PREDICTING SEAL RISK AND CHARGE CAPACITY USING CHIMNEY PROCESSING: THREE GULF OF MEXICO CASE HISTORIES

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Summary
This paper describes how seismically derived 3D chimney volumes or "cubes" can be used to assess seal risk in exploration wells in the shelf and upper slope of the Gulf of Mexico. For this evaluation four examples of hydrocarbon accumulations with effective seals, one example of a breached seal, and one untested prospect are evaluated. From these examples, we have developed criteria to quantify the seal risk and charge capacity by differentiating different types of chimneys and other information. Such criteria can then be applied to predict seal integrity on un-drilled prospects. The emphasis will be on how chimney cube interpretation can be used in an integrated workflow to constrain uncertainty on both seal and charge for hydrocarbon exploration and rank prospects.

For the intact seals, three of the examples studied had minor chimneys above the accumulation and clear evidence of chimneys providing vertical migration into the reservoir interval. These traps were also characterized by relatively low relief and inferred low strain rates. One of the intact seals was adjacent to a zone of vertical chimneys related to salt movement. However the reservoirs themselves were outside this disturbed zone and were characterized by moderate to low relief and low strain. In contrast, the trap which represented a breached accumulation was adjacent to a major chimney which vented hydrocarbons to the surface. It was also characterized by high structural relief and was within the disturbed zone, inferring higher strain rates. The prospect evaluated was also adjacent to a zone of vertical chimney development. However, the reservoir objectives for this prospect were outside the disturbed zone inferring lower strain rates. The trap also had moderate relief and is interpreted as a moderate to low risk for seal failure.

Introduction
Since the advent of 3D seismic technology, the primary focus of interpreters has been to delineate the structures and predict reservoir and its quality. While 3D has been mostly successful in determining geometry, many exploration post-mortem studies indicate seal failure or limited ca charge pacity and small hydrocarbon column heights, are the main cause of dry holes. The ability to predict seal effectiveness is especially critical in the deep water Gulf of Mexico, where drilling costs require traps with hydrocarbon column heights sufficient to hold sizable hydrocarbon accumulations. In a recent seminar on GOM deepwater dry holes (McVey, 2000) ten of the eleven dry holes were due in part to seal failure.

Most traditional technologies addressing seal prediction focus on two major issues. First, they address the sealing capacity and lateral continuity of the top seal, primarily by measuring capillary pressures from on trend or analogous intervals. Second, they calculate shale gouge ratios and sand on sand juxtaposition. This is appropriate in shallow water deltaic settings, where sand shale ratios are relatively high and the sealing capacity of the inter-deltaic silts and shales are often poor. However, in deepwater settings, the ratio of sand to shale is very low, and generally the quality of the sealing shales (often represented by high-stand condensed sections) is very good. Hydraulic fracturing, in contrast, may be much more frequent cause of seal failure in the deepwater depositional setting, both in the deeper geo-pressured intervals on the GOM shelf and in the present day upper slope. This is due in part to a narrower window between the pore pressure of the sands and the fracture gradient of the encasing shales in this setting. Any intense deformation, related to salt or shale movement, can result in the vertical fracturing and the formation of gas chimneys from gas dissolved in the formation waters.

Bolchert et al (2000) have shown the relationship of hydrocarbon accumulations to shallow seeps or chimneys and structural style in the upper slope of the Gulf of Mexico. They have suggested that major hydrocarbon seeps may be related to poor trap and /or seal development. Of the thirty-five fields and discoveries only six occur within 4.8 kilometers of seeps. Gas chimneys are usually caused by significant pressure gradients in the sub-surface and are characterized by low velocity and higher pressure. Finkbeiner, et al (2001) have discussed the mechanisms by which hydrocarbons can migrate vertically in the sedimentary section. In Eugene Island 330 Field, they showed that dynamically constrained reservoirs were characterized by short oil columns, whereas reservoirs with static conditions have very long gas and oil columns. Dynamically controlled traps are expected to be much more common in the deep water where sediments are not well consolidated and the differential between fracture gradient and pore pressure is small. With chimney cube we can detect such fault related migration patterns directly in the seismic data, (Heggland et al (1999), Aminzadeh et al (2002), Alvarado et al, (2003) Ligtenberg (2003) and Ligtenberg (2004). Through integration of gas chimney probability data, basin modeling information and pressure data, we can often determine areas of optimal seal.

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Chimney Processing

Chimney processing was undertaken to highlight vertical fluid migration pathways in the seismic data and relate them to seal integrity. Processing was conducted for three datasets, which included the sub-salt Tanzanite discovery in Eugene Island South Addition Block 346, (Figures 1, 2, 3 and 4), the Sazerac sub-salt breached trap in Green Canyon 99 & 143 (Figure 5) and the Cipango structure in the upper slope (Figure 6) and, These datasets included two Auger in Garden Banks 426 and the Raptor in Ship Shoal Block 296. For details of chimney processing procedure see Heggland et al (1999) and Aminzadeh et al (2002).

Among attributes used for training: Reference Time, Energy, , Polar Dip Variance, Polar Dip, Similarity, Cube Similarity, and Similarity Sum. A key step in this procedure is that most of the attributes are extracted in three separate time windows: one above, one centered around and one below the point of investigation. In this way we utilize the fact that chimneys are vertical bodies with a certain dimension. Another way to capture this vertical alignment is to perform a sum of the attribute over a wide window. Similarity sum was the single most important attribute for this training.

Interpretation

Here we want to determine criteria for resolving distinctly different types of chimneys related to trap-seal integrity. We utilize this information for effective seal prediction in similar sub-salt prospects. Essentially, gas chimney processing highlights vertically aligned chaotic seismic response which may be related to vertical gas migration. The reliability depends on a number of factors, including: the availability of good training data, the accuracy with which the interpreters can detect suspected gas chimneys as input to the training data set, and the quality of seismic data. The type of attributes and neural network used are also critical.

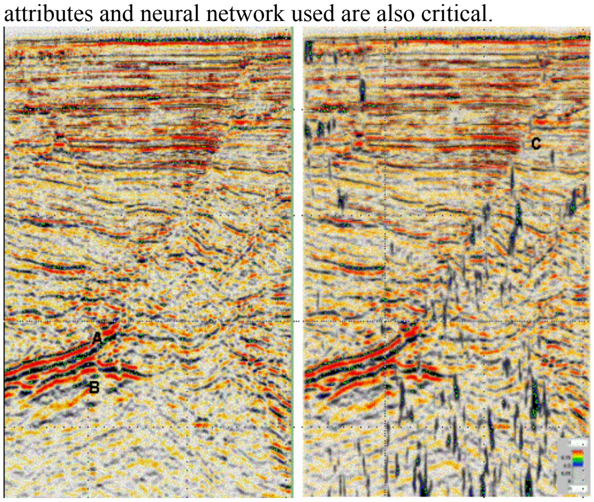

Figure 1, Original seismic (left) and Chimney overlaid on seismic data from Tanzanite (right), (Line A)

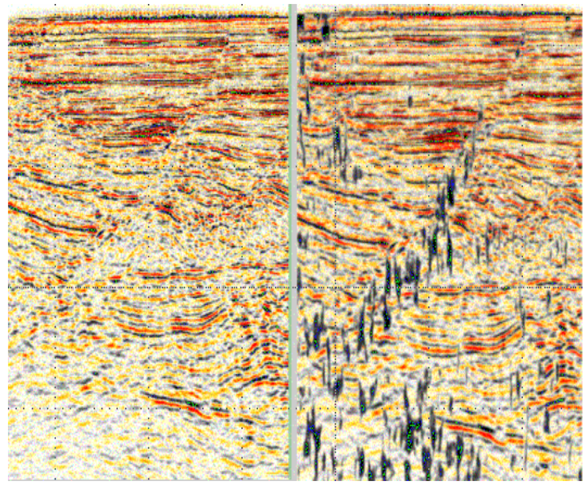

Figure 2, Original seismic (left) and Chimney overlaid on seismic data Tanzanite flank (right), Line B

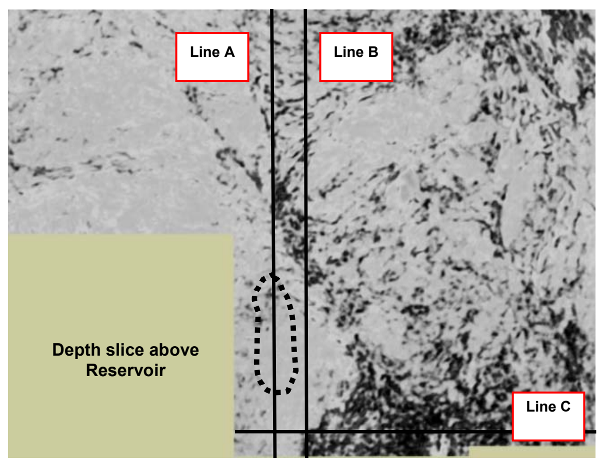

Figure 3, Chimney Probability Depth Slice above Tanzanite.

Not all vertical disturbances in seismic data are related to gas migration. False anomalies can result from a number of causes. They can be due statics issues, processing or acquisition anomalies (possibly due to differing vintages of data). These anomalies, however, will often show no clear relation to the structural or stratigraphic feature that is being investigated. Data wipe-out zones due to near surface topography imaging issues, shallow amplitude anomalies, or faults can also create false chimneys. These anomalies, however, often have a cone shaped appearance which is related to the shape of the object causing the ray-path distortion. True gas chimneys which are aligned along faults can be distinguished from fault shadows due to imaging issues. True chimneys generally have a circular pockmarked appearance when viewed on seismic time slices while fault shadows are normally a broader zone of energy attenuation or noisy data.

Chimney cube data must be integrated with other geologic information, both on the regional and prospect specific level, to improve the reliability of its interpretation and use it as an effective exploration tool. It is especially useful to integrate the chimney data with AVO and fluid factor attributes. Attenuation of high frequencies below thick gas sands has been recognized in many geologic settings. AVO by itself can not discriminate lithologic and fluid density (hydrocarbon) affects conclusively. However, AVO, frequency attenuation, and gas chimney data, together provide relatively independent indications of a hydrocarbon filled reservoir. Figure 4 shows a way that these attributes can be used together to constrain risk on hydrocarbon charge. These qualitative indications can then be supported by seismic modeling.

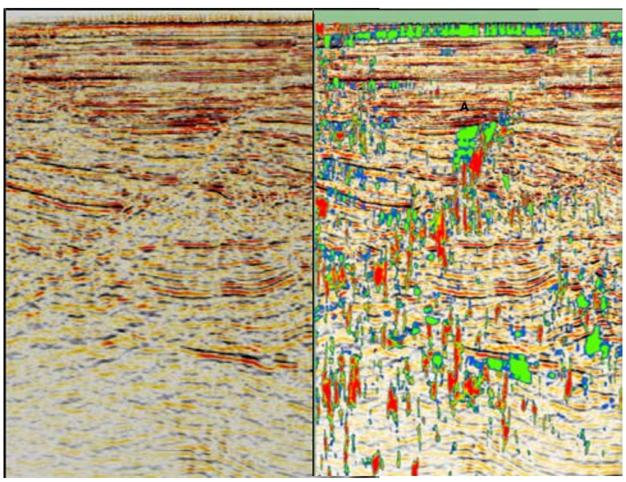

Figure 4, Chimney and frequency attributes overlain on seismic data from Tanzanite .

Observations

Tanzanite Discovery (Eugene Island 346): Figure 2 shows the Tanzanite objective reservoir (A) below a thin salt sheet (B). The seismic data is shown on the left, and the seismic data with the chimney probability data overlain is shown on the right. Only chimney probabilities above 50% are shown. Note that there are few chimneys above the reservoir, suggesting minor leakage from the reservoir. In contrast there are a number of chimneys below the reservoir objective which may contribute to the charging of the reservoirs. There is also an indication of chimneys on the flank of the Tanzanite trap which may be charging the shallow fault (C). There are also indications of fault related gas chimneys in the section below the Tanzanite reservoir interval. These chimneys may be involved in charging the Tanzanite reservoir.

It is important to note that the Tanzanite structure is a relatively low relief structure and thus may have not undergone a significant amount of strain. In contrast a strike line on the flank of the Tanzanite trap (Figure 2) shows significant chimney activity related to the shallow fault. These chimneys are inferred to be due to shear failure related to gas migration along the fault zone. This is supported by the shallow amplitude anomaly which is indicated to be gas bearing due to its strong low frequency shadow. A chimney probability depth slice, immediately above the reservoir interval, shows the lack of gas chimneys above the trap (Figure 3)

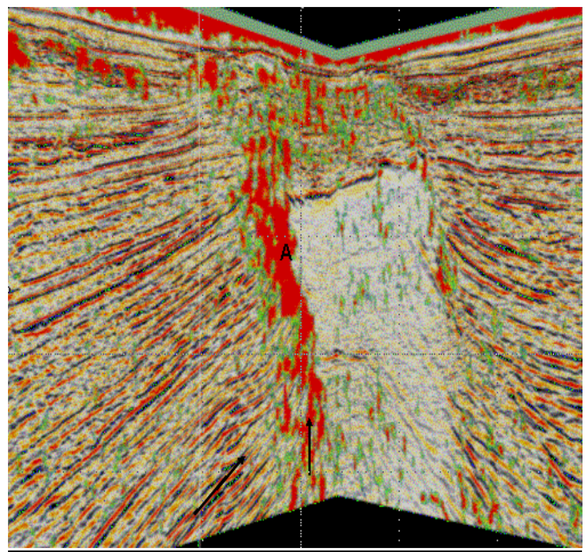

Figure 5, Chimney overlain on seismic for Sazerac dry hole.

Sazerac Breached Trap: A seismic in-line and cross-line close to the Sazerac dry hole (Green Canyon 99) is shown with chimney probability sections overlain. The Sazerac dry hole encountered reservoir quality sands in the sub-salt section (Figure 5). However these sands were wet, indicating either a breached trap or lack of charge. In contrast to the Tanzanite discovery, this structure has a significant gas chimney adjacent which leaks hydrocarbons to the surface. The Sazerac structure is a high relief structure which tends to create excess pressures in the reservoir interval due to the centroid effect. These excess pressures may inhibit seal capacity, because reservoir pressures may be near the fracture gradient. Also this may limit hydrocarbon charge into the reservoir interval. Hydrocarbons migrating vertically in the major chimney will flow from high to low pressure, and will thus bypass the reservoir interval and be vented to the surface.

Cipango Area A seismic cross-line through the Cipango structure with chimney probability overlain (Figure 6) shows the trap style for the prospect. The chimney overlay shows a strong chimney in the very shallow section. However, in the objective section, chimneys are weakly developed. The shallow chimneys are probably related to the low effective stress of the poorly lithified sediment in the very shallow subsurface. In contrast the objective section has less risk for seal failure.

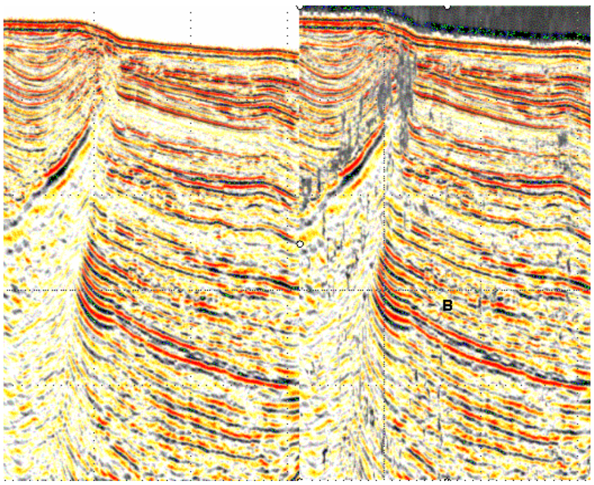

Figure 6, Chimney data overlain on seismic Cipango area.

Conclusions: Criteria for Seal and Charge Risk :
Based on the three data volumes used in this study the following criteria for assessing seal risk, using chimney processing are proposed:

- Traps with no significant gas chimneys over the crest of the structure are effective seals. Both the Tanzanite and Raptor (not presented) discoveries fall in this category. Both structures show vertical charge into the reservoir interval. Tanzanite also shows fault related vertical leakage very close to the spill point of the structure.
- Traps with reservoirs outside the fractured zone which are immediately adjacent to chimneys at their updip termination can be effective seals when: 1) the traps have low to moderate relief; 2) have undergone moderate to low strain. The Auger discovery and the Cipango structure fall into this category. Significantly these traps have low to moderate relief, and in the reservoir intervals the highest relief is often on an adjacent structure thus potentially releasing pressure on the reservoir and increasing its retention capacity. The character of the chimneys themselves may be an important factor. However we do not have enough data to confirm this. The chimneys adjacent to the Auger and Cipango reservoirs have discrete pencil-like chimneys.
- Traps with reservoirs outside the fractured zone and chimneys immediately adjacent to the up-dip termination are not effective seals when 1) the structure is high relief or undergone significant strain. Traps with this characteristic are recognized in these datasets. A lack of obvious direct hydrocarbon indicators associated with these structures, in the otherwise productive stratigraphic intervals, suggests probable breached accumulations.
- Traps with reservoirs within the fractured zone which are adjacent to chimneys are not effective seals when they have high relief or are highly strained. The Sazerac dry hole falls into this category. Because these traps are relatively high pressure, they may also fail because of a lack of charge. Hydrocarbons which are in the main chimney flow from high pressure to low, and thus bypass the more discontinuous high pressured sands. The high structural relief of this type of trap further accentuates the problem. The character of the chimneys themselves may be an important factor. The chimneys adjacent to the Sazerac structure are very extensive.
- Hydrocarbon reservoirs are underlain or immediately adjacent to chimneys. Significantly all three discoveries evaluated for this project had evidence of fault related hydrocarbon charge via chimneys, either immediately adjacent as in the Tanzanite and Auger discoveries or immediately below as in Raptor.
- Shear induced fracturing related to faulting is common for oil migration. Gas migration can occur via broad gas clouds, although additional mechanisms are possible. The Auger and Tanzanite oil discoveries had more subtle fault related vertical migration. Although this study was not large enough to distinguish hydrocarbon phase based on chimney type, prior work has demonstrated that broad gas clouds are often linked to leakage of gas dissolved in the pore water. Oil migration in contrast is generally via fracturing related to shear. In this structural setting shear is generally induced by faulting related to salt movement.
- Reservoirs are underlain by zones of increased strain. In this limited data set we recognize a relationship between zones of high strain and chimneys. This strain is induced by the underlying salt movement and faulting. Because we see a strong relationship between both proven and suspected (or possibly breached) hydrocarbon reservoirs and chimneys, zones of high strain are critical to providing vertical charge in the Gulf of Mexico. As we continue to look for hydrocarbons in deeper targets, where amplitudes are not reliable, detecting these highly strained areas and their associated chimneys can give us critical information to reduce prospect risk.

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