Steering Virtual Sources for Salt and Subsalt Imaging

Albena Mateeva, Javier Ferrandis, Andrey Bakulin, Patsy Jorgensen, Carol Gentry, and Jorge Lopez, Shell International E&P Inc*

Summary

Using walk-away or 3D VSP data to create Virtual Sources in salt is a new useful tool for imaging and assessing drilling hazards in salt and immediately below the base of salt. It can be also used for accurate positioning of steep salt flanks. Creating Virtual Sources inside homogeneous salt allows us to eliminate any distorting effects caused by rugged top salt and complex overburden. The Virtual Source radiation pattern can be controlled and steered in the direction of desired illumination by selecting appropriate shot ranges at the surface. These new Virtual Source applications can have significant business impact for de-risking drilling through salt and improving well targeting in areas with salt.

Introduction

The Virtual Source Method (Bakulin and Calvert, 2004, 2006) turns VSP receivers into down-hole "sources" and helps us see under complex overburden where other seismic methods have difficulties. A typical example of problematic overburden through which we would like to redatum via Virtual Source (VS) is rugged salt (Fig 1). Creating VS from VSP data underneath salt can help us image subsalt targets with unprecedented clarity. Ideally, such images would be based on receivers below salt. However, even if the VSP receivers are in salt (VSP-s are often acquired to look ahead in preparation for exiting salt), VS offers benefits. For example, we can still image subsalt sediments more clearly with VS than with surface sources because issues related to rough top salt become irrelevant. In addition, Virtual Sources in salt allow us to examine potential drilling hazards such as inclusions in salt and pore pressure anomalies below salt, as well as to see more accurately where the salt base/flanks are. These are the type of applications discussed in this paper. Cost benefits from them can be substantial, given that each drilling incident or sidetrack can cost $5M - $10M in the Gulf of Mexico. We start by a brief recap of VS computations. Then we show two examples of VS in salt for hazard prediction (offshore) and salt flank location (onshore).

Virtual Source creation

While many formal derivations of the Virtual Source Method have appeared in the literature, for the geophysical practitioner, the logic depicted in Fig. 1 seems to capture best the essence of the method. We take as input walk-away or 3D VSP data and use them to create a Virtual Source at every receiver location. From a processing standpoint it suffices to visualize the technique as a cross-correlation of direct-arrival energy at one buried geophone (the 'Virtual Source') with the trace recorded at a second geophone (the receiver). The result, once summed over a suitable set of illuminating physical sources, approximates the response of a buried source-receiver pair in the subsurface. This data-driven Virtual Source redatuming does not require any velocity information - this is the crucial factor allowing us to create VS data in any complex medium. Of course, to image targets with the so created VS data, we still need to know the velocity between the receivers and the target. But this is a much weaker requirement than knowing the entire velocity model to the surface, as required for conventional imaging with surface sources. And in the case of receivers in salt, imaging the salt flanks or inclusions in salt is particularly easy because we only need the salt velocity – relatively constant and readily measurable, for example, from Virtual Checkshots (Mateeva *et al.,* 2006).

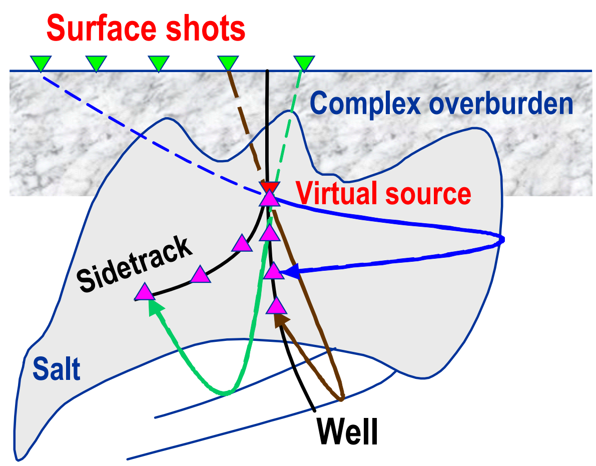

Figure 1: Steering Virtual Sources for salt and subsalt imaging.

Example I: Look-ahead VSP with Virtual Sources for in-salt hazard and salt-exit prediction

While a well was being drilled through thick salt in the Gulf of Mexico, a walk-away VSP was acquired some 4000 ft above the expected base of salt. Surface seismic showed potential troubles on the path ahead (Fig. 2):

- a small bright in-salt event of uncertain nature (artifact? hazard?) about half-way to the base of salt;
- a complex base of salt interface with a potential for highly over-pressured sands immediately below.

To obtain a high-resolution image of the path ahead, we resorted to Virtual Source. The VSP dataset consisted of 40 geophones at 50 ft spacing, which were transformed into 40 Virtual Sources, giving a total of 1600 source-receiver pairs illuminating a narrow path ahead of the well. This high-fold dataset confirmed that the prominent seismic feature in the salt was indeed an intra-salt reflection and not a multiple from the surface seismic. Careful study of the Virtual Source gathers allowed us to estimate the dip, time and seismic nature (hard) of the intra-salt reflector. A salt velocity estimate from the corresponding virtual check shot yielded a prediction to the depth of the reflector 2000 ft ahead of the well with 50 ft uncertainty; the prediction was communicated to the rig, which soon thereafter encountered the inclusion within 2 ft of prognosis (Fig 3).

A similar analysis yielded a prediction for the depth to base of salt 4000 ft ahead of the well with 70 ft uncertainty. This prediction was also validated by the well results. Further dissection of the base salt reflection on the Virtual Source data revealed a bright event just 350 ft below salt, suggestive of hydrocarbons, which drilling validated as well (Fig 3).

In making these predictions, we found it useful to steer the Virtual Source radiation pattern by using only subsets of all available VSP sources to create VS data. For example, if we use only VSP sources to the left of the well to "feed" the Virtual Sources, the resulting Virtual Sources radiate mainly (down and) to the right, and correspondingly, illuminate only reflectors dipping to the left. Such decomposition of the VS images is a helpful interpretation tool, even though for quantitative purposes (e.g., picking the time of a reflector) it is best to use the VS image obtained from all VSP sources because it is best focused.

Helpful insights into the nature of seismic events can be gained by combining P and S wave information. We obtained SS reflections from the in-salt inclusion by harvesting PS conversions in the VSP data to create Virtual Shear Sources in the salt (Bakulin and Calvert, 2005; Bakulin *et al*., 2007). Combining virtual PP and SS reflections from sub-salt interfaces can give an estimate of Vp/Vs below salt, which in turn, can be used for pore pressure prediction immediately below salt. This is a promising Virtual Source application even though it does not address existing uncertainties in translating Vp/Vs to pore pressure.

In principle, the VS data created for in-salt hazard characterization can be used to image the sediments below salt. However, the acquisition geometry in this case - a short receiver string in a vertical well – is not optimal for subsalt illumination. We can only get a narrow, almost 1D, image of mildly dipping subsalt sediments. To get a wider image, we would need a sidetrack in the salt that is deviated along the direction of expected subsalt dips (Fig 1). The angle between the instrumented well and the target reflector is the crucial factor controlling the VS image size. Virtual Sources in vertical wells are best suited for steep target illumination, such as the salt flank in the next example.

Example II: Salt flank positioning with Virtual Sources

In The Netherlands, a Shell operating unit is assisting the salt mining company Akzo Nobel in the evacuation of salt caverns for underground gas storage by the Dutch gas companies Gassunie and NUON. The caverns will be 300 m high and have 60 m diameter, starting at 1km depth and must not be less than 100 m from the salt flank (Fig 4). The Zuidwending salt dome is an upward lobe of the Zechstein salt formation, which tightly seals the huge Groningen gas field underneath. The geometry of the salt dome has been derived from surface seismic, but it remains rather uncertain (± 200 m) along the vertical flanks (Fig 4). A salt proximity survey would require very distant sources to image a useful portion of the salt flank, and would be very uncertain. On the other hand, generating Virtual Sources in the salt, we can accurately estimate the lateral position of the salt flank based only on salt velocity.

A conventional walkaway VSP with receivers in the salt cavern pilot holes would suffice to create the necessary Virtual Sources. A 30-level 3C receiver tool with 15 m spacing is a given (due to operation logistics). For optimal shot placement, pre-survey modeling is important. Shot locations were initially chosen based on ray tracing (Fig 5, top). Then we took a long line of shots approximately centered at those locations and generated full-waveform VSP synthetic data (2D elastic with a free surface) to study shot range and shot spacing effects on VS data. We found that 60 VSP shots at 50 m spacing would be enough to create high-quality VS data for salt flank imaging.

The salt flank reflection is much easier to see on the VS data than on the VSP. On the VSP data it is swamped by PS conversions and top-salt multiples. It would be difficult to extract by conventional VSP processing (e.g., as done by Zhao et al., 2006), and most importantly, the position of the salt flank on a VSP image would depend on the entire overburden velocity model, including sediments and the rather uncertain point of salt entry. On the VS data created from the horizontal (inline) receiver component of the VSP the salt reflection clearly stands out (Fig. 5 bottom). Picking the reflection time on the zero-offset VS gather (simplest), we reproduced the model interface with better than 25 m precision, which was sufficient to justify acquisition. The acquisition will include three walk-away VSP lines with slightly different azimuths to accommodate the existing uncertainty in the salt flank strike. In total, there will be 180 shots – more acquisition effort than in a classical salt prox but with much better prognosis for success.

Conclusion

Using walk-away or 3D VSP data to create Virtual Sources in salt is a new useful tool for assessing drilling hazards in salt and immediately below the base of salt. It can be also used for accurate positioning of steep salt flanks – a task hard to achieve by other means. These new VS applications can have significant business impact given how costly drilling incidents are, both in terms of money and HSE.

Acknowledgements

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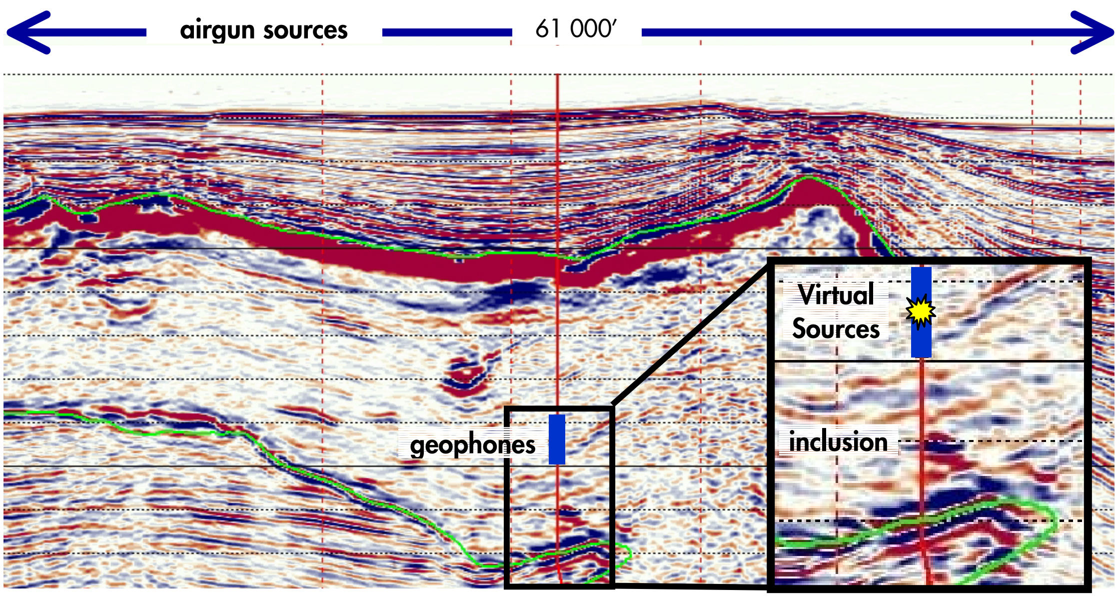

Figure 2: Surface seismic and walk-away VSP acquisition geometry for the Gulf of Mexico field example.

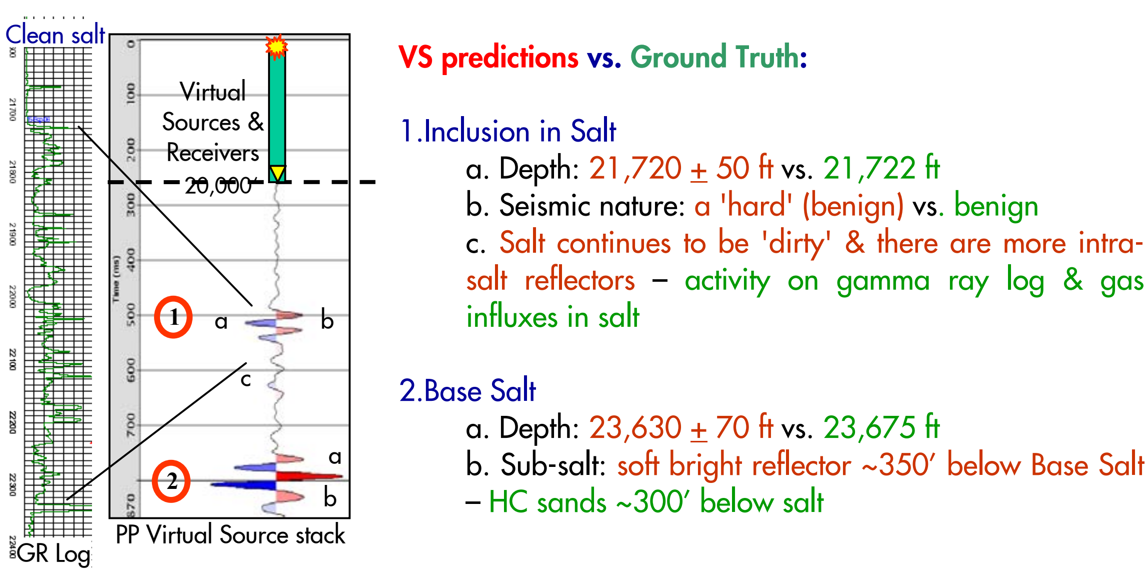

Figure 3: Summary of predictions based on Virtual Source data (red) versus actual well findings (green).

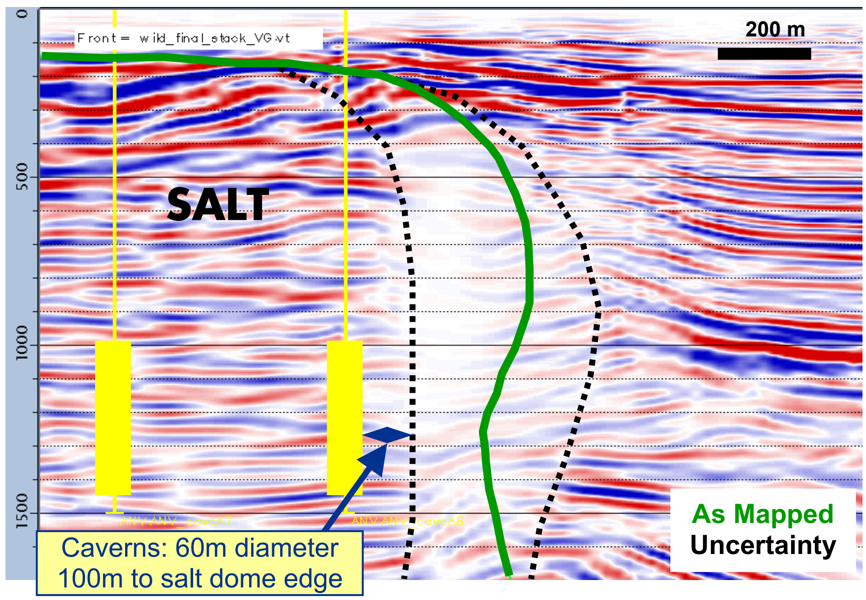

Figure 4: Planned salt caverns for underground gas storage in The Netherlands. Uncertainty of lateral positioning of salt flank from surface seismic needs to be reduced for safe placement of salt cavern.

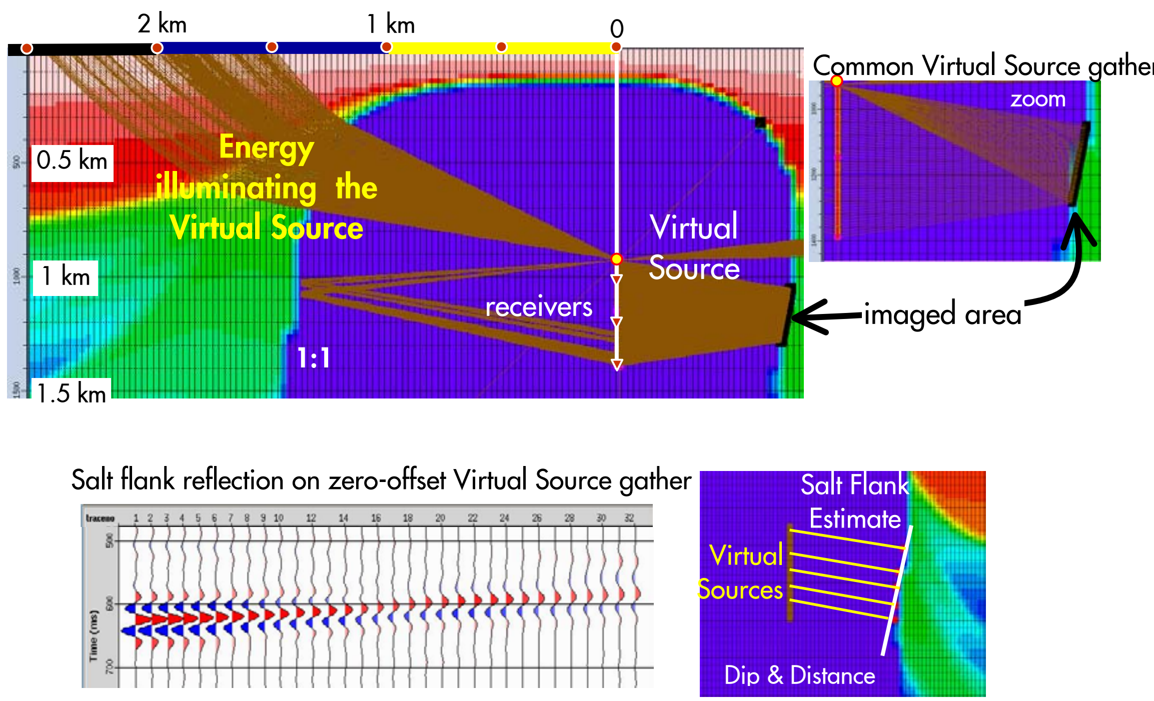

Figure 5: Ray-trace modeling to locate surface shots that send energy through the Virtual Source location in the borehole and illuminate the salt flank at the desired depth (top). Zero-offset Virtual Source traces can be used to estimate the distance to the salt flank in a simple way (bottom).

EDITED REFERENCES

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