Information From Walk-Away VSP and Cross-Hole Data Using Various Wave Modes: Tower Colliery, South Sydney Basin

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SUMMARY

Due to the poor quality of surface seismic data recorded at the Tower Colliery, South Sydney Basin, walk-away VSP and cross-hole data sets were acquired to image coal seams at a depth of 500 m. These data sets show the subsurface to be surprisingly complex structurally. In addition to P-wave reflections, high amplitude converted and shear reflected waves were observed in all data sets. All of these wave modes were analysed in the interpretation process. Several versions of VSP and cross-hole stacks of P-, converted and shear waves were produced by various mapping algorithms and by a Kirchhoff approach. The standard Kirchhoff migration method of offset VSP data was extended to incorporate converted waves and elliptical anisotropy. The results obtained by Kirchhoff migration compare favourably with VSP mapping techniques. Complex faulting is much better imaged by the Kirchhoff approach. However, VSP to CMP mapping is still useful for: a) building the velocity model to be used as input to Kirchhoff migration and b) global control of the migration output, particularly in the vicinity of the “blind zones” in cross-hole reflection imaging. Images produced by using converted and shear waves proved to be essential for the interpretation of this strongly heterogeneous area. P-wave and converted wave images were improved in part by the introduction of elliptical anisotropy.

INTRODUCTION

In the South Sydney Basin, the Bulli coal seam is mined by long wall methods at about 500 m. Due to high cost drilling, seismic methods are extensively used in the exploration stage. Most often, surface seismic methods are used (2-D and 3-D) since, in general, high quality data are recorded in this area. However, poor quality zones do exist. In such cases, walk-away VSP and cross-hole recording techniques are commonly used. Most of the mining problems can be related to the Tower Colliery. In this area faulting is more pronounced and, as revealed by this study, some quite complex zones exist. Initial studies using borehole, VSP, cross-hole and surface seismic information showed that strong layering anisotropy exists in the upper Hawkesbury Sandstone and Bald Hill Claystone (Figure 1a). The existence of minor gas accumulations related to the leakage of methane from the coal seams through faults was also suggested (Urosevic *et al.*, 1995). However, until now, the full structural complexity of the area has not been understood.

The main lithological units of the Tower area and, in general, the South Sydney Basin are shown in Figure 1a. All three main units consist of very competent rock and are practically impermeable. The faulting is the only source of leakage of methane from the Bulli and underlying seams into the upper formations. While normal faulting does not present a severe problem for long-wall mining, reverse faulting presents a significant hazard. Typically, such zones with reverse faulting are abandoned and not mined. Thus, the role of seismic methods in this area is not only to detect the faults ahead of the mining operation, but also to identify the type and properties of the faults. Consequently, in this study we analysed the performance of various VSP to CMP mapping schemes and compared them with results obtained by Kirchhoff migration methods. All three wave modes, compressional, converted and shear, are included in the study.

DATA ACQUISITION

Dual acquisition systems were used simultaneously to acquire surface seismic, walk-away VSP and cross-hole data (Figure 1a). Explosive charges (400 g) were fired in borehole 13, while 59 vertical geophones, which were cemented in borehole 12, recorded the cross-hole and surface shots. The shot spacing on the surface and in the borehole was 10 m. The receiver spacing was 10 m for surface geophones and 6.7 m for borehole geophones. The acquisition was performed by the BHP Steel (AIS) Pty. Ltd. seismic crew. High quality cross-hole data were acquired. Walk-away VSP data were of variable quality ranging from very high from shots fired in the vicinity of borehole 12 to very poor for those fired in the vicinity of borehole 13. Surface seismic data were of poor quality (Figure 1b).

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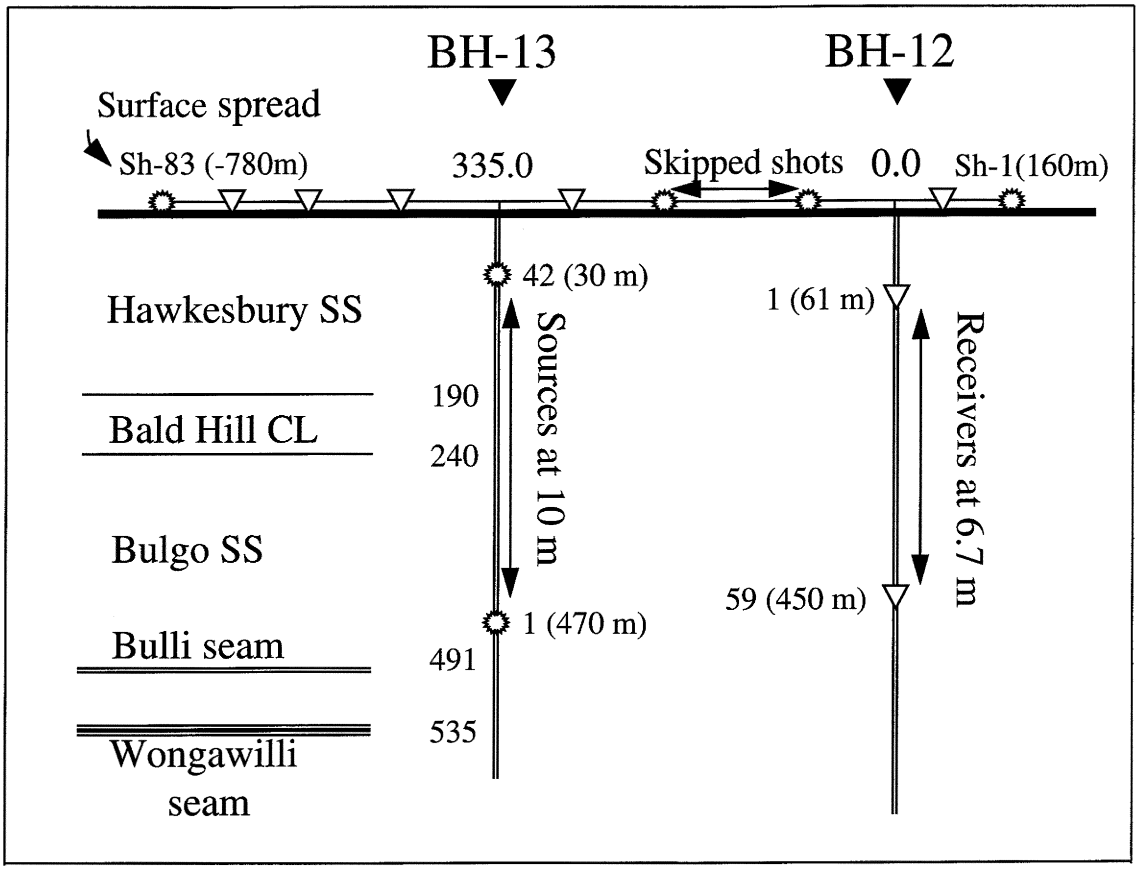

Figure 1a: *The main lithological units in South Sydney Basin and the acquisition geometry used for simultaneous surface and borehole data acquisition*

VSP DATA ANALYSIS

Existence of strong converted and shear waves is observed on all data, irrespective of the source and receiver geometry. Initial analysis using only P-waves showed that they are strongly attenuated by the gas pockets. Without the gas pockets the medium is nearly elliptically anisotropic to P-waves. However, the P-wave velocity was affected by the gas. In contrast, the shear wave velocity is much less affected by the gas zones. This observation led to the idea of using all the wave modes in VSP and cross-hole mapping for interpretation.

WALK-AWAY VSP MAPPING AND INTERPRETATION

VSP to CMP transformation was accomplished by several methods. Taylor's (1989) approach was modified to include a variable tilt angle in the input depth model to enable dip analysis. The actual mapping of P-, converted and S-waves was done by ray tracing. Elliptical anisotropy was included in the P-wave mapping.

Walk-away VSP data were processed to enhance upgoing waves. Subsequently, reflected P-, S- and converted waves were enhanced and separated into three independent data sets. Figure 2a-c shows the VSP stack of P-, converted and S-waves, constructed by geometrical mapping and converted to depth. The VSP stack of P-waves using an elliptical velocity function (anisotropy of 7.5%) is shown in Figure 2d. The Bulli reflector which is at a depth of around 500 m in the vicinity of borehole 12, appears more coherent in Figure 2d than on the corresponding P-wave stack obtained by using an isotropic velocity function (Figure 2a).

The Kirchhoff migration algorithm used is based on the work of Dillon (1988). However, it has been extended to include migration of converted waves and elliptical anisotropy. In Figure 3a-c, VSP depth migrated stacks are shown for P-, converted and S-waves, respectively. In addition, in Figure 3d, a converted wave depth migrated stack using an elliptical P-wave velocity function (anisotropy 7.5%) is shown. Again, more coherent reflections have been obtained by inclusion of elliptical anisotropy. Overall, there is agreement between the results shown in Figures 2 and 3. However, it is apparent that the Kirchhoff method produced more coherent stacks and higher frequency output, and provides better structural definition. VSP stacks obtained by geometrical mapping were used in this case primarily to help select the optimum aperture and to show the location of blind zones since several shots were not fired due to a creek in the vicinity of borehole 12. Kirchhoff migration will fill in this region and possibly create artifacts.

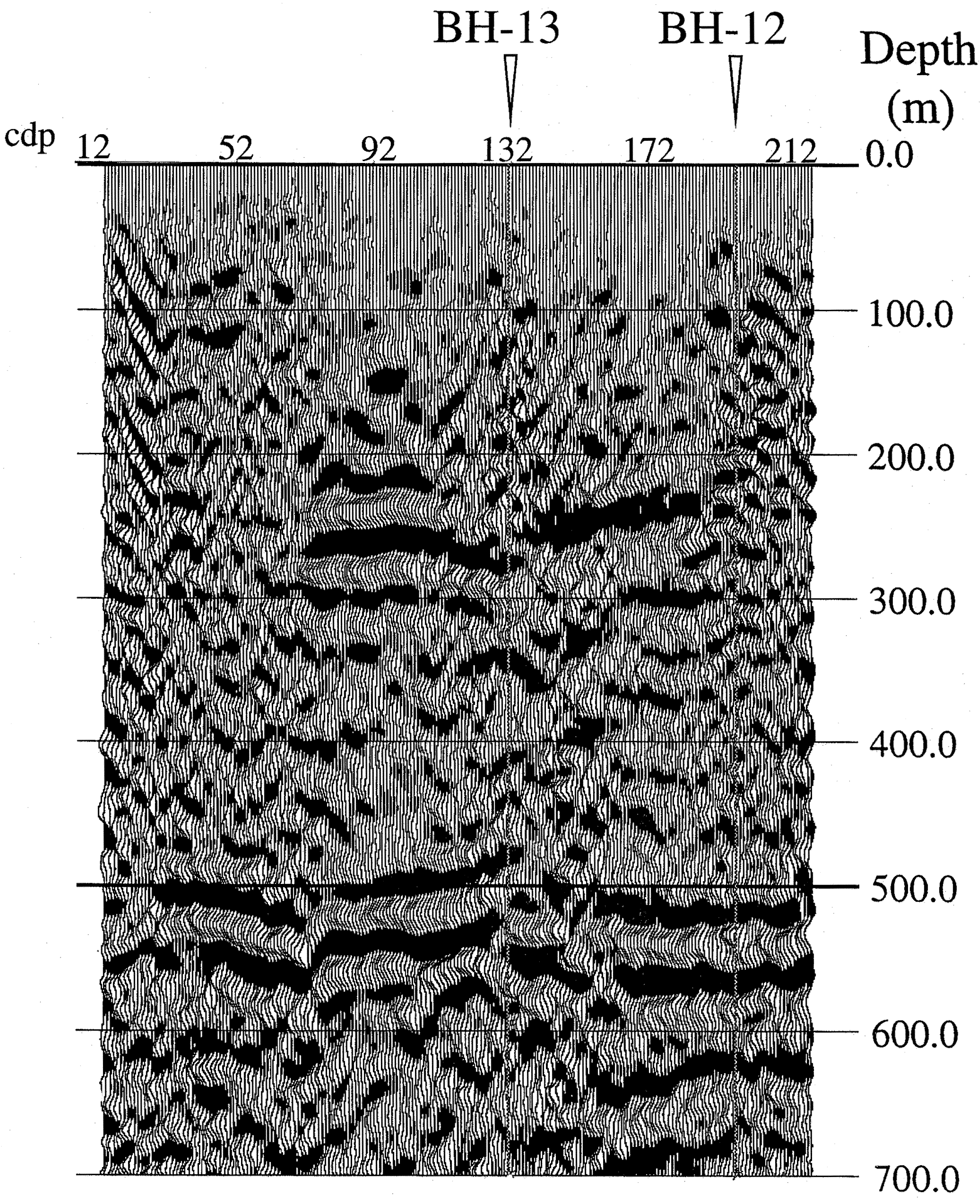

Figure 1b: *Resulting surface stacked section.*

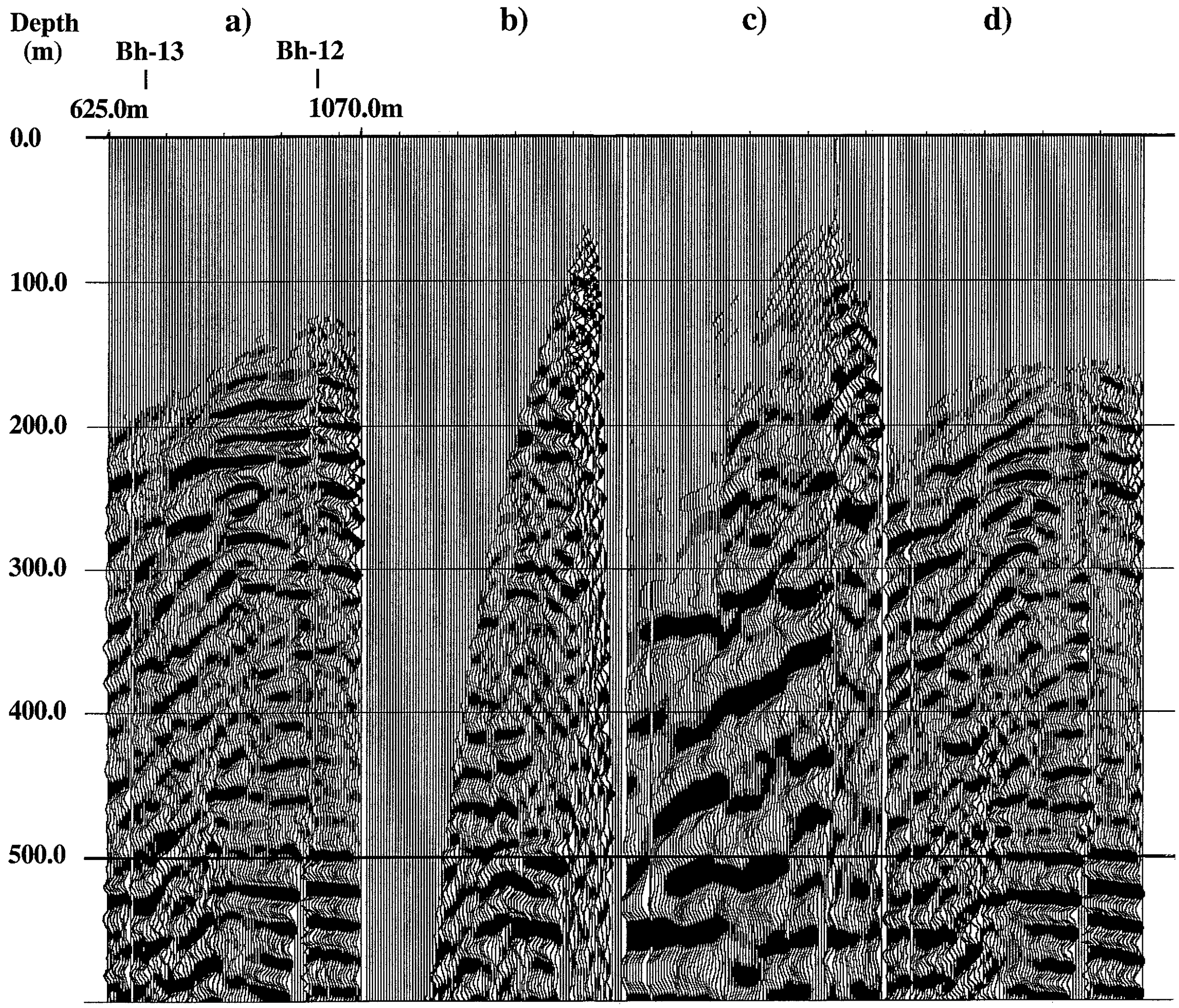

Figure 2: *Walk-away VSP stacks constructed by ray tracing: (**a**) P-wave stack, (**b**) converted (PS-type) wave stack, (**c**) shear-wave stack, and (**d**) P-wave stack using an anisotropy set to 7.5%.*

The results obtained by using all three wave modes are in good agreement. They express the same structural features. However, the lateral positions of the faults differ in the P- and S-wave stacks. They are better matched after elliptical anisotropy is accounted for in both the geometrical mapping and Kirchhoff migration of P-waves (Figures 2d and 3d). Figure 4 shows P-wave depth migrated stacks using two different percentages of anisotropy. While inclusion of weak anisotropy of 7.5% improved the image, strong anisotropy of 15% created a smeared and unrealistic image. The final interpretation is shown in Figure 4d, using the P-wave migrated stack with 7.5% anisotropy. Several of the faults shown in this figure were interpreted by combined analysis of the VSP data, surface data and cross-hole mapping (not shown here). We note that some faults are better seen in the S-data, some in the converted wave stacks and some in the P-wave stacks. At this stage it is not clear if the different fault expressions on the P and S data are the consequence of the fault style and fault type (e.g., a sealed fault or a water-saturated shear zone) or if they primarily depend on the way we have conditioned the data for each of the wave modes. Further drilling in this area is expected and we hope to resolve this problem.

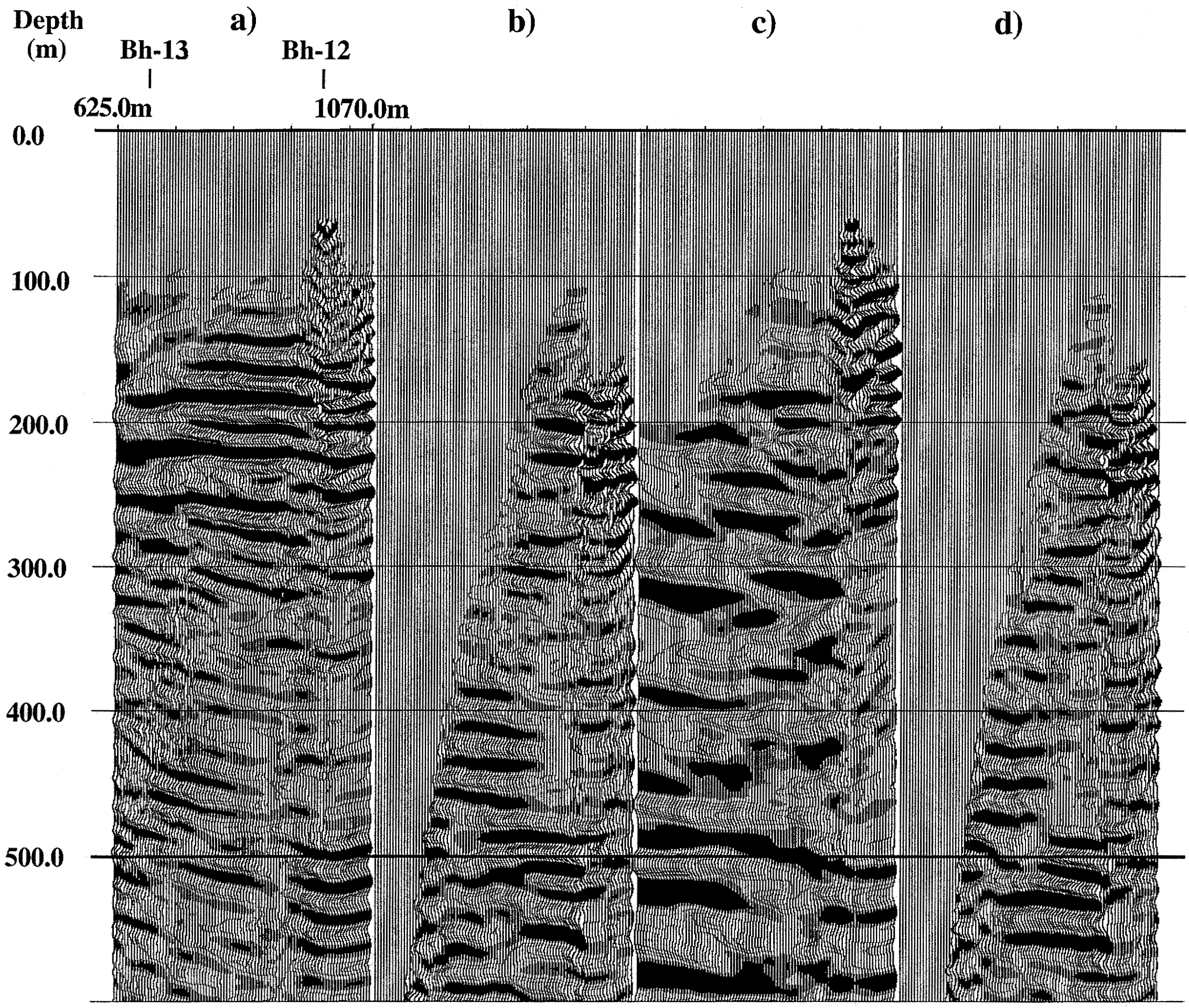

Figure 3: *Kirchhoff migration of VSP walk-away data: (**a**) P-wave image (**b**) converted wave image (**c**) shear-wave image, and (**d**) converted wave image using P-wave anisotropy set to 7.5%.*

CONCLUSION

The complex geology of the Tower Colliery has required modification and improvements of existing VSP processing codes. Analysis of the P-, converted and S-waves allowed a higher quality and more accurate interpretation of the data. Particular fault patterns are expressed differently on P- and S-wave stacks. This suggests that fault-type recognition may be achievable through the combined analysis of P- and S-wave modes. Extension of the Kirchhoff migration method to handle converted waves created a better image of the Bulli coal seam. More consistent P-wave stacks were obtained by introducing elliptical anisotropy. Geometrical mapping methods are now seen in a somewhat different light. The results of mapping are primarily used to optimise the input for Kirchhoff migration and to control the output near blind zones.

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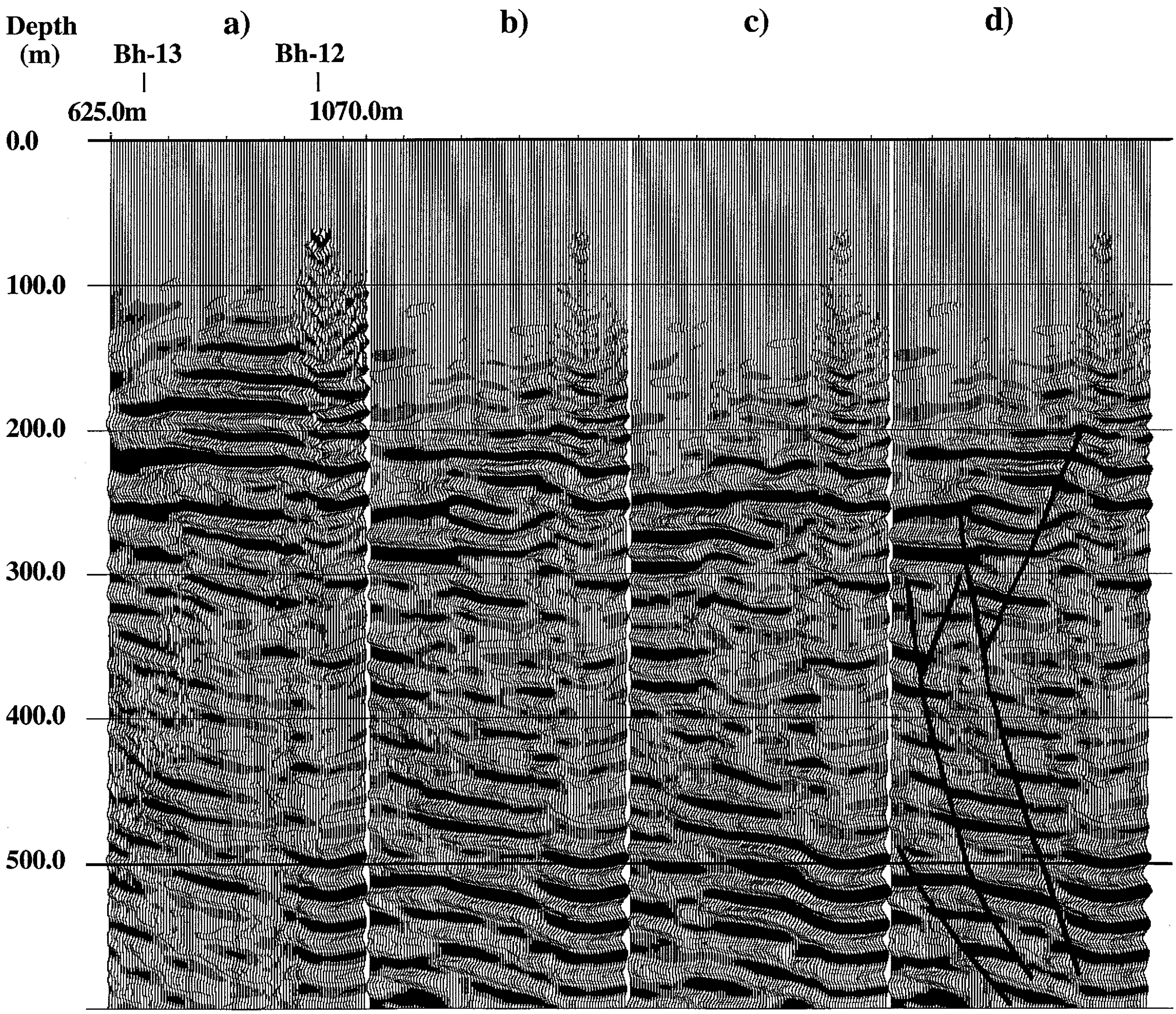

Figure 4: *P-wave VSP imagesusing Kirchhoff migration: (**a**) no anisotropy, (**b**) anisotropy of 7.5%, (**c**) anisotropy of 15%, and (**d**) final interpreted image using 7.5% anisotropy.*

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