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Integrated Seismic Illumination and Gravity Modeling in Refinement of a Subsalt Interpretation,

*David Walraven *, Jock Drummond and Arnold Rodriguez, (Anadarko Petroleum Corporation) Chih-Wen Kue and Toshi Chang, (WesternGeco) and Dale Bird, (Bird Geophysical)*

Summary
Top salt geometry exerts a strong effect on the illumination of both the base salt and on underlying subsalt reflectors. A 3D seismic illumination study can be useful for the interpretation of these events. It may also distinguish subsalt amplitude anomalies due to rock property changes (hydrocarbon saturation for example) from amplitude anomalies due to illumination differences. A 3D illumination study was carried out to assess the significance of an apparent bright spot on a key subsalt mapping horizon. The study indicated that the anomaly in question was probably ***not*** due to focusing effects. The illumination results also provided evidence for the existence of a salt root coinciding with the sudden disappearance of the base salt reflection event. The presence of the salt root is further supported by the results of a gravity modeling study.

Introduction
Prestack depth migration (PreSDM) has proven a powerful tool in sub-salt exploration. However interpretation of the resulting depth volumes can pose problems in understanding of the subsalt amplitude variations. Kirchhoff algorithms typically do not compensate for amplitude variations induced by salt geometry. In particular, crests or 'sails' in an otherwise roughly tabular salt body can introduce very significant focusing effects on the base salt and deeper reflectors. These focusing effects can be mis-interpreted as indicative of lateral rock property changes. A 3D illumination study can provide the means to at least partially differentiate the effects of amplitude variations caused by pore fill or lithology changes from those due to salt geometry-induced illumination. An illumination study, in conjunction with potential field modeling, can also help resolve salt geometry issues where the seismic time or depth volume alone is ambiguous.

The Problem
Interpretation of a Kirchhoff PreSDM volume showed an attractive subsalt structural closure (Figures 1 and 2). An apparent amplitude anomaly was observed on one of the key subsalt mapping horizons (Figure 3). Fluid substitution modeling using existing well control supported the presence of significant impedance changes due to gas saturation in subsalt reservoir units. The salt geometry is characterized by a roughly tabular salt body terminating in a deflated salt basin on the east. A prominent crest in the top salt forms a ridge paralleling the western side of the deflated zone.

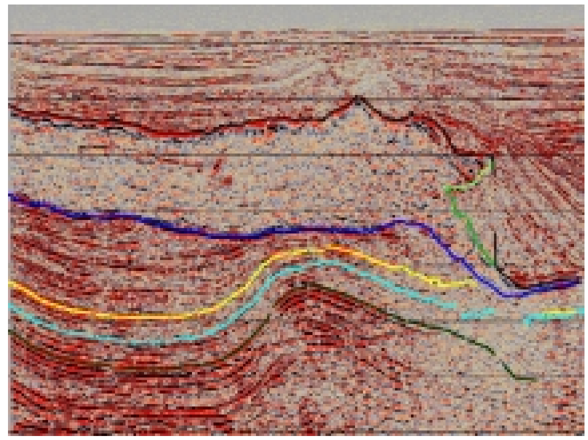

Figure 1: Inline "P" extracted from the Kirchhoff PreSDM volume. Horizons extracted for which illumination modeling was subsequently done are base salt (blue); subsalt A (yellow) and subsalt B (aquamarine). Data licensed from WesternGeco

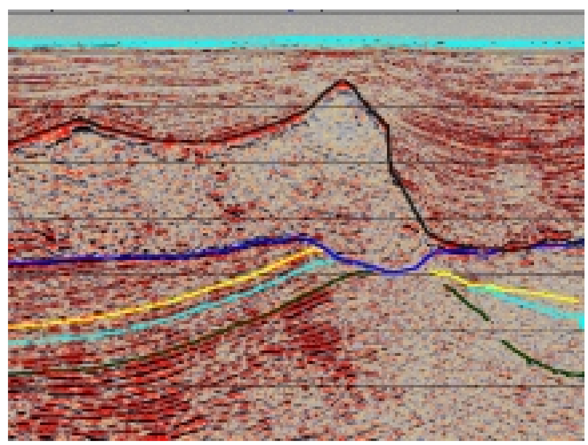

Figure 2: Crossline "M" extracted from the Kirchhoff PreSDM volume. The base of salt reflector disappears abruptly under the top salt crest. Potential illumination variations are evident on the western flank of the subsalt structure. Data licensed from WesternGeco

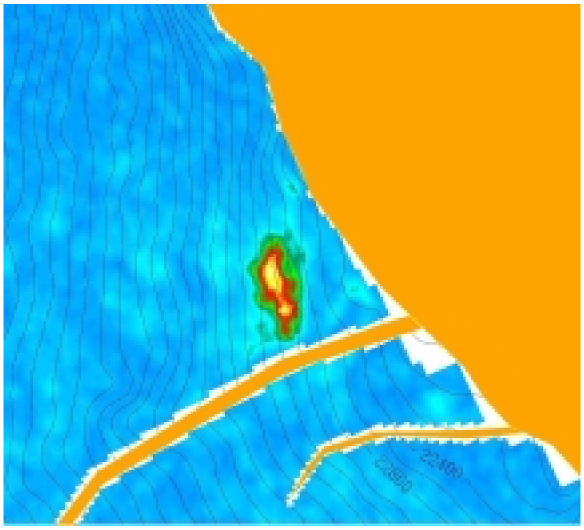

Figure 3: Amplitude map extracted for subsalt horizon "A" from the Kirchhoff PreSDM volume.

As indicated by seismic data, the base salt event suddenly disappears. The region of 'missing' base salt event is underlain by a zone of poor imaging. Southwesterly subsalt dip is observed to the west of this zone while northeast dip is present on the east of the disrupted data zone. One interpretation is that a simple anticline is present subsalt while another possibility is that a salt root accounts for the disturbed subsalt zone and the abrupt termination of base salt reflectivity above it. To resolve these various issues a 3D seismic illumination study was initiated.

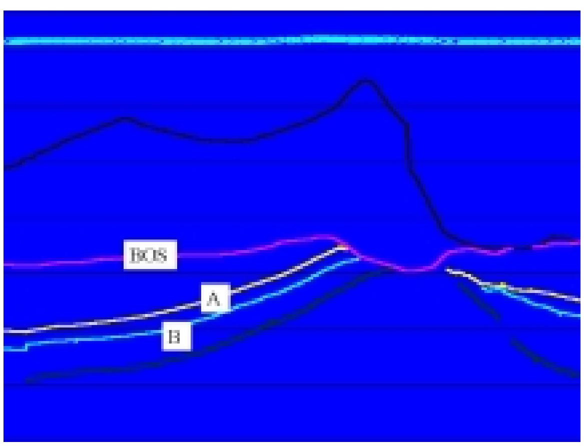

Figure 4: Profile through the 3D model corresponding to the position of crossline M. The three horizons for which illumination maps were computed are BOS, "A" and "B".

The Illumination Model

A 3D layer-based model was constructed for the illumination study. The model was built directly in depth using horizons interpreted from the Kirchhoff PreSDM volume. Two supra-salt horizons were used together with the top and base salt from the PreSDM velocity model. Three horizons were added subsalt. The generally good quality of the subsalt reflectivity facilitated the interpretation of the subsalt horizons. Appropriate velocities were extracted for each sedimentary layer from the PreSDM velocity model. Acquisition geometry was modeled using the P190 navigation data for the Western Ultra survey. Inline direction of the seismic data is northwest-southeast or approximately parallel to the strike of the top salt ridge on the western margin of the deflated zone. The crossline direction is close to a true dip orientation on the subsalt closure. Following review of various model horizons and acquisition data, illumination maps were computed for three target surfaces: base salt, and the two uppermost subsalt horizons. A 3D forward modeling code utilized wavefront reconstruction for seismic amplitude estimation on each of the target horizons. These amplitudes were then weighted with the hits per bin computed independently on each target horizon using raytracing. The result was a set of illumination depth maps equivalent to surfaces extracted from a PreSDM volume.

Analysis of Illumination Results

Inspection of the illumination maps (Figures 5, 6) provided a number of insights. First, the illumination map for Horizon A (Figure 5) shows a weak illumination response in the vicinity of the anomaly mapped from the PreSDM data volume (Figure 3). Thus the latter anomaly is most probably due to changes in rock properties not to focusing effects related to salt geometry. This is a very important finding and was the primary motivation for the entire illumination study. Secondly, the base salt illumination map (Figure 6) shows an intense amplitude anomaly pattern which coincides with the flanks of the top salt ridge. The relationship between top salt geometry and base salt illumination is indicated in the 3D rendering (Figure 7). This type of focusing phenomenon is typical of salt 'sail' features. Note however that there is no base salt amplitude present on Crossline M under the salt crest. There is an abrupt disappearance of the base salt reflection event as one moves under the overlying crest in the top salt. The most likely explanation for this situation is simply that the base salt is not as interpreted. Rather, the absence of the base salt event on the PreSDM data implies the likely presence of a salt root or stalk. This hypothesis is also consistent with results of gravity modeling. The final point that follows from inspection of the illumination maps is the progressive narrowing of the illuminated zone with increasing depth below base salt. [1] This phenomenon has been well illustrated by wave equation shot modeling elsewhere. The practical result of this salt-induced focusing is the progressive limitation of maximum angle with increasing depth below salt. This effect in turn reduces the sensitivity of subsalt event imaging (gather event flatness) to migration velocity.

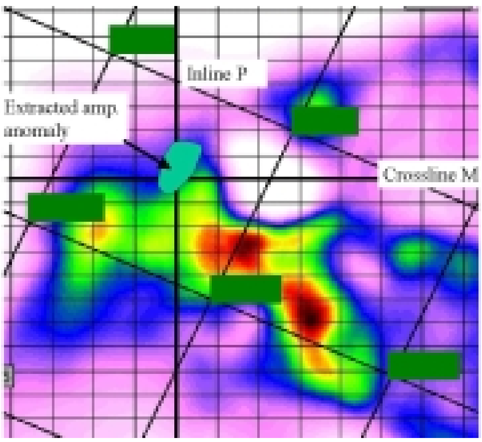

Figure 5: Illumination map computed for subsalt horizon "A". Note the position of the amplitude anomaly extracted from the PreSDM volume for this same horizon.

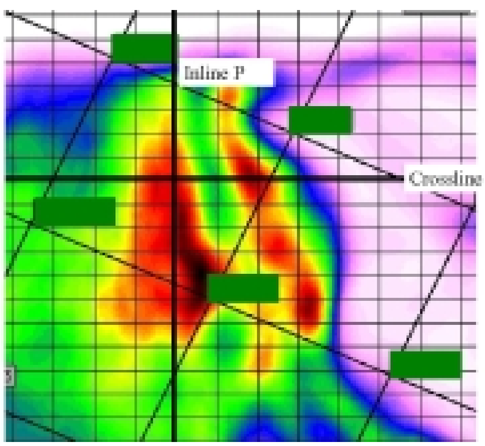

Figure 6: Illumination map for the base salt horizon. Very strong illumination is present at positions corresponding to the flanks of the crest in the top salt. The region between is still moderately well illuminated even though no base salt reflection event is evident on the seismic

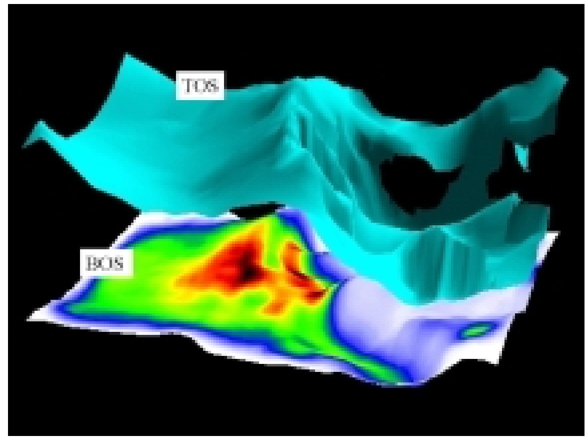

Figure 7: Rendering to the top salt surface (TOS) and illumination map on the base salt (BOS) from the illumination model. Note the bifurcation in the intense illumination pattern on the BOS.

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Potential Fields Analysis

Illumination modeling in conjunction with the PreSDM data volume supports the existence of a salt root on the west flank of the deflated zone. This finding is consistent with the results of gravity modeling. Marine gravity surveys over the area of interest were modeled for two salt geometry cases (one with a root and one without). Interval velocities from the PreSDM velocity model together with density data from nearby well control were used to constrain the density of both the supra and subsalt sediments. Top salt geometry was based the PreSDM velocity model as was the base salt with the exception of the area where no base salt reflection event is present. In case 1, the base salt was extended smoothly across this region of no reflection; in case 2 a slender salt root was incorporated (consistent with seismic reflection constraints). Modeling of the gravity data supports case 2. Thus two independent lines of geophysical evidence support the presence of a salt root on the western margin of the deflated zone.

Conclusions

Illumination modeling has traditionally been used for the past several years to validate amplitude anomalies and to assist in the optimization of seismic acquisition. As used in this instance, illumination modeling played an important role in validating a subsalt amplitude anomaly. However, it also proved very helpful in obtaining an improved salt geometry interpretation in conjunction with gravity modeling. Even with the benefits of Kirchhoff PreSDM, complex salt geometries can pose difficult interpretation issues. Additional sources of information such as those provided by illumination and potential field modeling can materially assist in improving the interpretation. . Ideally, these types of modeling should form an integral part of the subsalt interpretation process. Constructing a more accurate understanding of the subsurface, especially in a subsalt environment, requires the utilization of multiple datasets. It should be emphasized that illumination modeling and potential field methods have intrinsic limitations but their strengths can be leveraged when used in conjunction with more conventional seismic data volumes.

In regard to the issues addressed in this study, it should be emphasized that amplitude anomalies principally due to rock property changes may also have an amplitude component arising from salt geometry-induced focusing. However, illumination modeling indicates that the extracted amplitude anomaly on Horizon "A" is probably ***not*** due primarily to salt focusing effects. The dominant contribution to the observed amplitude is more likely due to rock property variations including the possibility of hydrocarbon saturation. An improved understanding of salt geometry also resulted from the study. Both the illumination and gravity modeling support the presence of a salt root underlying the prominent salt ridge in the prospect area.

Acknowledgement

We thank WesternGeco for the permission to show the seismic data examples and Anadarko Petroleum for the permission to publish this work.

[1] 3-D Subsalt Wave-Equation Depth Imaging: A Case Study From the Hickory Field, SEG Extended Abstracts, 2001, *John O'Brien, Danny Addis, Jock Drummond, Glenn Raney and David Walraven, Anadarko Petroleum Corporation, and John Wiegant, Jaime Stein and Scott Key, NuTec Sciences, Inc.*