.

ID	Year of IWSA	Year of Proceed-ings	Significant advances
			0IWSA – 3IWSA: Principally earthquake seismology
0IWSA	1975	1977	Synthetic seismograms in anisotropic layered models **(Keith and Crampin, 1977a, b, c)**. Anisotropy observed in Upper Mantle from *Pn*-wave velocity anisotropy beneath both oceans (Hess, 1964)] and continents **(Bamford, 1977)**. Anisotropy observed Crampin, 1966) and calculated in higher-mode surface-wave dispersion **(Crampin, and King, 1977)**. Shear-wave splitting first named (as *S-wave splitting*) and displayed in synthetic seismograms **(Keith, and Crampin, 1977c)**.
1IWSA	1982	1984	Observations of *P*-wave velocity anisotropy in field and laboratory **(Artemieva, and Chesnokov, 1991; Brodov et al., 1991; Brown et al., 1991; de Parscau, 1991; MacBeth, 1991a, 1991b)..** Elastic constants calculated for aligned cracks (Crampin, 1978, 1984b). Importance of shear-wave window above small earthquakes recognised **(Evans, 1984)**. Aligned microcracks (EDA-cracks) suggested in most crustal rocks **(Crampin *et al.*, 1984b)**. General behaviour of wave propagation in cracked media established (Crampin, 1981). Shear-wave splitting displayed in synthetic seismograms through cracked media (Crampin, 1978). Shear-wave splitting observed above earthquakes in both crust (Crampin *et al.,* 1980), and mantle (Ando *et al.,* 1980).
2IWSA	1986	1987	Observations of P-wave anisotropy in crust **(Leary et al., 1987; Li et al., 1987; Galperina and Galperin, 1987).** Speculation on how monitoring shear-wave splitting could predict earthquakes **(Chen *et al.*, 1987)**. Determination of the *Thomsen parameters* for seismic exploration (Thomsen, 1986). Double-contour integration for 3D full-wave-propagation in anisotropic substrates **(Taylor, 1987)**.
3IWSA	1988	1990	Observations of anisotropy in laboratory studies in both field and laboratory **(Kaneshima, 1990; Li et al., 1990; Savage et al., 1990; Shih and Meyer, 1990)**. First attempts at automatic measurement of shear-wave splitting **(Shih and Meyer, 1990)**. First correlation of microcracks with fractures and directions of preferred fluid flow (**Queen and Rizer, 1990)**. Shear-wave splitting time-delays seen to increase before two earthquakes **(Booth *et al.*, 1990; Crampin *et al.*, 1990)**. ANISEIS program developed for applying double-contour integration for full-wave synthetic seismograms through anisotropic layered models (Taylor, 1990).

Table 2. Continued.

			4IWSA – 12IWSA: Principally exploration seismology
4IWSA	1990	1991	First ten years of shear-wave splitting reviewed **(Crampin, *and* Lovell 1991)**. Review of theory of wave propagation in aligned cracks **(Hudson 1991)**. Shear-wave singularities: identified in cracked TIV-anisotropy **(Wild, and Crampin 1991)**; Synthetic seismograms of shear-wave singularities show 90º-flips and amplitude anomalies **(Crampin 1991)**; Effects of shear-wave singularities observed and modelled in VSP in the field **(Bush, and Crampin 1991)**. Many papers on observations of *P*-wave velocity anisotropy and shear-wave splitting. Shear-wave splitting used to guide horizontal drilling into heavily-fractured rock **(Mueller 1991)**. Linear-Transform Technique developed for processing anisotropic record sections **(Li, and Crampin 1991a, b)**.
5IWSA	1992	1992	Microcracks rather than macro-fractures suggested as source of shear-wave splitting **(Crampin 1993a)**. Effects of aligned cracks reviewed for a range of parameters **(Crampin 1993b)**. Many techniques for calculating synthetic seismograms presented **(Guest, and Kendall 1993; Igel *et al.* 1993; Leary *et al.* 1993; Wild *et al.* 1993; Yao, and Xiong 1993a, 1993b; Zhang *et al.* 1993)** Correlation of degree of shear-wave splitting and hydrocarbon production **(Li *et al.* 1993)** and **(Liu *et al.* 1993a)**. Anisotropic cusps observed in walk-away VSP and modelled with synthetic seismograms **(Slater *et al.* (1993)**.
6IWSA	1994	1996	Historical background of Lord Kelvin **(Helbig 1996)**. A number of case studies were presented **(Horne *et al.* 1996; Kebaili *et al.* 1996; Stawicki and Lynn 1996; Mjelde 1996)**. Non-linear response of shear-wave splitting more sensitive to near negligible changes than conventional wave speeds and moduli **(Rasolofossaon and Yin 1996)**.
7IWSA	1996	2001	Frequency-dependent anisotropy: systematic differences between intrinsic anisotropy of shales in cores at ultrasonic frequencies and walkaway VSPs **(Hornby 2001)**. Various theoretical and experimental papers.
8IWSA	1998	1998	Papers on theoretical wave propagation **(Helbig 1998; Chesnokov *et al.* 1998)** and processing techniques **(Raymer and Kendall 1998; Li 1998)**. Closely-spaced cracks forming critical systems first proposed **(Crampin 1998)**.
9IWSA	2000	2001	Many papers on amplitude variation with offset (AVO) **(Ikelle and Amundsen 2001; Liu *et al.* 2001)** and *P*-to-*S* converted *C*-waves **(Granger *et al.* 2001)**. Many papers on processing TIV media. Time, magnitude, and fault of *M*5 in SW Iceland stress-forecast (Crampin *et al.* 1999). Supporting evidence for closely spaced cracks as critical-systems **(Crampin and Chastin 2001)**.
10IWSA	2002	2003	Theory and observation of frequency-dependent anisotropy **(Chapman *et al.* 2003; Gurevich 2003; Li and Yuan 2003; Liu *et al.* 2003)**. Evidence for critical-systems from sensitivity of prototype borehole Stress-Monitoring Site (SMSs) **(Crampin *et al.* 2003)**.
11IWSA	2004	in press	The sensitivity of the prototype SMS suggests that GEMS, a global network of SMSs, presents the opportunity to forecast all damaging earthquakes worldwide.

Ikelle and Amundsen (2001) ***present preliminary techniques for interpreting*** **P-P, P-SV,** ***and*** **P-SH** ***data with the ambiguity of TIV-anisotropy and heterogeneity. Since anisotropy and heterogeneity may always be present in AVOs, these techniques could be important discriminants***. *Liu* et al. *(2001)* ***present techniques for extracting information about crack compliance and pore-fluid parameters from AVO analysis. Using synthetic seismograms*** *Liu* et al. *(2001)*