Karst Identification and Impact on Development Plan
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Abstract

Karstification (carbonate rock dissolution during sub aerial exposure), although frequent in modern analogues is often underestimated and not properly modeled in carbonate petroleum reservoirs. Poorly understood in cores and borehole image logs, too often the presence of rock property enhancing Karst networks is rather attributed to elusive high permeability faults or fractures.

The F6 field, located in the Central Luconia carbonate province (offshore Sarawak, Malaysia) is the largest gas field within the Sarawak Shell portfolio. The reservoir is an elongated carbonate build-up of Miocene age characterised by steep flanks, a generally flat top and a central pinnacle. So far, the field was modelled as a layered carbonate reservoir with laterally homogeneous properties. Gas is contained in three major zones, namely the highly porous Zone1, which forms the central pinnacle, the tighter Zone2, which extends over the central half of the build-up, and the good quality Zone3, which extends over the whole build-up. Commissioned in 1987, the field is now maturing, with over half the reserves produced.

A 3D seismic survey was acquired in mid 2002 to support an infill drilling campaign and a potential field re-development. Initial coherency seismic attributes used for the structural interpretation suggested an extensive dendritic Karst network within Zone3. Also initial 3D dynamic simulation suggested the need for enhanced properties in Zone3 and possibly higher volumes to match the combination of contact rise and pressure data in the field.

Karst networks are often poorly expressed features on 3D seismic due to their inherent complex shapes and lateral variability. In order to image the Karst, special post-processing attributes based on coherency, phase or frequency algorithms have been tested. None of these attributes would give a full image of the Karst (mostly due to the rapid lateral variation in thickness). Therefore, these attributes were then combined using a multi-attributes volume interpretation workflow in order to build a realistic Karst model. The model was then tested against drilling operational data (mud losses). The multi-attributes interpretation allowed for the merger of different Karst “signatures” while the 3D volume based approach allowed for the spatial definition of complex geometries. Karst network geometries were subsequently incorporated into a deterministic reservoir model and risked properties could be tested and further refined against 15 years of production history in an iterative dynamic simulation workflow.

This detailed reservoir architecture mapping based on 3D seismic had considerable impacts on the F6 field projects:

- Large (open) Karst features, combined with a depleted reservoir pressure, could create major drilling problems. Therefore, strategies had to be defined by the subsurface and drilling team to mitigate the risk of Karst-induced major losses while drilling the planned development wells.

- Although not fully sampled by wells, the Karst network effective properties could be roughly derived from seismic then refined during dynamic modelling by history matching of multiple scenarios. This work is still on going and will be used to screen re-development opportunities to safeguard and increase reserves.

Introduction

F6 is the largest gas field within the Sarawak Shell portfolio, with a GIIP of ca 7 Tscf. The field covers a large area of approx. 168 km2 and has a gas-bearing interval of over 850 feet thick at its highest point. It is an elongated carbonate build-up, with steep flanks and a generally flat top of Miocene age. Gas is contained in three major zones: the highly prolific Zone1, which forms the upper part of the build-up and contains less than 10% of the GIIP, the lower grade Zone2, which extends over the central half of the build-up and the intermediate quality Zone3 which contains about 2/3 of the gas in place (figure 1).

The field was discovered, appraised and developed by 11 producer wells drilled on a dataset of multi-vintage good
quality 2D seismic. So very little was known about the detailed reservoir architecture away from the well penetrations.

Following 15 years of production and half of the reserves produced, a 3D survey was acquired in mid 2002 to support an infill drilling campaign and a potential field re-development.

**Quick looks volume seismic interpretation**

The initial structural seismic interpretation (figure 2) was carried out using GeoProbe multi-volumes (reflectivity and phase) interpretation in Sarawak Shell Bhd. 3D Visualisation room. In this workflow the primary pick is stabilised with a phase volume conditioning to increase the productivity and the quality of the picks by minimizing the artifacts created by data geometries such as stratigraphic convergence or divergence. In addition regular team reviews were held all along the project in Sarawak Shell Bhd. 3D Visualisation room to help developing an early and common understanding of the subsurface issues and focusing the team integration effort. Resulting structural surfaces in the overburden and the carbonate buildup were then refined, merged and integrated into an initial seismic model using Shell proprietary technology (reference 1).

This set provided the base for the initial “3D All-the-Way”™ model (reference 2) and for the Jason Acoustic Impedance Solid model. This interpretation was subsequently iterated twice on the basis of the two passes of Jason Constrained Sparse Spiked Inversion (CSSI): the first re-interpretation iteration was used to fine-tune the solid model of the second pass CSSI.

At this stage it became clear that the initial field model (layered and rather laterally homogeneous) based on seismic surfaces and matrix property characterisation (from well logs and cores) was quickly becoming obsolete: a strong heterogeneity could be seen within the extensive Zone3 and foresets could be mapped in Zone1. Also as the first 3D dynamic simulation models were generated on the basis of this initial field static model, it became clear that a combination of enhanced properties in the lower producing intervals (Zone3) and possibly higher volumes were required to match the combination of rise of contact and pressure data in the field (reference 2). Karstification features could explain the matrix property enhancement, but so far had not been evidenced via seismic.

**Karst imaging: predictive model based on seismic and operational data**

As the first phase multi-attributes seismic interpretation was on-going additional post-processing attributes were produced using Shell proprietary technology as well as Landmark Spectral Decomposition and GeoProbe volume attributes utilities. Once quality horizons have been produced, the value of these seismic post-processing attributes could be quickly realised through stratigraphic slicing along the intra-carbonate reflectors (figure 2): attributes values are extracted along the geological grain on the fly (GeoProbe) via horizon consistent slicing. For some subtle features or noisy areas, the optical rendering of thin slices of semi opaque volume attributes (geobodies) along the structural grain could further boost the features.

Karst features are highly laterally variable and elusive on seismic. They are often complex in shapes and highly variable in thickness. As a result no single attribute will adequately describe them. Some will map the edge (discontinuity attributes such as semblance or coherency) while others will highlight part of the feature fill and provide some basis for fill properties or geometries (figure 3). In areas where the Karst can be imaged on Jason CSSI data it corresponds to very low amplitudes (i.e. very high porosities) but calibration to log data is not possible as penetration of such features resulted in total losses and the well had to be sidetracked. It is important to note that only large Karst features can be imaged in seismic (25m x 12.5m horizontal resolution) and resolution below and around the installation is poorer due to reduced data coverage.

These results pointed towards the presence of significant Karst features in the lower gas-bearing Zone3, where most wells were TD-ing. A review of the drilling history confirmed that nearly 80% of the wells suffered some losses in this interval, of which 50% experienced very severe losses.

The match of losses (mud while drilling and sometimes cement during water shut off) to Karst highlighting on seismic is correlatable on all wells, which experienced losses (see figure 2 & 4): - for wells F06-114 (figure 2 & 4) and F06-120 (figure 4) the correlation is very good as seismic quality is high and imaging is unambiguous. Both wells intersected the same Zone3 dendritic Karst complex on the southern edge of the build-up. These wells experienced total losses and were successfully side-tracked.

- In well F06-119 and F06-113 (figure 4) the correlation requires a careful scanning of a large number of attributes as seismic quality is average due to lack of coverage in the shadow of the installation. These wells seem to have encountered the same Zone3 dendritic Karst feature.
- For the well F06-107 (figure 4) the correlation with seismic is more ambiguous as no major Karst feature can be highlighted (good quality "clean seismic" with smooth reflectors) along the trajectory but on the other hand the well is located above a deeper Zone3 Karst system, some 200 feet deeper in the build-up.
- In well F06-106 (figure 4) massive cement losses occurred during the last water shut-off campaign (none while drilling the original hole). No indication of Karst can be seen along the well trajectory but the well is located above the intersection of the "fracture induced" Karst sitting below F06-107 and the shallower fuzzy (data quality issue) dendritic Karst observed in the vicinity of wells F06-113 and F06-119.

The wells, which incurred total losses, seem to correlate well with the Karst network imaged from post-processing seismic attributes in a vertical sense (see well F06-114 in red colour on figure 2): either the well hit the level of the imaged Karst or total losses occurred up within a zone of 200ft above
Refining the Karst attributes and initial well planning

This calibration process allowed to identify the different attributes (around 15 in total) which were best at unraveling the different aspects of the karst geometries (figure 3): edges, fill, thickness, ... Then few additional iterations (around 50 attributes combination tested) varying the post-processing parameters (such as filter footprint, algorithm, etc...) helped electing the “best in class” attributes (7 to 9 attributes).

At this stage, preliminary well targets and well trajectories were picked and screened against the attributes using GeoProbe stratigraphic slicing and Landmark WellBorePlanner. This method allowed for first pass well trajectory positioning in low CSSI sweet spots (high porosity) away from Karst features highlighted by optimum post-processing attributes. Large Karst features, combined with a depleted reservoir pressure, could create major drilling problems. The confirmation of Karst being a key operational risk allowed the subsurface and drilling team to define strategies to mitigate the risk of Karst-induced major losses. No areas of major Karst development have been identified on any of the available seismic attributes along the well paths in Zone 3 (well in magenta on figure 2). This does not preclude the possibility of sub-seismic Karst features along the trajectories that might induce some losses; these possible sub-seismic Karst features could be related to Karst located deeper in the build-up in the base of Zone 3. However, field-drilling history indicates that the associated losses with sub-seismic Karst (F06-107 for instance) are manageable.

Karst geometries “merging” for static model building

Seismic attributes information merging is key to the reservoir architecture mapping from seismic. For simple geometries, it is often performed through manual picking in 3D while examining the signature of the different seismic post-processing attributes; speed is often key to toggle attributes swiftly and to make an educated guess (with reference to analogues) as well as advanced opacity rendering capabilities to interpret through artefacts and noise via surface fitting. In some cases with good data quality, geometries can be elegantly described by a combination of two well-chosen attributes and most of the features can be picked via semi-automatic voxel picking. In the case of Karst features, the information provided by the large number of attributes necessary to describe the full geometries need to be merged consistently to envisage using semi-automatic voxel picking techniques. For this project we elected to cluster the geometries using Shell Neural Networks technology to classify these complex geological features in many attributes dimensions (reference 2). The resulting classification was then segmented in voxel classes using Shell “body-checking” techniques and classes were subsequently inspected against well data and post-processing attributes signatures to determine meaningful Karst classes (figure 5). Following some Karst bodies editing, the envelope (top and bottom) was exported to our static modelling environment (Petrel) where the initial well trajectories could be refined for maximum delivery and the model upscaled to the reservoir simulator. Subsequently uncalibrated Karst properties could then be tested in our reservoir simulator model as part of an integrated 3D-All-The-Way workflow (reference 2 & figure 6).

Then the karst network effective properties are modeled as well as some other key parameters, by history matching multiple scenarios against 15 years of production. This study is currently being finalized and will be deriving a range of possible realisations that will be used to screen re-development opportunities to safeguard and increase reserves.

Conclusions

The number of post-processing seismic attributes has steadily risen through years and visualisation engines have increased dramatically in speed and ability of handling larger datasets but we are still often struggling to incorporate this overwhelming amount of information directly (i.e. not just visual trends) into our geological models to realise the full value of multi-attributes interpretation. The workflow applied in this project is by no mean unique but it is a fit for purpose solution to generate a more robust and also more detailed (sometimes nearly down to loop level) interpretation that could be used in effectively constraining geological static model and de-risking well drilling operations in hazardous reservoirs.

A specific learning from the F6 study was that focus on Reservoir Architecture from 3D seismic using multi-attributes could dramatically improve the geological modelling. Conventional model building utilises seismic information to define the broad structural framework and to extrapolate well properties away from the well using seismic acoustic impedance as a guide. Karst networks although not properly sampled by the wells can be incorporated deterministically in the static model with risked properties. This concept, tested against 15 years of production history and operational experience in our iterative 3D-All-The-Way methodology clearly demonstrated the benefit of the additional information extracted from multi-attributes seismic interpretation.

Acknowledgments

The authors would like to thank Petronas for authorizing the publication of this paper. Special thanks to the members of the extended team that has been involved in the various stages of the study: Mah Kok-Gin for the petrophysical support, Miltos Xynogalas for his detailed work on seismic inversion as well as Eric Merrall and Norbert Beelen (drilling engineers).
References

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Figures

Figure1: Cross section of the field (seismic attribute is CSS Absolute Acoustic Impedance)
Figure 2: Multi-attributes seismic interpretation showing
1. Top Reservoir mapping
2. Mapping of seismic attributes on internal reflector
3. Imaging of Karst using Opacity blending
4. Karst calibration (total losses occurred in red well F06-114 while green well F06-114S1) was drilled loss free) and well planning with coherency attribute (purple trajectories)
Figure 3: Top view Karst features highlighting from Attributes mapped parallel to Top Zone3 (from top to bottom):
1. Coherency highlighting the Karst edges
2. Maximum Entropy Spectral Decomposition highlighting the karst fill
Figure 4: Top view Karst features highlighting using combination of three Attributes mapped parallel to Top Zone3 (coherency, Maximum Entropy Spectral Decomposition and third iteration CSSI) with severe to total losses wells:

1. Wells in yellow (F06-113, 114, 119 & 120) experienced total losses
2. Wells in green experienced severe but manageable losses (F06-106 was drilled nearly loss-free but experienced losses during workover following acidisation)
Figure 5: Karst Volume Interpretation from Attributes Neural Networks classification (from top to bottom)

1. Seismic cross section with facies clustering
2. Data segmentation on non Karst related facies
3. Data segmentation on Karst related facies 1
4. Data segmentation on Karst related facies 2
Figure 6: Karst Interpretation from seismic interpretation to dynamic simulator in “3D-All-The-Way” iterative workflow “powered” by 3D Immersive Review Sessions

Clockwise from top left:
1. Karst envelope interpreted from multi-attributes
2. Base of Karst modeled in Petrel
3. Karst cells (Top View) in dynamic model

Architecture
Properties
From seismic

3D All the Way™ (Immersive) Reviews for fast iterations

Poro/Perm Upscaling

Karst/Matrix volumes
Tight layers