S-wave Reflection Seismology with P-source

In my last post, titled '*Can add value, will add value'*, I had written about my frustration at an SEG workshop, when some panel members alluded to seismic data not being useful for the characterization of shale formations. Quite contrary to this experience, my overall experience at the SEG Convention, as always, was very enriching.

In this post, I discuss about an interesting technology that had a complete session devoted to its theory and applications. Special Session-2 (SS2) on *'S-wave Reflection Seismology with P-source'* was co-chaired by Bob Hardage and Mike Graul, and had eight presentations on the topic. Just to add some background on this topic here, I begin with some general information, and then go on to the details of the technology and its applications. Thereafter, I will briefly discuss about the individual presentations made at this session.

Background information

A full elastic wavefield would propagate in a homogeneous Earth in the form of three independent seismic wave modes, namely, a compressional mode (P), and two shear modes, vertical (S_V) and horizontal (S_H). Each wave mode travels through the Earth with a different velocity, and due to the nature of the propagation of the wave modes, displaces the particles of the medium differently. The particles are displaced in the direction of propagation for the P-waves, and perpendicular vertical to the direction of S_V waves, and in a direction orthogonal to that of S_V waves and to the direction of propagation. The velocities of propagation for S_V and S_H shear modes may be close, but are significantly less than the velocity of propagation for P-waves. This difference in the velocity can be gauged by computing their ratio (V_P/V_S) which may vary from 45 or so at unconsolidated seafloor sediments to 1.5 in well-consolidated rocks. To acquire a real full elastic wavefield, we would be using 3-component geophones and acquiring data with three sources oriented in three different directions, one generating displacements in the vertical direction, the other in the inline horizontal direction, and a third in the crossline horizontal direction. This would generate a real 9C seismic data volume. The acquisition of such a 9C seismic data volume would be expensive and would also entail higher costs for processing and interpretation.

Bob Hardage has been one of the pioneers who spearheaded the development and application of vertical seismic profiles in the 1980s and 1990s. During those days, besides the downgoing and upgoing wavetrains, Bob would notice noise and an additional signal in the data. VSP data are typically recorded over broad intervals of interest, and definitely not from the surface, and so it was difficult for Bob to confirm where the additional signal was coming from, except to speculate.

Later, on acquiring data all the way to the surface, Bob did find that the additional signal was S_V waves, which converged with the P-waves at the source point. The next question Bob had to answer was, where did the S_V waves originate from?

To answer this question, Bob acquired seismic data using the available type of sources that included explosive, vertical and horizontal vibrators and impact types. His findings suggested that a P-wave source, in addition to the downgoing P-energy, also generates downgoing S_V energy, and that the shear energy is more than the P-wave energy. Both these forms of energy radiate away from the source point, and illuminate the subsurface geology. In addition to the reflected P-wave energy, some of the propagating S_V energy gets converted into P-wave energy at different subsurface rock interfaces. There would be mode conversions of the P to S_V and S_V to S_V types too, but would need 3-component geophones for their recording.

Thus, the wavefield recorded by the vertical geophones planted on the surface of the Earth record both the P-P data as well as S_V – P data, the former referring to a downgoing P-wave reflected as P-wave, and the latter to a downgoing S_V wave reflected as a P-wave. What this also implies is that the seismic data that we have traditionally been acquiring, has both the P-P and S_V -P data. But we have always processed it for P-P data.

Bob Hardage, working at the Bureau of Economic Geology (BEG) at the University of Texas at Austin, has been active over the last 5 years or so in practicing *S-wave reflection seismology with P sources*. He has spearheaded the separation and development of the S_V -P data from the convention P-P data recorded in our legacy surveys and the creation S_V -P images for our target reservoir intervals.

SEG Special Session

Bob organized a full technical session on **S-Wave Reflection Seismology with P Sources**, that took place on Monday afternoon at the 2017 SEG Annual Meeting in Houston. In this session, 8 papers were presented and addressed different aspects of this interesting and promising technology.

Bob in his opening presentation of the session described how traditional P-wave source generate two types of wavefields, namely P- and S_V. A study of the radiation patterns of these produced wavefields at a source station show that S_V-energy is more than the P-energy, and that after reflection at the rock interfaces, the S_V illuminating wavefield undergoes conversion into P waves. Such converted P-waves along with the reflected P-waves are recorded by the vertical displacement geophones. The irony is that these S_V to P converted waves have been recorded over the last several decades, but not processed, and so have been overlooked. The work carried out at BEG shows that the processing of S_V -P data results in images that are similar to P-S_V images obtained by recording multicomponent data with P sources or S sources. Thus S-wave data generated by P-wave sources and recorded on vertical geophones provides advantages in terms of the reduced cost, no longer necessary to deploy horizontal-displacement sources to generated S-waves, and no separate equipment required for recording them. The large amount of legacy P-wave seismic data that is stored in data libraries across different countries could be reprocessed and used for producing S_V-P images without acquiring new data.

Mike Graul, who runs his own processing company, TexSeis Inc., in his talk highlighted the issues that come up during processing of S_V-P data and require some extra effort. In particular, S_V-static corrections and velocity analysis need to be addressed, as well as the determination of velocities for depth migration.

In the next talk, Pugin from Geological Survey of Canada, amongst other observations suggested that, there are no pure P- and S-wave land seismic sources. Any source type may generate a combination of wave modes, which lends support to the fact that a P-wave source generates P- and S_V-energy, as mentioned before.

Seismic modeling of the propagating wavefield is a good way to study and understand the wavefield illumination of the subsurface. The next speaker, Wagner from BEG demonstrated the results of numerical modeling performed especially pertaining to S_V-P wavefield. Generation of synthetic shot gathers using finite-difference model helps with processing and interpretation of S_V-P data.

Next, a case study from western China presented by Li from PetroChina showed convincing examples depicting P-P and S_V-P events on real and modeled shot gathers. The processed section comparisons showed accurate imaging of the top and base of gas reservoir on S_V-P sections, which are almost invisible on the P-P section. This analysis further depicts the areal extent of the porous gas zone and the distinction between three prolific gas wells and one dry well.

As Graul had alluded to before, Karr, from FairfieldNodal, mentioned similar challenges in terms of statics and velocities while processing the S_V-P data, and its separation from the P-P data, which is buried in the deeper portion of the seismic P-record and falls in the slower velocity range. The P-wave NMO-corrected offset gathers often show moved-out events, especially pronounced at increasing times, and are considered as noise, coherent noise, multiples or mode-converted responses. Karr demonstrated that knowing the velocity field from processing of P- S_V stack as is normally carried out in traditional converted wave data, helps in resolving statics and velocities for generation of S_V-P images.

The talk by Gupta from University of Texas at Austin (as part of his Ph.D. work) discussed the interpretation of multicomponent data from the Wellington Field in Kansas, and showed the results of joint inversion of PP-AVO gathers and S_V-P stacks for estimation of elastic properties and compared then with simultaneous inversion. Significant improvement in S-impedance was observed when S_V-P data was used with PP-AVO gather for joint inversion. S_V-P image was found to be equivalent to the S_V-P image from horizontal-vibrator data, except the former had higher frequencies than the latter.

Finally, Hardage wrapped up the session with examples demonstrating the application of S_V-P data for conventional (Ellenburger karst and Strawn reservoirs from Midland Basin) as well as unconventional reservoirs (Wolfberry turbidite reservoirs from Midland Basin, Marcellus Shale from Appalachian Basin), and Midcontinent (Kansas) CO_2 storage reservoir, which were all very convincing.

All the talks had something insightful to share, and there were some interesting and searching questions posed at each of the talks, showing audience interest in the technology. Looks like we will see this technology develop further and its applications will benefit oil and gas companies utilize legacy seismic data for finding more hydrocarbons.

I had invited different experts to comment on the whole idea of SV-P data and what their take was. I am happy to append below the comments I received from three experts, Jim Gaiser, who also conducted the 2016 SEG Distinguished Instructor's Short Course, Chris Thompson and Oz Yilmaz.

Comments by experts

Jim Gaiser

To Bob's credit, his proposal is very intriguing. As I point out in my 2016 DISC, the strongest signals we see in general are those that arise from a single conversion. That includes the SP-wave reflection and indicates that we need to reconsider all the "multiples" we see on vertical. And the two nice examples we saw from China and Texas in the SS2 session demonstrate some validity.

That said, the processing remains very challenging in the presence of the stronger P-wave signal. The SP-wave signal that illuminates the subsurface is not 2 to 5 times larger than the P-wave as Bob suggests. These strong, high angle S-waves that radiate from a vertical source do not convert to SP-wave reflections but rather generate mostly refractions, turning waves, and surface waves. Anecdotally, I have heard about other studies where the SP-waves could not be retrieved. Perhaps a big challenge is the neglect of anisotropy since Bob and everyone else assumes SvP-waves. We know that isotropy is an oversimplification and S-wave splitting is usually considered for PS-wave processing.

If SP-waves can be retrieved, it is not surprising to me that a joint inversion with P-wave would be beneficial. But I don't think that means we will stop recording 3C data. The S/N of PS-waves should always be better than SP-waves from vertical sources. My opinion is based on the radiation and reflection coefficient amplitudes of these waves. Also, the processing effort of the two is similar, where PS-wave might be a bit easier.

I cover many of these issues in my 2016 DISC plus the role of anisotropy. It is pity Calgary showed little interest.

Chris Thompson

Jim G. raises a good point about anisotropy. Most (albeit not all) datasets exhibit at least a small amount of shear wave splitting, and as you know, a little bit of anisotropy, if left uncorrected, can have a profound effect on data quality. With P-S data you at least can recover the polarization of the S leg (assuming multi-component phones); with S-P data that polarization information has been lost – any significant time delays in the S-leg can destructively interfere at the conversion point. Perhaps this is why there have been inconsistent results from processing for S-P?

In my (and many others') experience, there is abundant shear energy generated from P sources, and I routinely process shear arrival times for VSPs recorded from P sources, even with minimal lateral source-receiver offset. So, the energy is there, although I can't say how clean a source signal it is. Processing Sv-P should be fundamentally similar to P-Sv processing, so I have no doubt that Bob H has been getting valid sections using Sv-P data recorded by regular vertical geophones. Directivity might be an issue (the P leg of the Sv-P wave may tend to impinge the receiver non-vertically) for fast surface velocities and vertical P-phones, but as Peter Cary pointed out in the workshop, most of the data these days, at least in Alberta, is 3C anyway. Which begs the question, for the 3C case, is there any benefit in working with Sv-P when one can use established P-Sv workflows and thereby be able to correct for simple anisotropy?

Oz Yilmaz

- Extracting SV-P mode energy from data acquired by vertical-impact source and vertical-geophone is an idea pursued by Bob Hardage for the past decade or more. I recently tried to do just that using a 3-D data set that Bob gave me --- Decatur 3D data acquired by the US DoE for CO2 sequestration. It was extremely difficult --- we just could not get an acceptable result. Multiples interfering with the assumingly SV-P mode were the biggest challenge.
- The work I have been pursuing jointly with Andre Pugin has led us to conclude that you need the following source-geophone (S-R) configuration to obtain images from different modes:
- Mode S-R configuration
- PP VV
- SS H2H2
- PS VH1
- SP H1V

where

V: vertical component,

H1: radial (inline) horizontal component, and H2: transversal (crossline) horizontal component --- e.g. VH1: vertical-impact source and radial (inline) horizontal component geophone.

So, our conclusion is that to get the S-wave image and S-wave velocities in addition to P-wave image and P-wave velocities, you really need to acquire multicomponent seismic data. The idea of extracting the SV-P image from the legacy vertical-geophone data poses so many difficulties in processing so much so that the result may not have the fidelity you need.