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Accurate Estimation of Subsalt Velocities Using Virtual Checkshots

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Abstract

We describe a new application of the Virtual Source Method, the Virtual Checkshot, for accurately estimating sub-salt interval velocities of P- and S-waves from walk-away or 3D VSP data. Complex overburden may lead to erroneous velocity profiles when conventional check-shots and zero-offset VSP-s are used. The new technique overcomes the challenge by creating a Virtual Source at each downhole geophone. When both Virtual Source and receivers are placed below the most complex part of the section, the obtained velocity profiles are not distorted by the overburden. The Virtual Checkshot can correct for overburden of any complexity since no velocity information between the surface and the geophones is required. We apply the Virtual Checkshot technique to a sub-salt deep-water prospect in the Gulf of Mexico. We obtain P- and S-wave velocity profiles that are in excellent agreement with sonic logs in salt and below salt.

Introduction

Extracting velocity profiles from checkshots under complicated overburden is challenging because: (i) first arrival waveforms may be distorted and difficult to pick; (ii) the fastest arrival may not come along the shortest path between the source and the receiver (Fig. 1a). Both of these problems could be alleviated by placing the source in the well, so that the travel-path of the first arrival is short and close to a straight line between the source and the receiver (Fig. 1b). In practice, it is difficult to place a physical source downhole. However, it is easy to create a Virtual Source in the well from walk-away or 3D VSP data ([1], [2], [3]). Measuring the first arrival traveltime from a Virtual Source to a number of receivers below it, we can construct a "Virtual Checkshot" that is insensitive to overburden complexity.

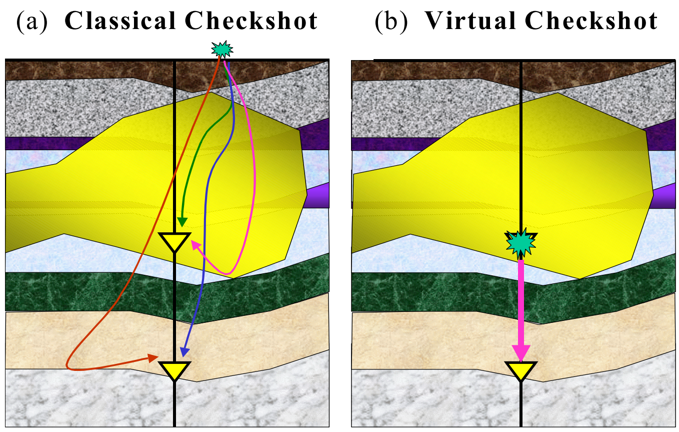

Figure 1: Checkshot in complex medium

An extension of this idea would be to create a Virtual Shear Source in the borehole and construct a Shear Virtual Checkshot. Conventional checkshots measure only P-wave velocity from first arrivals. Shear waves, even if emitted from the surface source or generated by P-S conversions in the overburden, arrive later and are difficult to unravel and pick (for a successful attempt see [4]). *Bakulin and Calvert [5]* showed that we could harvest P-S conversions in the overburden to create a pure Shear Virtual Source in the borehole. The first arrival from such a source (easy to pick) would be an S-wave, yielding a shear-velocity profile.

We have tested these ideas on a data set from a sub-salt prospect in the deepwater Gulf of Mexico (GOM). We obtain profiles of P- and S-wave velocities that are in good agreement with sonic logs under salt at more than 7 km depth.

Input Data

Virtual Checkshots are generated from conventional walk-away (WAW) VSP data. Our example dataset was acquired in a vertical well through a massive salt body in the deepwater GOM. The survey was shot in four passes of the same shot line, with four receiver tool settings, giving a total of 96 receiver depths (4x24). About two-thirds of the receivers were in the salt, near its base, and the rest were below the salt (Figure 2). The receivers were interlaced to provide an effective spacing of 50 ft. However, we found some systematic time shifts between the acquisition lines. For this reason, we performed our velocity estimation using only receivers from the same tool setting (100 ft spacing).

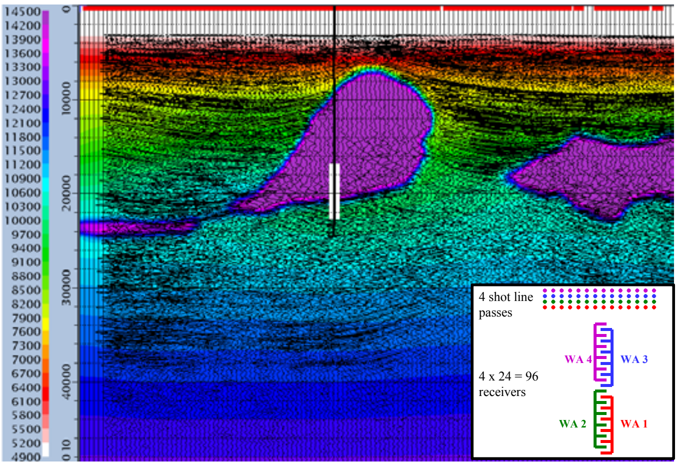

Figure 2: Walk-away VSP acquisition: The red bar at the top shows the extent of the shot line with 612 shot points at 100 ft spacing; the source was airgun. Receiver positions are shown by a white bar in the well. The insert in the lower right shows the four receiver tool settings acquired in four line passes with the same nominal shot positions. Processed surface seismic is shown on the background of a P velocity model (colour scale in ft/s; vertical-to-horizontal ratio is 1:1). The vertical axis is depth in feet.

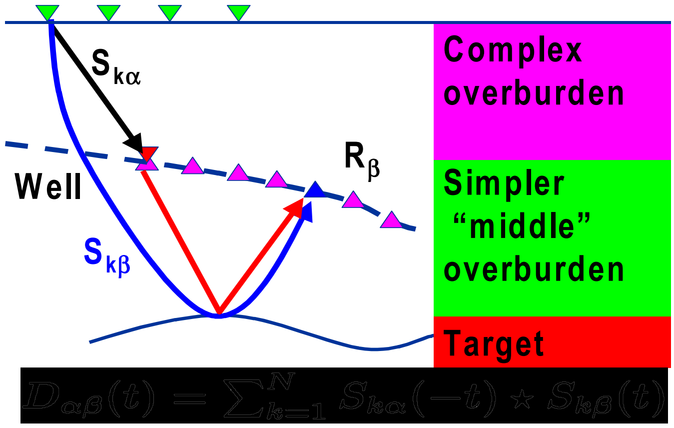

Figure 3: Virtual Source Concept and Computation: Virtual Source creation can be seen as a special kind of source redatuming. 'Special' because: (i) new source positions must coincide with existing receiver locations; (ii) velocity model is not needed. The Virtual Source trace from α to β, $D_{\alpha\beta}(t)$, can be computed according to the formula in the picture, where $S_{k\alpha}$ (t) and $S_{k\beta}(t)$ are traces from a surface shot k to receivers α and β respectively, and the star means convolution. Note that convolution with a time-reversed series is equivalent to cross-correlation.

P-wave Virtual Checkshot

The Virtual Source (VS) method takes data recorded from surface sources into down-hole receivers (i.e., WAW or 3D VSP) and converts them to data that would have been recorded in the same receivers if we had a source in the borehole, at an existing receiver location. The conversion is entirely data-driven – we do not need to have a velocity model of the medium to create VS data. All we have to do to create a Virtual Source at Receiver α and "record" it at Receiver β is (Figure 3):

- Take a trace from Shot k (at the surface) to Receiver α and gate the first arrival (the gate size and position does not matter much as long as it captures most of the down-going energy of the desired mode – in this case P-wave).
- Cross-correlate with the whole trace from Shot k to Receiver β
- Repeat for all surface shots
- Sum cross-correlations over all surface shots

Theoretical explanations of why this would yield the trace from α to β can be found in [2] and [3].

To create a P-wave Virtual Source we used as input the vertical (Z) component of the VSP data. A Virtual Source was created at every receiver depth. A common Virtual Shot gather with a P-wave Virtual Source located at the top-most receiver location is shown on the left in Figure 4. The first arrival on the Virtual Source data is clear and easy to pick. We used only picks on receivers from the same tool setting (exactly 100 ft apart) for interval velocity estimation. The zone of interest in our example is below the salt. The first arrivals on sub-salt receivers from several Virtual Shots gave a Vp profile that is in very good agreement with the smoothed sonic log (Figure 5). The difference between the Virtual Checkshot and the smoothed log is zero-mean (i.e., the checkshot neither underestimates, nor overestimates velocity), with average deviation of only about 2% and maximum deviation of 5% over a small depth interval (less than 100 ft). For this particular dataset the conventional checkshot to sub-salt receivers matched the smoothed log equally well (Figure 6). This is because the base of salt is quite flat, allowing all first arrivals to follow the same sub-salt path (essentially vertical along the well). So, strictly speaking, the P-wave Virtual Checkshot was not a necessity at this location – we derived it to confirm that the Virtual Source would give an accurate Vp profile below salt. The P-wave Virtual Checkshot would be of greater importance in areas with more complicated overburden where checkshot, log, and seismic velocities often disagree (due to sloping or rough salt boundaries).

S-wave Virtual Checkshot

Our example VSP was acquired with airguns in the water - they do not directly excite shear waves. Nevertheless, a Shear Virtual Source can be created by harvesting P-S conversions at heterogeneities above the receivers [5]. The beauty of the method is that we do not need to know where in the overburden the conversions occurred. They may occur at many places at once and be very complicated – the VS method collapses them all to a useful shear signal radiated from the Shear Virtual Source as a simple zero-phase wavelet.

Even though we need not know where the P-S conversions were generated, one may still wonder where the strongest ones come from. In this example, as perhaps in any other salt example, the strongest P-S conversion occurs at the top of salt. We verified this by raytracing. To create the Shear VS, we

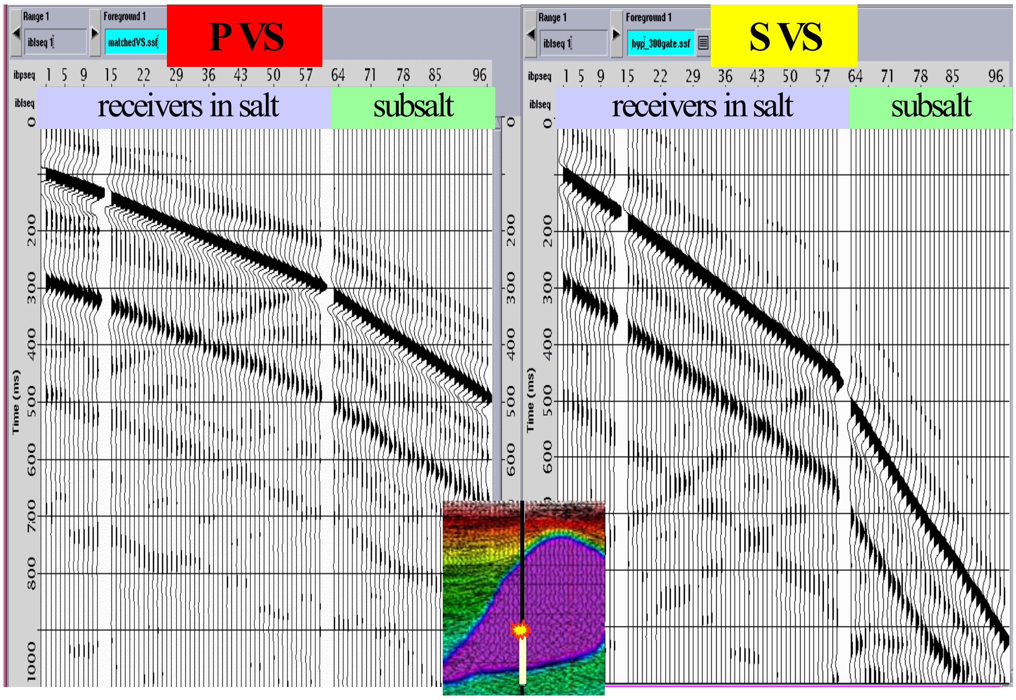

Figure 4: Common Virtual Shot Gather with a P (left) and an S (right) Virtual Source. In both cases the Virtual Source location coincides with the top-most VSP receiver (receivers shown by pale yellow bar in insert). The Virtual Source "fires" a zero-phase impulse at t=100 ms. The gaps at traces 12-13 and 60-61 are caused by a dead receiver. A linear fit to the first arrival moveout provides the following velocity estimates: in salt Vp = 14660 ft/s, Vs = 8390 ft/s, Vp/Vs=1.75; below salt Vp ≈ 9400 ft/s, Vs ≈ 4000 ft/s, Vp/Vs ≈ 2.35.

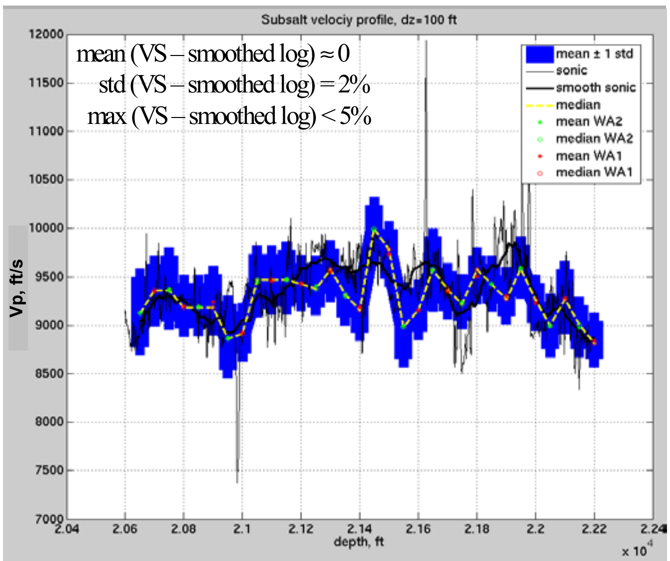

Figure 5: Virtual Checkshot (P-wave) versus sonic log: Virtual Checkshot (yellow line and blue corridor around it) is in very good agreement with the sonic log (black; thick black is the sonic smoothed to the VSP resolution of 100 ft).

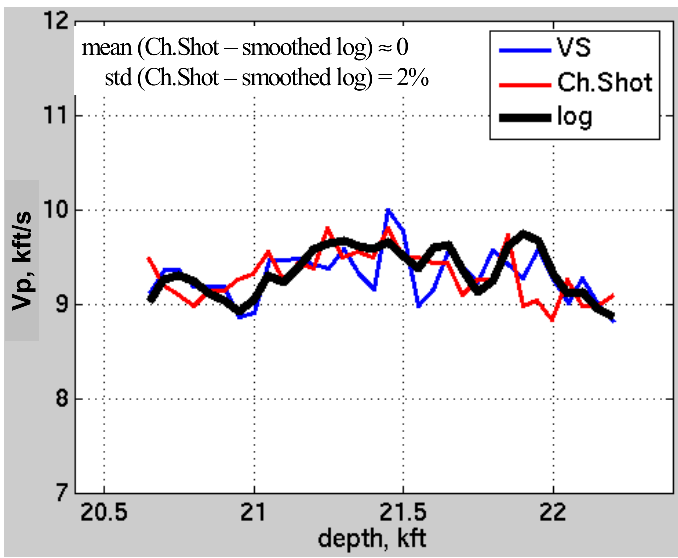

Figure 6: Sub-salt Checkshots (Virtual and Real) vs. Smoothed Sonic Log: both the standard checkshot (red) and virtual checkshot (blue) match the 100'-smoothed sonic log (black) to within 2%.

used the inline horizontal (X) component of the VSP, muting it before the top-salt P-S arrival to remove substantial P remnants from the first arrival. Resulting Shear Virtual Source data are shown on the right in Figure 4.

Picking the first arrival on sub-salt Shear VS traces, we obtained the sub-salt Vs profile shown in Figure 7. It matches the smoothed shear sonic log very well. Percentage-wise, the difference between the log and the checkshot appears larger for Vs than for Vp. However, this is entirely due to Vs been substantially lower than Vp. In absolute terms, P and S Virtual Checkshots agree with the smoothed logs equally well (Figure 8).

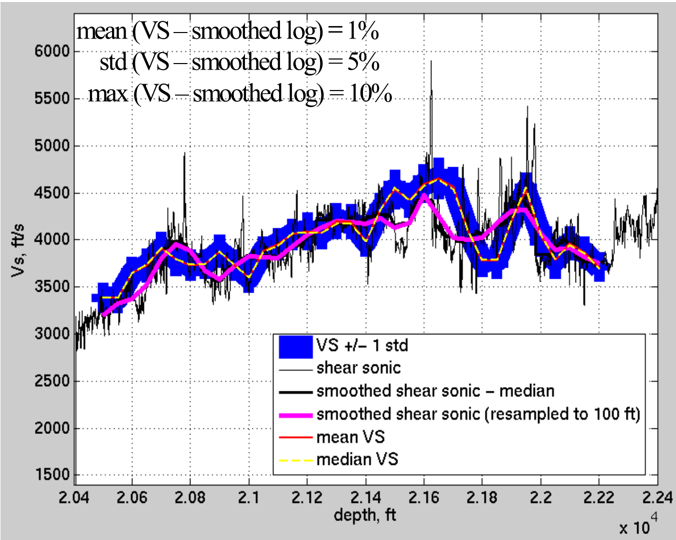

Figure 7: Shear Virtual Checkshot vs. Shear Sonic Log: Shear Virtual Checkshot (blue corridor around yellow line) is in good agreement with the shear sonic log (black; magenta is the sonic smoothed to the VSP resolution of 100 ft).

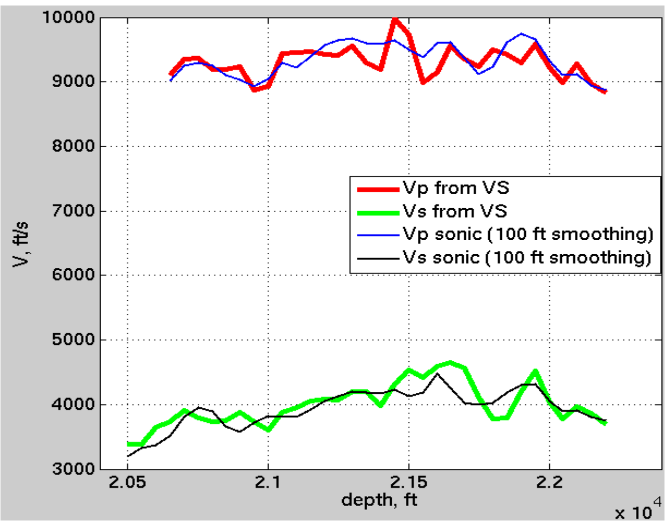

Figure 8: P and S Virtual Checkshots (sub-salt) versus 100'-smoothed Sonic Logs

Salt Velocities

Since Virtual Checkshots measure interval velocities, our primary focus was on the sediments below the salt rather than on the relatively homogeneous salt. But for the sake of completeness, we also used the Virtual Checkshots to measure the average P- and S-wave velocities in salt. We opted for measuring the average as opposed to a detailed velocity profile in salt mainly because it is a common practice to assign a single velocity value to salt bodies for seismic processing. Also, since the salt is much faster than sediments, interval velocities (average over 100 ft) would have much larger uncertainties than interval velocities below salt.

A linear regression through the VS first arrivals in salt gave Vp = 14660 ± 330 ft/s and Vs = 8390 ± 350 ft/s. Smoothed logs over the same depth interval (1600 ft) gave Vp=14650 ± 60 ft/s, Vs = 8340 ± 35 ft/s, where the error bars reflect inhomogeneity rather than measurement uncertainty. So, once again, Virtual Checkshot and well velocities are in excellent agreement.

These salt velocity estimates can be useful in seismic processing as sonic logs are typically not acquired in salt and conventional checkshots can be very sensitive to distortions from top of salt geometry.

Discussion and Conclusions

The Virtual Checkshot technique circumvents fundamental difficulties faced by conventional checkshots under complicated overburden, and allows us to estimate shear interval velocities in addition to compressional velocities, even when the source at the surface emits only P-waves. We showed that the method is capable of delivering very accurate estimates of P- and S-wave velocities at a great depth in and under salt. The more complicated the overburden, the better and more valuable the Virtual Checkshot. This new technique is not restricted to vertical boreholes – it can be used to accurately evaluate along-the-well velocities for deviated boreholes in the presence of any heterogeneity and anisotropy.

Virtual Checkshots use only the first arrivals of Virtual Source data while the VS data contain a wealth of arrivals. The full VS wavefield has many promising applications (e.g., in imaging), and therefore, it may soon be a standard practice to create P- and S-wave VS data from every new WAW or 3D VSP acquired. Virtual Checkshots should become inexpensive by-products.

To reap the benefits that the Virtual Source method (including Virtual Checkshot) can provide, we recommend designing VSP surveys with at least one walk-away line and proper shot and receiver sampling.

Acknowledgements

We thank Shell for the permission to publish this paper. Seismic data used in the examples are property of TGS – we thank TGS for the permission to show the data.

References

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