Fractured Reservoirs: Using State of the Art VSP Processing and Interpretation in the Construction of Constrained Reservoir Models

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ABSTRACT

This case study was undertaken for a low porosity fractured carbonate reservoir with a complex fracture network resulting from several phases of tectonic activity. The optimization of field development requires an understanding of the structural geometry of the reservoir over a range of scales, from fractures imaged in the well bore using image logs to lower resolution but wider coverage surface seismic data. Where complex fracture networks exist the inclusion of interpretations derived from VSP data, having an intermediate scale, leads to a more robust understanding of the reservoir. The integration of the image log and seismic derived interpretations was problematic due to the complexity of the image log signature and the variably poor quality seismic data. Consequently, specialist VSP processing techniques were used to identify and map reflectors in 3D space. In this study data acquired in two wells were reprocessed to interpret structural features and determine their geometries. The reprocessing involved undertaking 3-component Image Point Transform (IPT) (Cosma, 1995), polarization analysis and dip determination. The interpreted VSP reflectors were validated and integrated with the analysis of image logs and the interpretation of surface seismic data. The results showed that two reflector families were identified from the VSP data that included low angle planes interpreted as bedding and sub-parallel to bedding planes identified from the image log analysis and high angle planes interpreted as faults and sub-parallel to one of the two major fracture sets identified by image log analysis. VSP reflector elements were loaded into seismic interpretation workstations and integrated with the well and surface seismic information. This provided a constrained structural model that allowed the interpretation of seismic geometries away from well control and provided a starting point for seismic interpretation in areas where structural geometries are poorly imaged on surface seismic.

KEY WORDS: VSP, processing, integration, wireline, surface seismic.

INTRODUCTION

This study was the first phase of a larger programme of interpretation and integration undertaken for a low porosity fractured carbonate reservoir. The reservoir has a complex fracture network that has resulted from several phases of tectonic activity. An understanding of the geometry and permeability of complex fracture networks across several orders of magnitude is required for the optimisation of field development. Typically, characterization of the geometry of the fracture network involves integration of fractures imaged in the well bore derived from the interpretation of image logs with the interpretation of lower resolution but wider coverage surface seismic data. In this study area the integration of these data sets was problematic due to:

1. the complexity of the image log signature. The image log showed large numbers of faults and fractures with a great variability in dip and dip direction and it was unclear how the small scale fracturing seen in the well bore related to seismic scale features and
2. the variably poor quality seismic data made interpretation of seismic scale faults difficult.

As a consequence of the problematic integration this study utilised specialist VSP reprocessing techniques, that were applied to data acquired in two wells, to identify and map reflectors in 3D space. The reprocessing involved undertaking state of the art processing of the VSP data, the essential components of which were 3-component Image Point Transform (IPT), polarization analysis and dip determination.

STATE OF THE ART VSP REPROCESSING

To bridge the scale gap between the well derived image log data and the surface seismic data state of art VSP processing was undertaken to allow fracture imaging. VSP data from two wells were reprocessed with the specific objectives of:

- imaging fracture systems and other geological features, displaying a contrast in reflectivity and to map these in 3D space and
- producing geometric information on any structures identified that could be integrated with the interpretation of the well log information and the seismic interpretation.

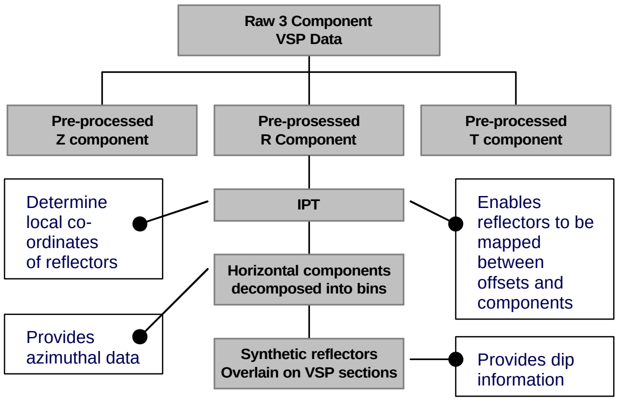

Figure 1. Processing flowchart - overview

Whether these objectives could be met was dependent on the limitations imposed on the data by the frequency content of the data, the number of components recorded (i.e. single or three component data) and the available geometries between source points, well and receiver string.

The VSP data that were available for reprocessing were acquired on land using a Vibrator source and were recorded using three component geophone strings with 20 metres between levels.

The VSP data consisted of:

Well 1: one zero offset and three far offset data sets, having different azimuths, with the far offsets located approximately 1600 metres from the well head.

Well 2: one zero offset and one far offset source approximately 2625 metres from the well head.

The signal-to-noise ratio of the data was high, with the raw data having well defined and therefore easily identifiable first onsets and all three components were used in the reprocessing of the VSP data sets. Frequency content of the data was low as may be anticipated from the general acquisition parameters discussed above.

The processing was carried out in two stages, in the first, a relatively standard sequence was undertaken including, time picking, rotation of the horizontal components; frequency analysis, velocity determination and wavefield separation.

Velocity determination, however, utilised constrained tomographic inversion incorporating anisotropy. This approach was considered more appropriate than other methods and had the additional advantage of providing additional information on the subsurface velocity structure that could be interpreted in terms of structure.
On completion of the first stage of processing, described in the flow chart (Figure 1) as *"Pre-processing"* or better termed data conditioning, the pre-processed data sets contained a large amount of reflected energy, was visible, although with interfering reflections and largely masked by non-coherent back scattered energy. Consequently the principal reflectors could not be seen clearly (Figure 2).

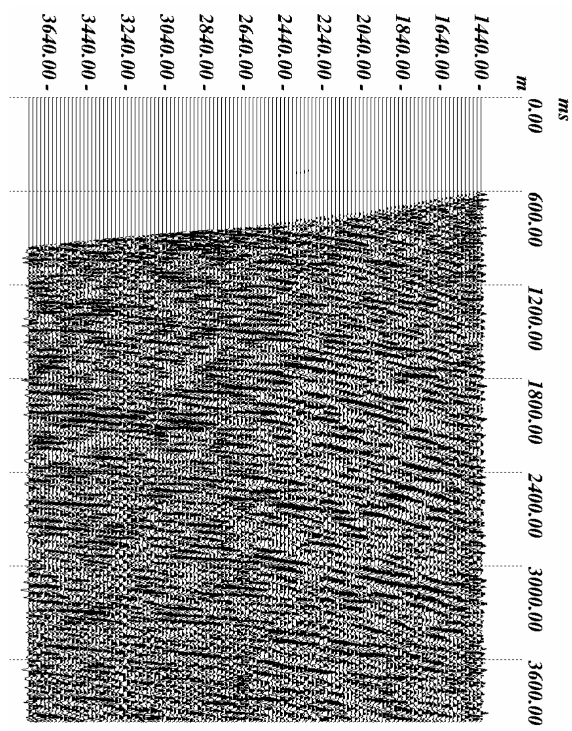

Figure 2. Z-Component data following standard processing.

The second phase of the process can be described as interpretive processing. To allow the principal reflectors of interest to be clearly seen and to determine the spatial positions 3D space further processing is undertaken. This second processing stage uses leading edge processing capabilities to separate reflected energy from back-scattered energy and to determine their locations in 3D. This phase involved 3-component Image Point Transform (IPT) (Cosma, 1995), polarization analysis and dip determination.

The IPT methodology was developed both as an interpretation tool and a filtering methodology. The methodology also exploits signal coherence to enhance weak reflections. Following IPT processing, the resultant sections were inverse transformed an example is shown in Figure 3. The difference in these two images (Figures 2 and 3) is striking. Following the removal of the back scattered source generated noise, reflectors are more clearly visible.

The interpretation of the data was based upon the ability to identify and locate reflectors within the sections following IPT processing. This approach permits the determination of both the 3D position and local orientation of the observed reflectors.

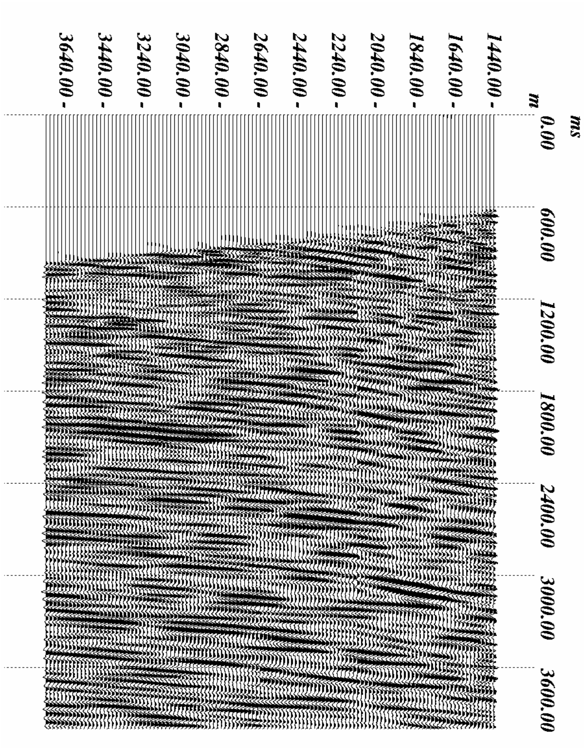

Figure 3: Inverse IPT transformed Z-Component data.

Although the IPT processing enables reflectors to be identified, it does not provide complete information on the direction to the reflector. To provide an estimate of the azimuth of the events to be determined polarisation analysis was undertaken. Reflectors are interpreted from the processed data by fitting hyperbolae corresponding to potential reflectors on the processed sections, with their directions being determined by simultaneously fitting these on several VSP sections acquired with different azimuths and searching through the polarisation processed data. The dip information for individual reflectors was then determined by additional interpretative modelling techniques following polarisation processing.

The geometrical information obtained on completion of this sequence of processing steps allows for the complete description of the reflector and these can be loaded into a visualisation code (Figure 4).

From Figure 4 it can be seen that some of the interpreted reflectors are more than 2000 metres from the well bores and some are 2000 metres below the wells.

VALIDATION AND INTEGRATION

Clearly for this processing to be of benefit and use in the construction of reservoir models the data have to be validated against and integrated with other data sources.

The results of the VSP processing were validated by comparing identified reflectors with the interpretation of the image log analysis.

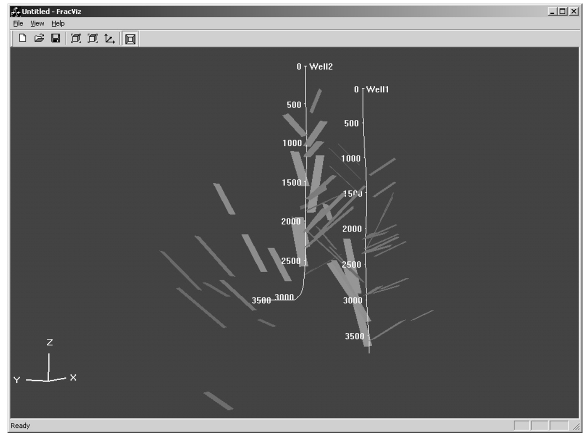

Figure 4. Visualisation of the interpreted reflector elements.

From Figures 4 and 5 it can be seen that the results show that two reflector families can be identified from the VSP data. (Only selected VSP reflectors seen in Figure 4 have been transferred to Figure 5 for reasons of clarity.)

1 Low angle planes. Those identified from the image log analysis are interpreted as bedding and sub-parallel to bedding planes (shown by Xs in Figure 5). The low angle VSP reflectors correspond to well bedded intervals in the wellbore as determined from the image log.
2 High angle planes interpreted as faults/fractures and sub-parallel to one of the two major fracture sets identified by image log analysis (shown by open triangles in Figure 5). The high angle VSP reflectors correspond to the zones of intense fracturing at the wellbore scale, suggesting that seismic scale faults represent an envelope of intensely fractured carbonate. Two types of fault were identified:

- narrow, intense fracture zones in which the majority of fractures have the same strike as the VSP fault
- wide, diffuse fracture zone associated with the development of multiple fracture sets, generally oriented obliquely to the VSP fault.

The complexity of image-log fracture distributions within seismic scale fault zones makes reconstructing large scale fault geometries extremely problematic without the additional information provided by VSP processing.

The interpreted VSP reflector elements were loaded into seismic interpretation workstations and integrated with the well and surface seismic information. This process is illustrated in Figure 6, which shows some of the elements only. Where VSP reflector elements do not intersect the wellbore these can be correlated with fracture zones identified by image log analysis.

Furthermore, integration of this fault geometry with the Top reservoir reflection on the surface seismic strongly

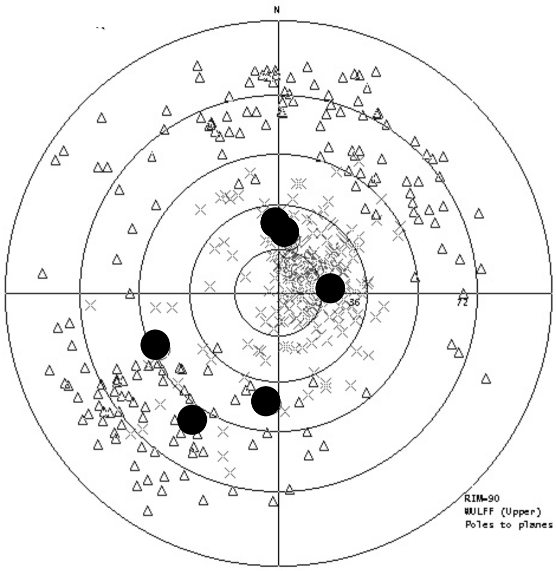

Figure 5: Stereonet comparing planes identified by VSP processing (large black circles) and image log analysis (at the wellbore scale faults/fractures are shown as open triangles, bedding planes as crosses) for the reservoir section in one of the study wells.

suggests that the two faults on the left, closest to the wellbore (Figure 6) are extensional or strike slip faults, whilst the lower angle faults on the right of this section are probably thrust faults. This provides a constrained structural model that can be used to interpret seismic geometries away from well control.

CONCLUSIONS

The results of state of the art reprocessing of the VSP data were integrated with the image log data and seismic interpretation contributing to the understanding of the reservoir.

The results of this initial study showed:

- that VSP acquisition can be powerful tool for fractured reservoir characterization when processed fully
- integration with the image log interpretation highlights elements of the image log analysis that are important at the seismic scale
- this process provides starting points for seismic interpretation in areas where structural geometries are poorly imaged on surface seismic
- integration of image log, VSP and surface seismic constrains the structural model that can then be applied in areas away from well control.

The reflector elements derived from the interpretative VSP processing added significant detail and enhanced resolution to the structural model of the reservoir. The reprocessing of the 2D VSP data sets indicated that structural features can be imaged and located in 3D space. As a consequence of this study further specialist VSP processing is being undertaken for other parts of the field.

REFERENCE

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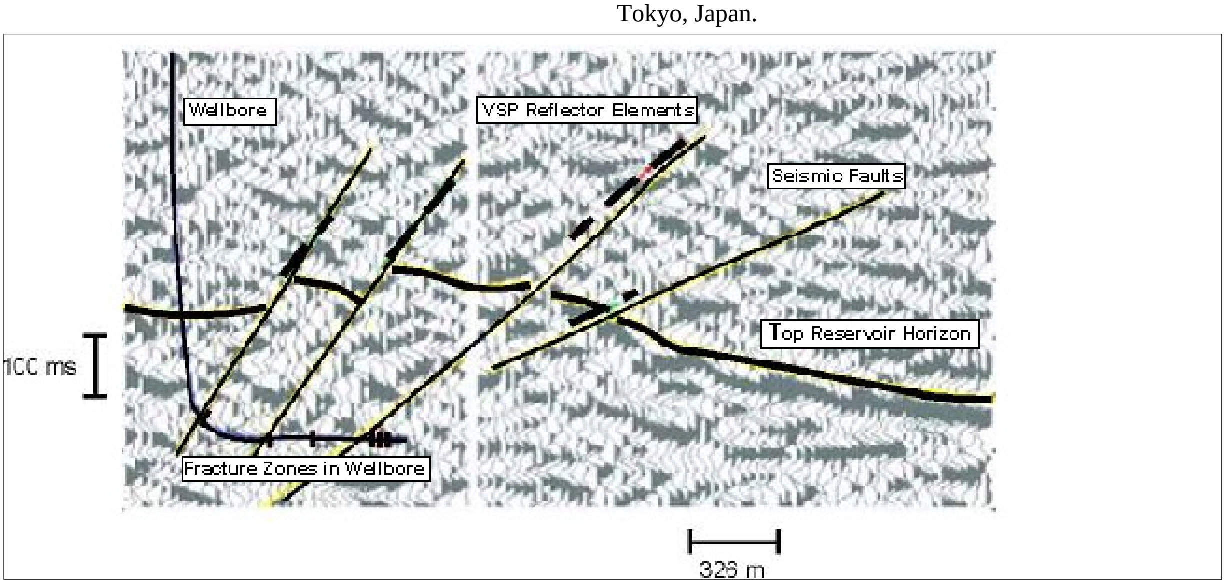

Figure 6: Seismic line through well showing how integration of seismic (solid lines), VSP (dashed lines) and well-derived information enables a well-constrained subsurface structural model to be produced.