The potential of shear-wave VSPs for monitoring recovery: A letter to management

By STUART CRAMPIN
British Geological Survey
Edinburgh, Scotland

Much of the ultimate success (or failure) of hydrocarbon recovery depends on the assessment, usually implicit, of the internal crack-, pore-, and stress-geometry, and pore fluids of the reservoir rock. It also depends on the estimation (again usually implicit) of the changes to these quantities as the secondary and tertiary production or enhanced oil recovery (EOR) proceeds. At present, we are able to recover only a small proportion of the oil in a reservoir. Amos Nur wrote in *TLE* (September 1989): "The most obvious way to significantly improve recovery...is to obtain much better descriptions of the internal structure..." Recent advances in seismology, reported at the SEG Research Workshop on Recording and Processing Vector Wave Field Data (Snowbird, Utah, August 1989), have shown that many details of this internal structure may be monitored in situ by appropriate shear-wave (three-component) VSPs.

The behavior of shear waves is very sensitive to the internal structure of the rock through which they pass and particularly sensitive to changes in crack- and pore-geometry caused by changes in pore pressure, changes in pore-fluid properties, and changes in stress, and other phenomena affecting either the inclusions or the rock mass. Thus, shear waves provide a possible opportunity for monitoring changes to the rock mass by analyzing VSPs, repeated as often as necessary to maintain detailed surveillance. In the future, this is likely to be an important advance for reservoir management as it allows many of the effects of secondary and tertiary production and EOR on the reservoir rocks to be monitored as often as is required by established geophysical techniques.

The great advantage of VSPs over recordings taken at the surface is that in VSPs the geophones can be sited in the zone of interest, the reservoir. Since records of shear waves are most sensitive to the rocks immediately surrounding the geophones, data from VSPs display the effects on the reservoir most clearly. They are not contaminated by the "noise" introduced by the intervening layers, particularly by the low-velocity layers near the surface which may cause severe disturbances to *P* waves and, particularly, shear waves when both source and geophone are on the surface as in more conventional seismic reflection surveys.

(It might be thought that crosshole techniques where both source and geophones are in wells within the reservoir would offer good prospects for monitoring the behavior of EDA-cracks in the reservoir. Perhaps surprisingly, Liu et al. have shown that the geometry of crosshole observations, with shear waves propagating nearly horizontally, is not really appropriate for monitoring shear-wave splitting. However, analyzing channel waves, which propagate along interfaces where there is some change of seismic velocities—as happens throughout most sedimentary reservoirs—offers some promise for recognizing small changes to the reservoir rock and is currently being investigated.)

Two types of seismic wave propagate through rock: a faster *P* wave with particles vibrating parallel to the raypath (like sound waves) and a slower shear wave with particles vibrating at right angles to the raypath. Figure 1 shows schematically the transverse polarizations of shear waves propagating through a uniform isotropic (structureless) rock, where the polarization of the shear wave is determined by the source. In the past, most seismic investigations have used the traveltimes of *P* waves to identify and characterize (isotropic, structureless) layering, but *P* waves are not very sensitive to the internal structure of stress-aligned fluid-filled microinclusions within the rock mass. In the past I have shown that the transverse vibrations of shear waves contain three or four times more information about the raypath than *P* waves. In particular, shear waves are very sensitive to the properties of the rock through which they pass. When recorded on three-component instruments, they yield unique information about the rock's internal structure. Figure 2 contrasts the behavior of shear waves in rocks having an internal anisotropic structure with the isotropic structureless model in Figure 1.

Recent observations of shear waves propagating along *most* raypaths in *most* rocks in the uppermost 50 000 ft of the crust display the phenomena of shear-wave splitting indicated schematically in Figure 2. Seismic shear-wave splitting is similar to the optical birefringence observed in mineral specimens. This splitting in the crust is caused by propagation through the internal structure of fluid-filled cracks, microcracks, and pore space known to exist in most rocks. These fluid-filled inclusions are the softest, most compliant elements of the rock mass. Consequently, the inclusions respond very readily to stress and are aligned by the stress (just like hydraulic fractures) perpendicular to the direction of minimum compressional stress. At depth, the inclusions are usually aligned vertically, parallel to the direction of local compressional stress (again like hydraulic fractures), and can be modeled by distributions of parallel vertical fluid-filled microcracks.

These distributions of aligned inclusions are known as extensive dilatancy anisotropy (EDA)—*extensive*, as it exists nearly everywhere; *dilatancy*, as the cracks are open giving the porosity; and *anisotropy*, as the effects vary with direction. The inclusions themselves are known as EDA-cracks, although it is recognized that they may often be oriented pores rather than flat cracks. Figure 2 is a schematic illustration of shear-wave splitting in EDA-cracks and shows the remarkable feature that the polarization of the faster split shear wave is parallel to the strike of the EDA-cracks and parallel to the direction of compressional stress (the delay between the split shear waves is proportional to the crack density). Such splitting is observed almost everywhere in the crust, and the behavior of the splitting displayed in three-component seismograms can be interpreted in terms of the detailed internal structure of aligned inclusions in the rock mass.

These EDA-cracks, seen by shear waves, are the preferentially aligned elements of the porosity. Thus EDA-cracks are usually small—with dimensions typically ranging from submillimeter in sedimentary rocks to possibly a few microns (millionths of a meter) in igneous and metamorphic rocks. Their small size and fluid content make EDA-cracks very responsive to *changes* in rock and pore conditions; such changes in the crack geometry in turn *modify* the behavior of shear waves propagating through the cracked rock. The great sensitivity of shear waves to changes in crack geometry and the sensitivity of the EDA-cracks to

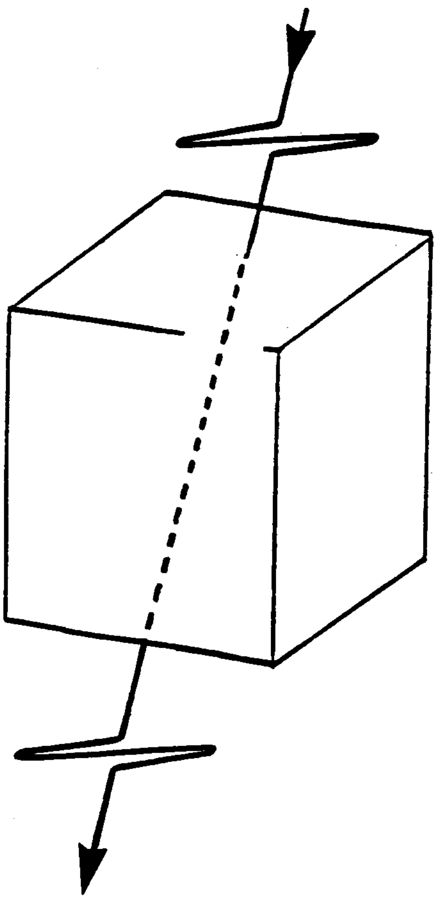

Figure 1. Schematic illustration of shear-wave propagation through (hypothetical) isotropic rock without an internal structure.

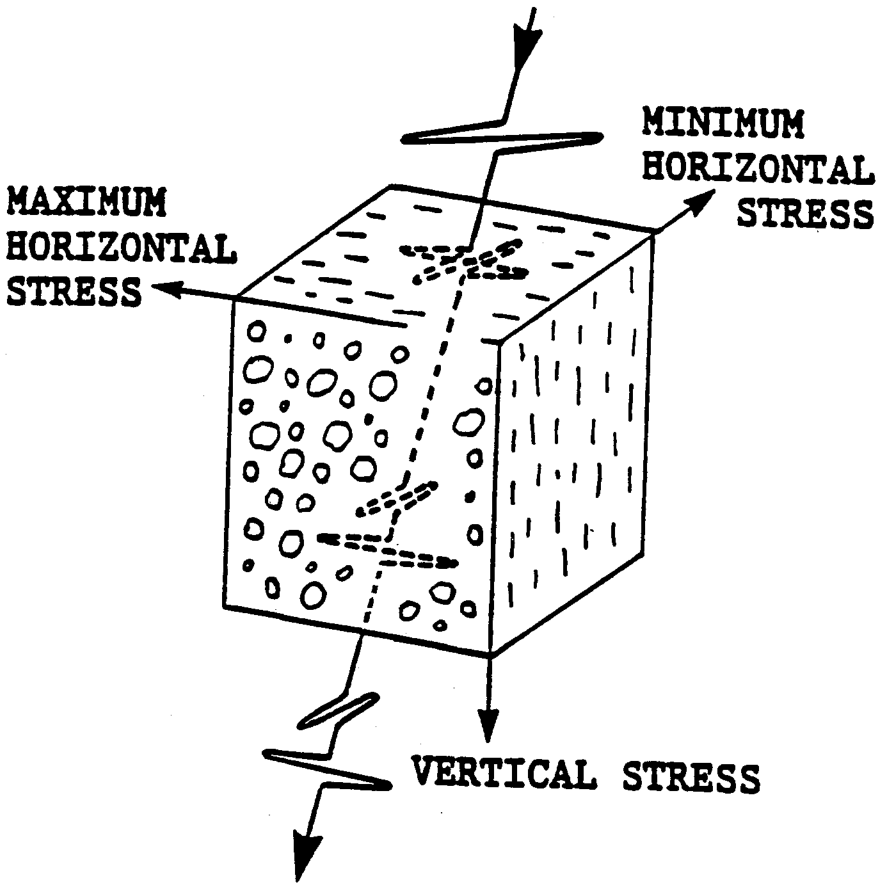

Figure 2. Schematic illustration of shear-wave splitting in real rock containing stress-aligned fluid-filled microinclusions (EDA-cracks). Shear waves necessarily split, with the polarization parallel to the crack faces traveling faster and less attenuated than the polarization perpendicular to the crack faces.

changing crack conditions have important implications for reservoir management. It means that conditions in the internal in-situ structure of the reservoir can be monitored by shear-wave VSPs, repeated as often as necessary during production and EOR.

All these results are very recent. Until a few years ago, neither the recording technology nor the understanding of shear-wave propagation could cope with the precision required. Consequently, we are right at the beginning of these investigations. However, it is clear that there are potentially very important opportunities and implications.

- Increasing pore pressure or stress is likely to increase the aspect ratio of the microcracks (make the cracks "bow" elastically), as happens in stressed samples in the laboratory. Examples of such changes in the field are reports by Peacock et al., Crampin et al., and Booth et al. of appropriate changes in shear-wave splitting before and after earthquakes, which can be modeled by stress-induced changes to EDA-cracks. Changes in the stress direction will alter the orientations of EDA-cracks, and Booth and I reported changes in polarization of shear-wave splitting, before and after hydraulic pumping in a hot dry rock geothermal reservoir, which can be interpreted in this way.
- Any change in the pore fluid properties, such as the marked decrease in velocity of heavy-oil saturated rocks with temperature during steam flooding (first noted by Nur, with Tosaya, in 1984), will also modify the seismic behavior. This was demonstrated during heat treatment by Justice et al. (*TLE*, February 1989) in model and field studies in a heavy oil reservoir by crosshole seismic tomography (source in one hole and recorders in another) and by de Buyl in (surface-to-surface) seismic reflection surveys over an oil-producing sand. Both studies used *P* waves as the seismic signal. Shear waves contain more information and can be interpreted more accurately, so shear-wave VSPs could offer real precision in monitoring EOR.

Theoretical investigations suggest many other possibilities. Changing the proportion of gas to liquid in the reservoir or replacing oil by water are likely to alter the seismic response, particularly the attenuation of shear waves in the reservoir, which can again be monitored with VSPs. In fact, almost any change to the aligned pores or their contents can in principle be modeled theoretically, its effect on shear waves calculated, and be potentially recognized by the changing behavior of shear waves in VSPs. I suggest it is probable that such techniques, repeated in critical wells, will open a new phase in reservoir management where VSPs provide detailed monitoring of the changing conditions within the reservoir during recovery. Shear-wave three-component VSPs have the potential for bringing geophysical precision to recovery by the year 2000. The final message to management is that I suggest that you do not plug and abandon wells in what, with current technology, appear to be depleted fields. New technologies are being developed which can give a more complete image of the reservoir rock and may lead to a higher percentage of recoverable oil.

Suggestions for further reading. Nur and Tosaya first drew attention to the substantial change in seismic velocities of hydrocarbons in heat fronts in *Monitoring of thermal EOR fronts by seismic methods* (*Society of Petroleum Engineers*, 1984). Nur identified the importance of better understanding the internal structure for EOR in *Four-dimensional seismology and (true) direct detection of hydrocarbons: The petrophysical basis* (*TLE*, September 1989). Crampin et al. identified the importance of shear-wave VSPs for recognizing the internal structure of reservoirs in an article by that name (*TLE*, November 1986). A review of widespread observations of shear-wave splitting is Crampin's article *Geological and industrial implications of extensive-dilatancy anisotropy* (*Nature* 1987). Crampin et al. first recognized widespread shear-wave splitting and EDA in *Earthquake prediction: A new physical basis* (*Geophysical Journal of the Royal Astronomical Society*, 1984) and *Evidence for aligned cracks in the Earth's crust* (*First Break*, March 1985). Changes in shear-wave splitting before and after earthquakes have been identified by Peacock et al. in *Shear-wave splitting in the Anza seismic gap, southern California: Temporal variations as possible precursors* (*Journal of Geophysical Research* 1988); Crampin et al. in *Changes in shear-wave splitting at Anza near the time of the North Palm Springs earthquake*; and Booth et al. in *Temporal changes in shear-wave splitting during an earthquake swarm in Arkansas* (both submitted to *Journal of Geophysical Research* 1989); and by Crampin and Booth before and after hydraulic pumping in *Shear-wave splitting showing hydraulic dilatation of pre-existing joints in granite* (*Scientific Drilling* 1989). Liu et al. recognized the difficulty of interpreting shear-wave splitting in crosshole surveys in *Shear-wave splitting in cross-hole surveys* (GEOPHYSICS 1989). Related papers by Crampin include *A review of wave propagation in cracked an anisotropic media* (*Wave Motion* 1981), *Shear-wave polarizations: A plea for three-component recording* (*SEG Expanded Abstracts* 1983), and *Evaluation of anisotropy by shear-wave splitting* (GEOPHYSICS 1985). LE

Acknowledgments: This work was supported by the Edinburgh Anisotropy Project and the Natural Environment Research Council. It is published with the approval of the director of the British Geological Survey (NERC).

Stuart Crampin is director of the Edinburgh Anisotropy Project and is a deputy chief scientific officer (individual merit) in the Global Seismology Research Group of the British Geological Survey, Edinburgh. He received a Ph.D. (1965) and an Sc.D. (1977) in geophysics from the University of Cambridge. He received EAEG's Conrad Schlumberger Award ('86) and SEG's Virgil Kauffman Gold Medal (1988) for his pioneering work in the theoretical, observational, and computational development of seismic anisotropy. He is a Fellow of the Royal Society of Edinburgh and an Honorary Professor of Geophysics of the University of Edinburgh. Crampin has been co-convenor of three International Workshops on Seismic Anisotropy (Suzdal, 1982; Moscow, 1986; and Berkeley, 1988, as an AGU Chapman Conference). He has been co-editor of their Proceedings (Geophysical Journal of the Royal Astronomical Society, *1984, 1987;* Journal of Geophysical Research, *1990).*