The application for surface seismic to the detection of methane producing fractures in coal seams

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ABSTRACT

Methane production from deeply buried coal seams, is of great economic importance in the USA. In Australia, such gas presents a danger to underground mining and is largely unused and vented to the atmosphere in subeconomic amounts. If a remote sensing method could be devised to locate fractures, disseminated gas within coals seams could be released more readily. This paper proposes that surface seismic methods can be used to detect favourable seam geometries, as well as the presence of fractures and their orientation, thereby assisting the future economic methane production from Australian coal fields.

INTRODUCTION

During the last decade, coalbed methane production has grown at a rapid rate in the USA, from which enormous economic benefits have resulted (Carter, 1991). The basic principles and problems involved in exploration and production of methane have been documented (Laubach *et al.*, 1991). Typically, methane production is obtained from deeply buried, thick and permeable coal seams. In general, the following can be stated:

1. That the potential for methane production is dependent on the coal's thermal maturity, its rank and depth of burial.

2. Methane production is controlled by coal seam thickness, and its permeability.

3. Permeability is controlled by the coal fracture system and orientation.

In seams under investigation, the initial target is to detect permeable zones and secondly to determine permeability anisotropy, in order to develop an efficient drilling program for methane extraction. Apart from the mapping of favourable coal seam and structural geometries, seismic methods may also have a role in directly detecting fractures. The effect of fractures on seismic wave amplitudes may be observed on conventional seismic sections. In addition, the propagation of compressional (P) and shear (S) waves is affected.

Linear oriented systems of fractures effectively create an anisotropic medium for the propagation of seismic waves. In such media, the propagation of body waves differs considerably from the propagation in an isotropic medium. Seismic wave velocities, amplitudes and even frequency content are azimuthally dependent. P and S waves are coupled and often referred to as quasi-P and quasi-S waves. When an oriented system of fractures is present, the S-wave splits into two waves, usually denoted as S1 and S2, which propagate along and perpendicular to fracture planes with different velocities and amplitudes. Consequently, for coalseams, there is a relationship between seismic and permeability anisotropy.

COAL SEAM FRACTURES

A typical system of coal seam fractures is shown in Figure 1. There is an orthogonal pattern of intrinsic fractures: face and butt cleats, which are characteristic of mature coal seams. Superimposed on this system are often fault related fractures. Permeability varies considerably with fracture size and fill, and is dependent on how well face cleats are developed. An important contribution to permeability is made by fault induced fractures, since they are greater in scale than face cleats and often cut through several layers of seams. These fractures are commonly triggered by small throw faults.

SEISMIC MODELLING

In order to predict the seismic response from fractured coals seams, a computer simulation of the seismic method may be employed. This approach calls on seismic numerical modelling in which the geological properties of interest are input data, and the seismic section outputs the results.

The correct approach requires the use of heterogeneous anisotropic elastic wave equation modelling. A hindrance in performing such numerical modelling is that a knowledge is required of at least four elastic constants, the computation is lengthy and involved, and the inclusion of complex fracturing as well as difference fracture fill is not simple.

Another way to examine the effects of a fractured medium on seismic wave propagation is to use physical modelling. In physical modelling, scaled synthetic three dimensional models of coal seam geology may be built from rubbers, resins and acrylics. Surface seismic methods are then adopted by using ultrasonic 450 kHz and 1 MHz transducers as seismic source and geophones, to simulate the true seismic field response. Seismic data is recorded on magnetic tape just as it is done in the field. Resulting shot records are very similar to the real field records and it is often difficult to distinguish between the two.

Using this approach, the seismic response due to an oriented system of fractures were observed and examined in experiments performed some years ago (Urosevic and McDonald, 1984a; 1984b). The results obtained then were discarded due to their perceived irrelevance to oil exploration at that time, but are extremely relevant to coalbed methane exploration today, and provide a starting point for investigation in this area.

Figure 2 shows a simple physical model representing a thick horizontal layer containing a system of vertical fractures, in which two acrylic (plexiglas) slabs had a number of acrylic sheets placed under pressure between them to simulate the geology of a vertically fractured layer. Seismic lines were recorded parallel, at 45 degrees and orthogonal to the fracture plane in order to observe directional properties of such a medium. The resulting shot records are shown in Figure 3. Another seismic line was recorded over an unfractured acrylic block in order to have a reference data set.

Primary reflections of interest from the ray paths shown in the schematic diagram of Figure 2 are labelled as PP, PPPP, PPSP and PSSP in the shot records of Figure 3. The initial two wave types correspond to the model's top and base P-wave reflections. The other two are one way and two way converted S_V-waves, respectively. That is, the initial compressional P-waves have been converted to vertically polarized S_V-waves during transmission down and back up after reflection. The dynamic relationship between these two waves (P and S) might be of great importance for coalbed methane exploration.

Note in Figure 3 that as the seismic line azimuth changes with respect to the fracture orientation, there is a reduction in reflection amplitude and a frequency shift in both P and S_V-waves. There is a distinct difference between the shot records when the orientation of the line with respect to the preferred fracture direction is changed. A stacked seismic section, recorded orthogonal to the fracture direction, displays similar features in Figure 4, where reflection amplitude dimming is clearly evident as a result of the presence of fractures, while the effect is dependent on the size of the fracture zone.

When coal seam thickness is reduced, beyond the seismic resolution, the effects are proportionally weaker. However, subtle changes in amplitude can be highlighted by the use of attribute displays on an interactive workstation, so that a minor amplitude shadow or frequency reduction may still be observed on an amplitude or frequency attribute display, as shown in Figure 5.

The results of these simple experiments show that it is possible to detect zones of intense fracturing, as well as to observe azimuthal variations in rock properties, by using the common surface seismic method. We conclude that more sophisticated models are needed to simulate water/gas filled and mineralized fractures, to further support the detection of directional trends in fracture systems, as indicated above. Two and/or three component survey data over such models would assist the study of azimuthal variations of properties of coal seams containing different fracture orientations and fill.

FIELD DATA

3-D Seismic Surveys

The role of 2-D surface seismic methods for defining coal seam geometry is well established. While 2-D methods are effective in a reconnaissance role, their use for detailed mapping is limited by the inherent spatial resolution limit. To overcome this, the petroleum industry often uses 3-D seismic methods. Such 3-D methods are used for the mapping of complex fault patterns, subtle structures and zones of intense fracturing that are often associated with small throw faults. From a coal economics stand-point, 3-D seismic methods can be more cost effective than drilling to locate complex seam structures. Subtle structural details can only be inferred by 3-D seismic. For example in Figure 6, complex faulting of the Bulli coal seam at Appin Colliery was unable to be mapped using 2-D seismic methods, but a 3-D survey resolved its complexity. In Figure 7, the three dimensional time map over a part of Newlands Mine indicated a small throw fault which could not be observed without the support of 3-D data.

Fracture detection

To our knowledge, there has been no documented experimental field work done to remotely detect anisotropy effects due to fracturing in coal seams, which have been indicated by modelling results.

However, in oil exploration, various downhole measurements such as full waveform logging and 3-component VSP have been accomplished utilizing shear wave splitting phenomena, in order to detect fractures and define their geometry (Crampin *et al.*, 1984). Similarly 3-D 3-component surface seismic methods have been employed over known reservoirs to detect zones of intense fracturing (Davis and Lewis, 1990; Mueller, 1991). Initial results of their work are encouraging for this approach's application to coalbed methane fracture detection.

Our own work with single component 2-D seismic data has indicated the presence of converted S_V-waves, which may play an important role in coalbed methane exploration. A strong impedance contrast between a coal-seam and it surrounding rocks is likely to produce a strong converted S_V-wave. In Figure 8 the event labelled PS corresponds to an incident P-wave that has been reflected from the Bulli seam as an S_V-wave. This event is not present on the near offset traces the amplitude is greater at far offset traces, indicating the presence of a converted wave. Assuming a Poisson's ratio of 0.3 for the overlying layers numerical modelling indicates timing agreement for this event. The reflection labelled PP is the top Bulli P-wave reflection. In Figure 9, results from our single component VSP research show strong shear waves, confirming that converted waves should be expected on surface seismic shot records.

A number of 2-D seismic lines from this survey area have also displayed PP and PS waves, the amplitude ratio of which varies along the line. Such amplitude changes might be related to the intensity of fracturing and their orientation, if well control and VSP data are available.

CONCLUSION

This paper proposes that the surface seismic method could be a major tool in the future of coalbed methane exploration and development. We believe that seismic methods can be of great use in the remote detection of zones of intense fracturing (for the location of sweet spots), in the remote detection of permeability anisotropy, and that they offer support for the improved efficiency and optimization of drilling programs in existing and virgin areas.

Results from physical modelling suggest that azimuthal variation of coal seam properties is likely to be detectable. Initial results from 3-D seismic field data are encouraging, indicating that more information can be provided buy 3-D seismic data, not only to infer structural complexity but also to indirectly indicate the likely distribution of fractured zones. Further study of converted S_V-waves observed in conventional 2-D seismic data may provide important information relevant to coalbed methane exploration and development. Numerical and physical modelling results should be combined with detailed geological and seismic data, in order to make further progress in the area of the remote detection of methane-filled fractures.

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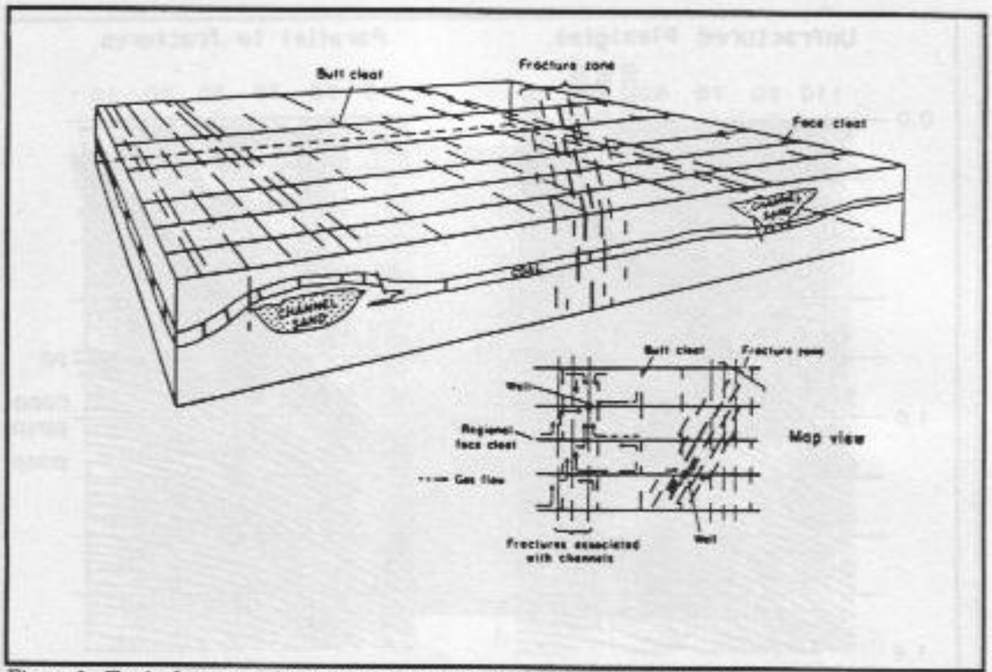

Figure 1. Typical systematic regional fractures (after Laubach *et al.*, 1991)

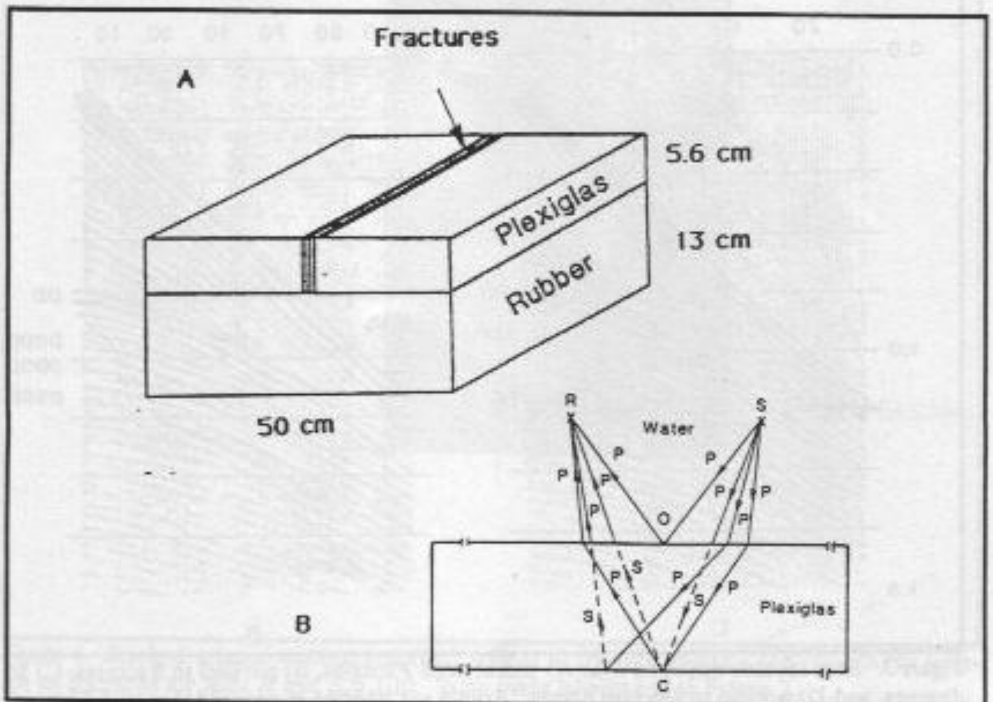

Figure 2. A) A physical model containing a system of vertical fractures B) Schematic diagram showing travel paths of P and mode converted S_v (quasi-$_v$) waves reflected from the top and base of a Plexiglas layer. PPSP-base one way converted S_v- wave reflection and PSSP-base two way converted S_v-wave reflection. The source and receivers were 5 cm above the model.

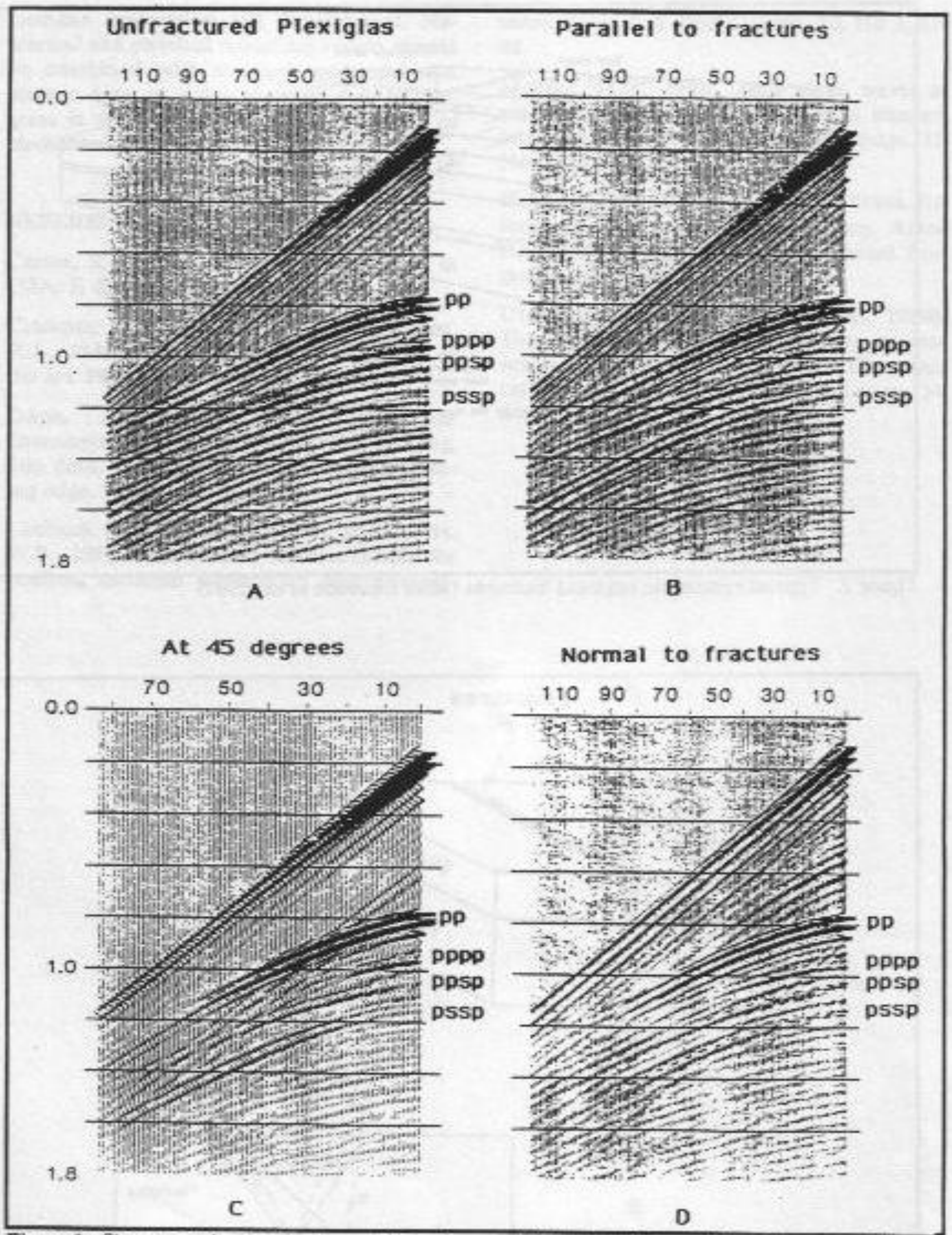

Figure 3. Shot records acquired over A) unfractured Plexiglas, B) parallel to fractures, C) at 45 degrees, and D) normal to fracture planes. Events are labelled in concordance with Figure 2.

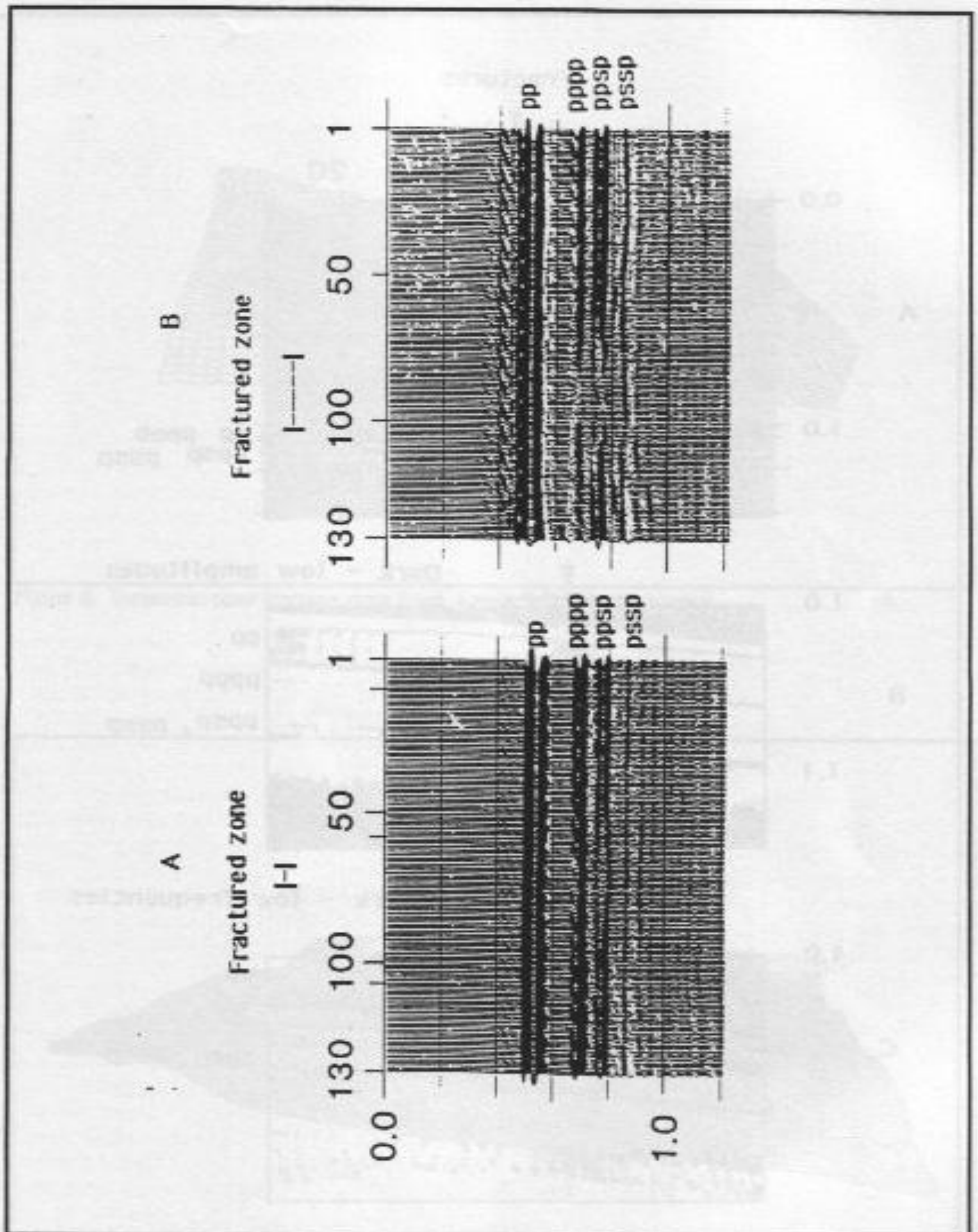

Figure 4. Stacked seismic sections recorded normal to fracture planes. The ratio of the number of fractures for lines A and B is 1:10. Same event labelling as in Figure 2.

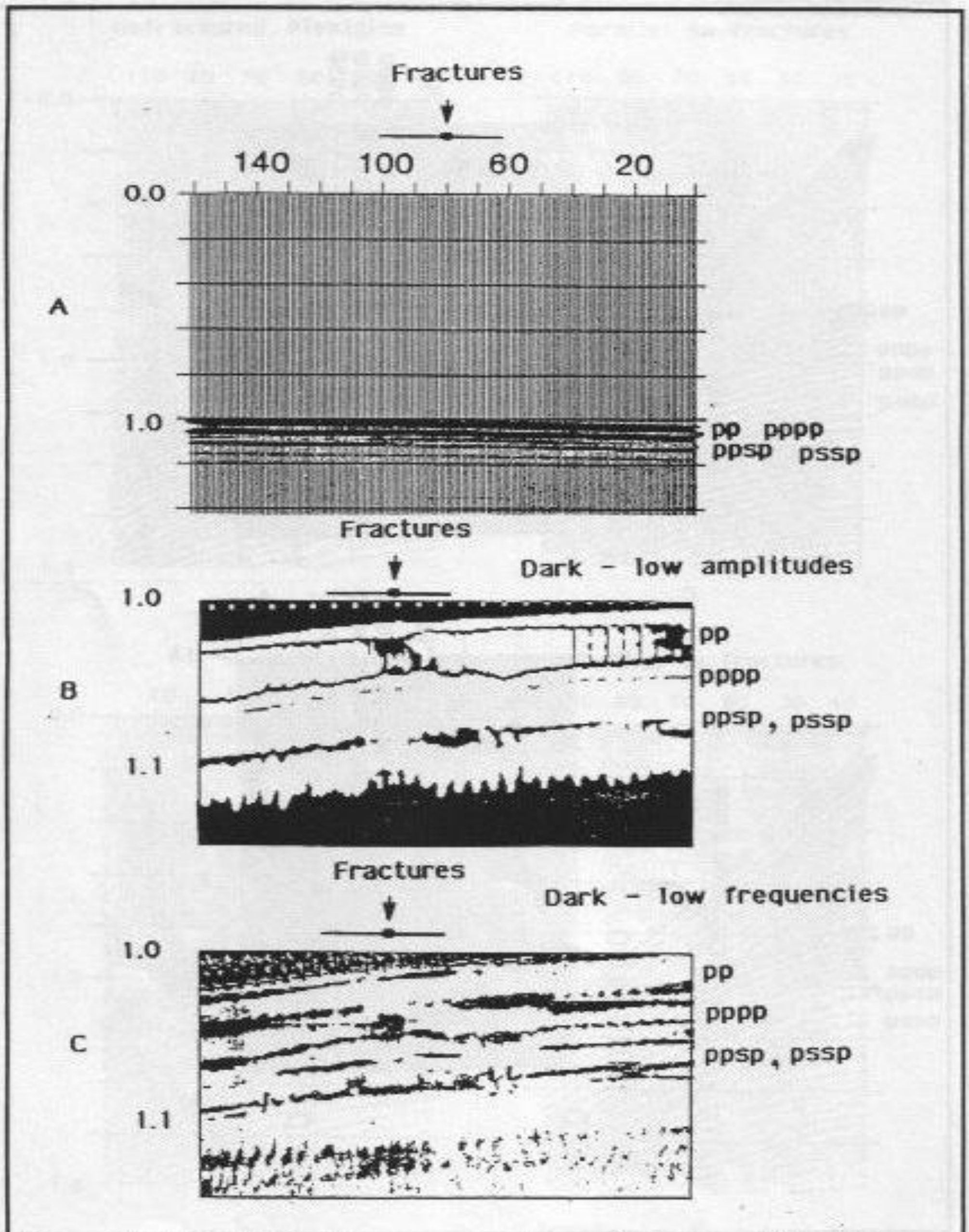

Figure 5. Time section (A) acquired over a thin (below resolution) fractured Plexiglas slab, and its instantaneous amplitude (B) and frequency (C) attributes between 1.0 and 1.1 seconds. Note that amplitude dimming and reduction of frequency content occur across the fractured zone.

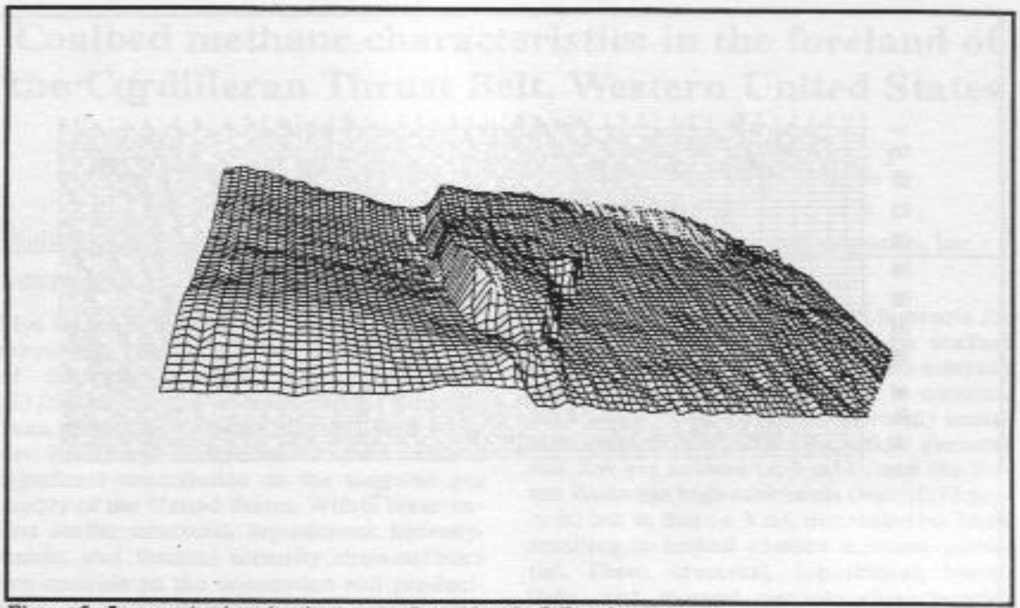

Figure 6. Isometric time horizon map from Appin 3-D seismic survey.

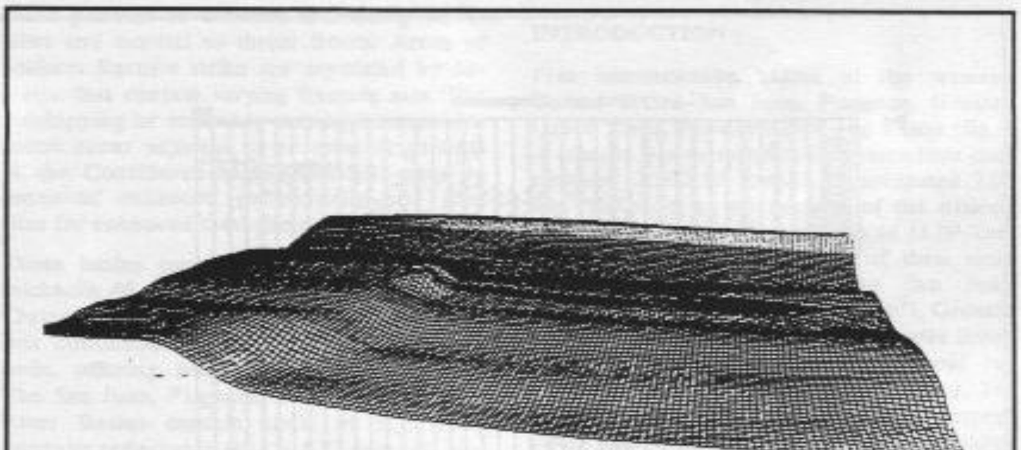

Figure 7. Isometric time horizon map from Newlands 3-D seismic survey.

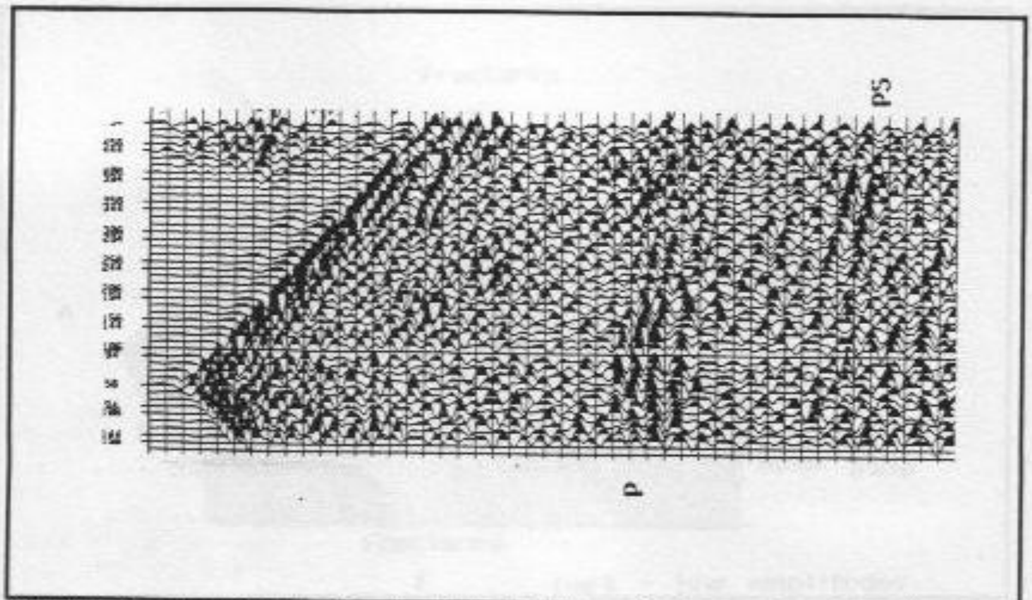

Figure 8. Shot record showing P-wave and mode converted S_v-wave (PS reflections from Bulli seam.

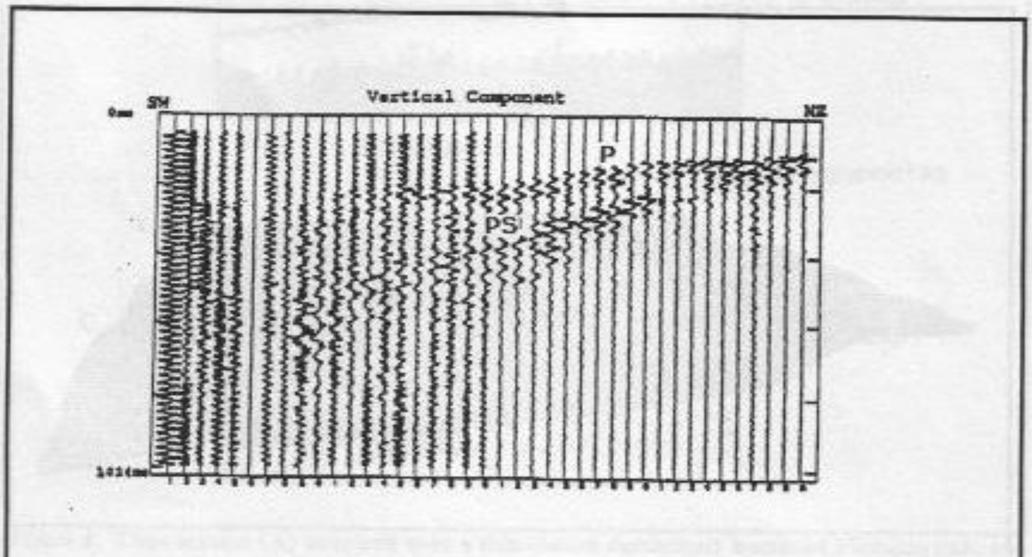

Figure 9. A single component VSP survey. Events labelled P and PS are downgoing P and S Waves, respectively.