Summary

Poor seismic data quality and significant well misties in excess of 100ms adjacent to salt diapirs on 3D post-stack depth migration (post-SDM) data in the Pierce Field led to seismic re-processing with anisotropic pre-stack depth migration (pre-SDM). Here we describe how we initially determined the presence of seismic anisotropy within the overburden using ‘legacy’ VSP data and how this was subsequently confirmed during seismic velocity analysis.

Introduction and Nature of the Problem

Pierce Field lies in Blocks 23/22a and 23/27 of the UK central North Sea, and comprises two accumulations, Pierce North and Pierce South, associated with twin salt diapirs. The salt diapirs have created steeply-dipping Palaeocene reservoirs truncated by the salt. Development drilling in 1998-99 relied on a reservoir depth model based on the interpretation of 3D seismic data acquired in 1992 (dual source, triple streamer) and processed to 3D post-SDM in 1993.

Seismic reflectors commonly overlap with conflicting dips in the target zone and data quality is severely degraded adjacent to the salt diapir. Steeply dipping reflectors show spatial aliasing. Significant well misties between 100ms and 260ms for target horizons exist adjacent to the salt diapirs. These misties are believed to result from mis-positioning of steeply-dipping seismic events during post-SDM with an isotropic velocity model. The magnitude of vertical and lateral positioning errors due to ignoring overburden anisotropy can be significant (errors of order 300m are reported, eg. Hawkins et al. 2001; Vestrum & Lawton, 1999; Vestrum, Lawton and Schmid, 1999).

In view of these imaging and positioning problems associated with the 1993 post-SDM data, a pre-SDM project was initiated. Was it worth including seismic anisotropy?

Overburden Velocities

Velocity issues included seismic anisotropy, shallow velocity anomalies (Quaternary canyons, shallow gas, a gas escape features?), fast-velocities adjacent to diapirs due to structural uplift of sediments, and the presence and location of the salt. Given the potential impact of seismic anisotropy for both lateral and vertical positioning of seismic reflectors, made even worse by the steep sedimentary dips exceeding 50° close to the salt diapirs, we needed to determine whether or not this was likely to be a significant factor in the Pierce overburden.

Banik (1984) measured seismic anisotropy in the North Sea by a comparison of the well-log sonic data and the interval velocity profile obtained from the surface seismic data (and also from a comparison of the seismically predicted depth and the well-log depth). He attributed
the seismic anisotropy primarily to the presence of shales. However, the reliability of seismically-derived conventional ‘stacking’ velocities over Pierce in the presence of both shallow velocity anomalies (Al-Chalabi, 1979; Armstrong et al., 2001) and steeply-dipping beds was a concern. Therefore, we decided to investigate the suitability of existing ‘legacy’ VSP data to estimate the degree of seismic anisotropy in the overburden.

**Seismic Anisotropy from VSPs**

There are hundreds of VSP surveys in the North Sea. It is probably true to say that very few of these are used to their full potential and that many are relegated to little more than over-sampled check shot surveys. Many exist in dusty paper format on a geophysicist’s shelf or in digital format on ageing 9-track magnetic tape in an even dustier offsite archive. Here we bring to life some of this ‘legacy’ VSP data to investigate overburden anisotropy.

There were a number fixed offset VSPs acquired in some of the Pierce area exploration wells. Figure 1 shows the shooting geometry for three VSP experiments carried out in well 23/27-9. The salt proximity survey was carried out in order to define the salt-sediment interface of the nearby diapir. All raypaths encounter the salt and this invalidates their use in quantifying the seismic anisotropy of the adjacent overburden. Ray paths for the rig source and NE fixed-offset source surveys traverse the overburden in different directions. In the presence of seismic anisotropy, the velocity along these slant paths will be different. Ignoring refraction through the overburden, the difference in velocity along straight slant paths could give an indication of the strength of seismic anisotropy (this also assumes that the overburden traversed by raypaths for each survey does not contain lateral velocity variations or discrete velocity anomalies). This analysis would only be valid provided that raypaths were not affected by the salt. Ray tracing of the rig source survey carried out by the SSL (the VSP contractor) showed that there were no direct arrivals for the deepest levels due to refraction through the salt.

Figure 2 shows the average velocity of the NE fixed-offset versus rig source surveys for straight slant paths into each downhole geophone location. Note that, with exception of the shallowest depths, the average velocities calculated for the rig source survey are greater than those calculated for the NE fixed-offset survey. For the shallow recordings above 3500 feet, the angles of incidence to the layering are largest for the NE fixed-offset survey. However, in the presence of a 45° geological dip encountered beneath 3500 feet, the angle of incidence varies between only 0 and 11° for the NE fixed-offset survey and between 30° and 44° for the rig source survey. Assuming that the symmetry axis of any seismic anisotropy is perpendicular to bedding (tilted transverse isotropy or TTI), we would predict that, for depths beneath 3500 feet, the slant path average velocity of the rig source survey to be greater than for the NE fixed-offset survey at each recording level. This prediction is confirmed by the results shown on Figure 2.

The anisotropy factor varies with depth (Figure 3), calculated assuming elliptical anisotropy and a geological dip of 45°, and showing variations of up to 8% (anisotropic factor is defined as the ratio of average velocity parallel to bedding, $V_t$, to average velocity normal to bedding, $V_n$). Two other wells indicated similar anisotropic behaviour.
Processing Results

A simple analysis of available VSP data established a strong likelihood that the Pierce overburden shows significant seismic anisotropy. We therefore chose to proceed with anisotropic pre-SDM. The initial velocity layering was defined by 12 seismic horizons and sonic and checkshot data in well 23/27-6. Anisotropic parameters, $\delta$ and $\varepsilon$ (Thomsen, 1986) were estimated from analysis of isotropic pre-stack depth migrated gathers around the well. The gathers had been migrated with a well consistent velocity (Figure 4). Seismic anisotropy was confirmed and it varied with depth. In particular, a shallow horizon at 1450ms, Marker D, showed significant residual moveout (over-correction). This implied a 700 feet interval immediately above Marker D exhibiting very significant anisotropy ($\delta = 0.159$ and $\varepsilon = 0.365$).

Conclusions

- Simple analysis of the existing VSP data indicated a strong likelihood that the Pierce overburden shows significant seismic anisotropy.
- The presence of seismic anisotropy was subsequently confirmed by analysis of depth-migrated pre-stack gathers.

Acknowledgements

We wish to express our thanks to: Pierce partners for granting permission to publish this paper - Agip (UK) Ltd., CNR International (UK) Ltd., Enterprise Oil plc and MOC Exploration UK Limited; Prof. Colin MacBeth for initial discussion and suggestions about how we might use our legacy VSP data to investigate anisotropy in the Pierce overburden.

References

Figure 1 VSP shooting geometry for well 23/27-9 with thumbnail seismic cross-section along well bore

Figure 2 Average velocity of NE fixed-offset survey versus rig source survey for straight ray paths into each downhole geophone location. (The black line indicates where the two average velocities are equal - to the right, rig source \(V_{avg}\) is faster).

Figure 3 Anisotropy factor versus depth for VSP data in well 23/27-9.

Figure 4 Isotropic pre-stack depth migration gathers using well consistent velocity.