Practical 3D VSP

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For the past 15 years, 3D surface seismic surveys have been the accepted standard mode of subsurface geophysical illumination. The change from acquiring and processing seismic data in single 2D lines to massive 3D seismic surveys has come about due to large dollar amounts of R&D investments, as well as the dramatic drop in the computation power per dollar ratio. Today, more seismic data can be acquired, and the computer power exists that enables these large data volumes to be efficiently and economically processed. Subsequently, most of the earth's sedimentary basins have been imaged by 3D seismic data.

VSP (Vertical Seismic Profile) technology has likewise evolved significantly over the last decade. Perhaps the most important technological advance in the borehole seismic sector has been the development of the multi-level downhole array tool. Before this development, each desired VSP receiver position required that the tool be transported up or down the hole, locked to the borehole wall at some discrete depth, and after recording the data, unlocked and transported to the next desired location. This is a very time-consuming, and hence expensive, operation.

The VSP multi-level array tool generally contains between five and 20 downhole receiver satellite assemblies. The spacing of these receiver satellites is variable, but in general they are spaced at approximately 15 m (50 foot) intervals. Each receiver satellite contains three orthogonally positioned geophones which are capable of recording the full downhole seismic vector waveform response. Compressional (P) and Shear (S) wave data can be recorded, and the waveforms identified and separated with careful VSP processing. Being able to deploy and record waveform data at multiple subsurface depths from a single source position has dramatically reduced VSP data acquisition cost, while dramatically increasing the amount of borehole seismic data that can be acquired.

The deployment of multiple downhole receivers meant that 3D VSP surveys could now be recorded with significantly less rig-time cost. It was now economically feasible to lay out a large surface shotpoint grid, lock the VSP multi-level receiver to the borehole wall at one position, and quickly and efficiently record a 3D VSP survey. Oil companies quickly began to plan and acquire 3D VSP surveys. Although the major problem with 3D VSP data acquisition was solved, the seismic industry soon found out that although the techniques and methodologies for processing 3D surface seismic surveys were well known and in place, processing a 3D VSP survey proved to be a difficult task.

Fig. 1. VSP multi-level receiver array.

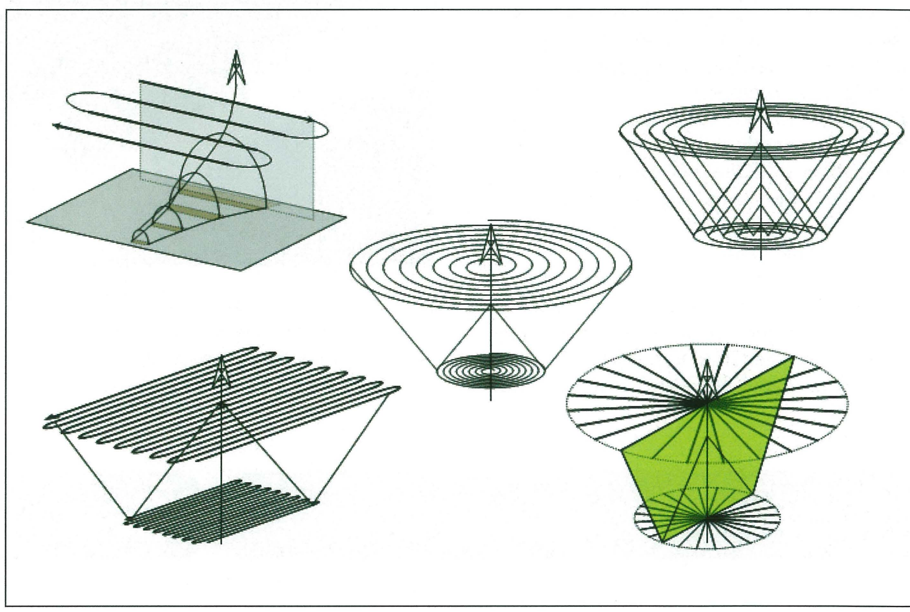

Fig. 2. Sample 3DVSP survey design.

While the money and R&D effort for VSP hardware acquisition technology has been available and in place for the past several years, there have been a number of problems with the commercialisation of 3D VSP. Processing a 3D VSP presented a unique set of issues and problems that were as yet unaddressed by the VSP industry. The first problem faced was simply that of data storage and manipulation. Traditionally, specialised VSP processing companies have been small relative to their surface seismic brethren. Their business model has been developed for relatively small conventional VSP datasets, generally on the order of 1,000 to 10,000 data traces per survey. The computer hardware and data storage requirements have been purchased and developed accordingly for these small data volumes. A standard 3-Component (3C) 3D VSP survey will yield a significantly larger seismic data volume. It is not uncommon for a 3D VSP survey to contain 500,000 to 1,000,000 data traces. These large 3D VSP surveys have overwhelmed the hardware resources of the VSP industry.

Another issue has been that the software investment required to build specialised software programs to process these large data

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volumes has not kept pace with the investment put into VSP hardware technology. VSP data is similar to surface seismic data with respect to frequency content (VSP data should contain higher frequencies). Therefore, many of the standard seismic processing tools can be leveraged when processing VSP. However, the differences between VSP (subsurface receiver – surface source) and surface seismic (surface receiver – surface source) wave propagation requires that a specialised set of data processing tools be available for VSP data. The survey geometry differences between borehole and surface data, as well as the utilisation of 3C receivers, requires that new 3D VSP migration imaging techniques be researched and subsequently developed.

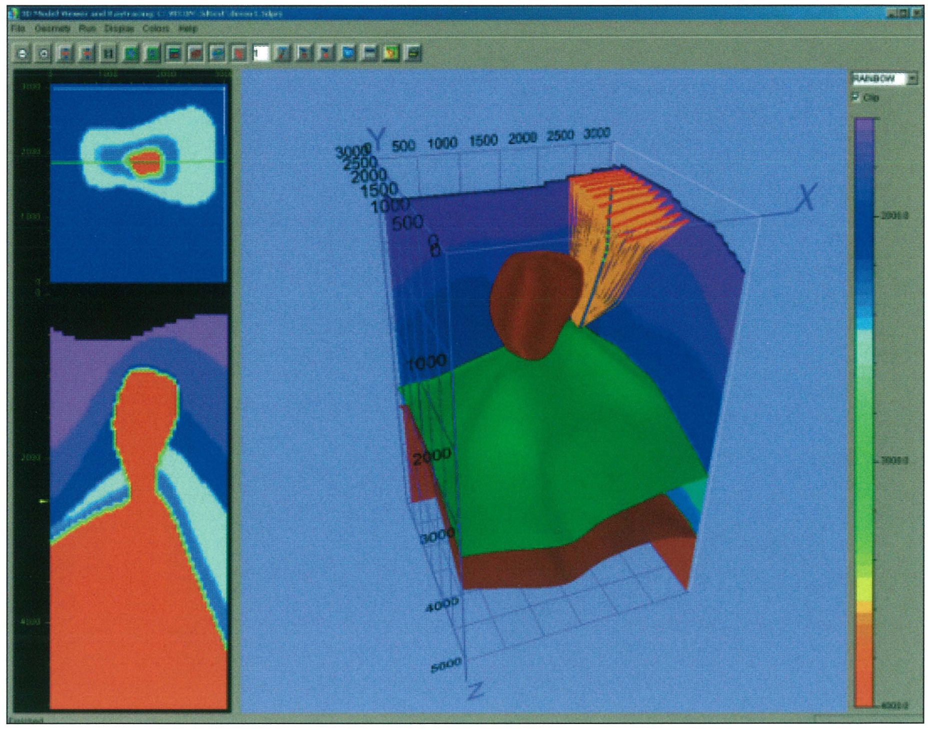

Fig. 3. 3D VSP pre-survey modelling. Accurate 3D models can be quickly constructed and the optimum 3D VSP survey parameters can be ascertained.

In addition to the deficiency in the available software tools, VSP processing companies have found that the traditional methodologies used to turn around conventional VSP datasets, such as zero offset, offset, and walkaway VSP, did not work well for large data volume 3D VSPs. Traditional VSP processing systems were designed to be interactive systems. Because of the relatively small data sizes inherent to conventional VSP services, these systems were designed to interactively view the data going in to each process, view the results of the software operation, and output the result. This process was repeated for each required step. This methodology is highly accurate and efficient for small data volumes. However, for large volume 3D VSP processing, an interactive data processing system becomes an inefficient system.

All of the above mentioned deficiencies in the standard VSP business model have produced cycle times for 3D VSP surveys from data acquisition to image delivery of approximately six months to one year's time. This has been justifiably deemed unacceptable by the seismic industry. It is clear that a new business model needs to be adopted for 3D VSP data processing by the VSP service industry in order to commercialise the 3D VSP service.

This issue became one of the driving reasons behind the formation of *VSFusion* in February 2003. *VSFusion* is a joint venture company between *Baker Hughes* and *Compagnie Generale de Geophysique* (*CGG*). It is the industry's largest and most experienced global group offering borehole seismic application design, data processing, interpretation, and integration. The new company serves as a bridge between well log information, surface seismic, and reservoir geophysics, offering specialisation in complex and special processes such as 3D VSP, AVO, fracture monitoring, fracture delineation, and time-lapse VSP. According to James Jackson, General Manager of *VSFusion*, "*VSFusion* brings together two of the leading companies in the borehole seismic business. We believe that the borehole seismic software and hardware tools available within Baker and CGG, as well as the many experienced people that both companies had, give us all of the components necessary to build the industry's leading borehole seismic company. Our goal is to leverage the best available technology in both companies and offer services to the seismic industry to enhance the resolution and to reduce uncertainties in the surface seismic data."

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Having access to the resources of both *Baker Hughes* and *CGG*, *VSFusion* quickly began work on addressing the numerous logistical, hardware, and software problems inherent to 3D VSP processing. *VSFusion* addressed each of those concerns and has developed the *VS3* system for 3D VSP processing. The *VSFusion VS3* system is an integrated system of software components designed to efficiently process 3C 3D VSP data and produce a state-of-the-industry, high resolution, 3D seismic volume around the well. In order to explain the process, we can roughly decompose the 3D VSP processing flow into four main components: model building and validation, data pre-processing, 3D VSP migration imaging, and image data presentation and validation.

Pre-survey modelling is a key component to the success of any VSP survey, whether it is 2D or 3D. Without the proper survey design parameters, the target area may not be sufficiently imaged. It is extremely important in the pre-survey modelling process that the most accurate 3D velocity model be constructed. All available geological and geophysical information should be used to build the model. VSFusion uses an integrated modelling sub-system designed by *GeoTomo LLC* in its *VS3* 3D VSP processing system. Using the *VS3* system, complex 3D models can be quickly constructed and modified. The optimum VSP survey geometry design can be verified by both ray tracing and finite difference modelling. Synthetic VSP data is generated and will be used after the 3D VSP data is actually acquired to assist in model validation and data verification.

Once the 3D VSP survey is acquired, the seismic data is processed in the *CGG Geocluster* system. *Geocluster* is a comprehensive seismic processing system designed to process large seismic datasets. Almost every imaginable seismic processing tool is available to prepare the 3C 3D VSP data for imaging. In addition to the standard seismic processing tools, *Geocluster* also contains the full range of borehole seismic specific programs required to perform multi-component data rotations and VSP downgoing and upcoming wavefield separations. Having all of the required seismic and VSP specific tools available in a single integrated package

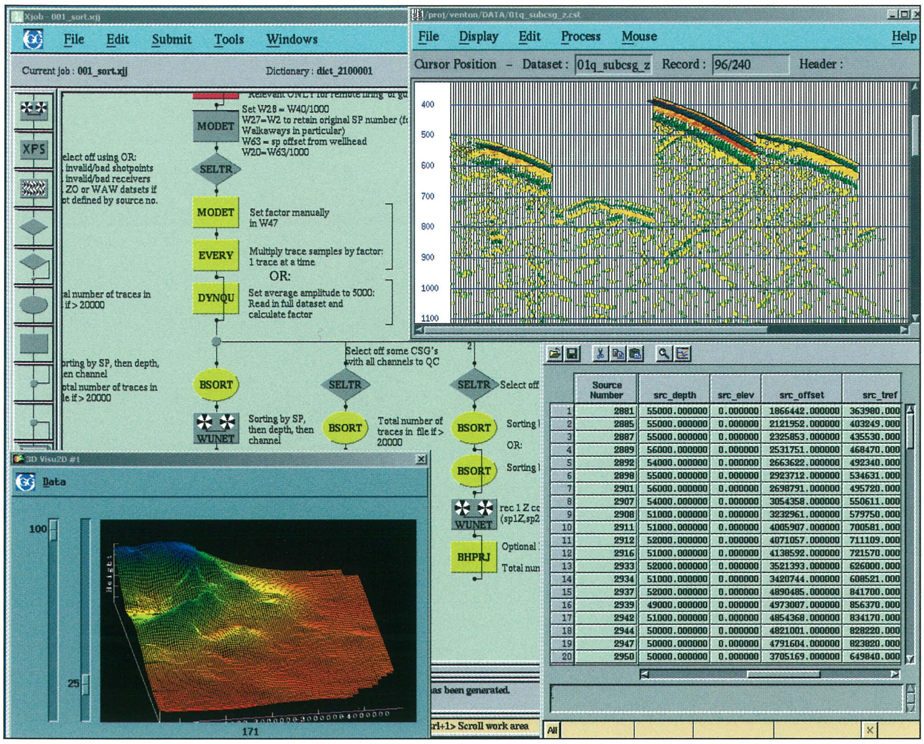

Fig. 4. The CGG Geocluster system can process large data volume VSP surveys very efficiently. Geocluster contains the full range of seismic processing tools, including those specific to borehole seismic processing.

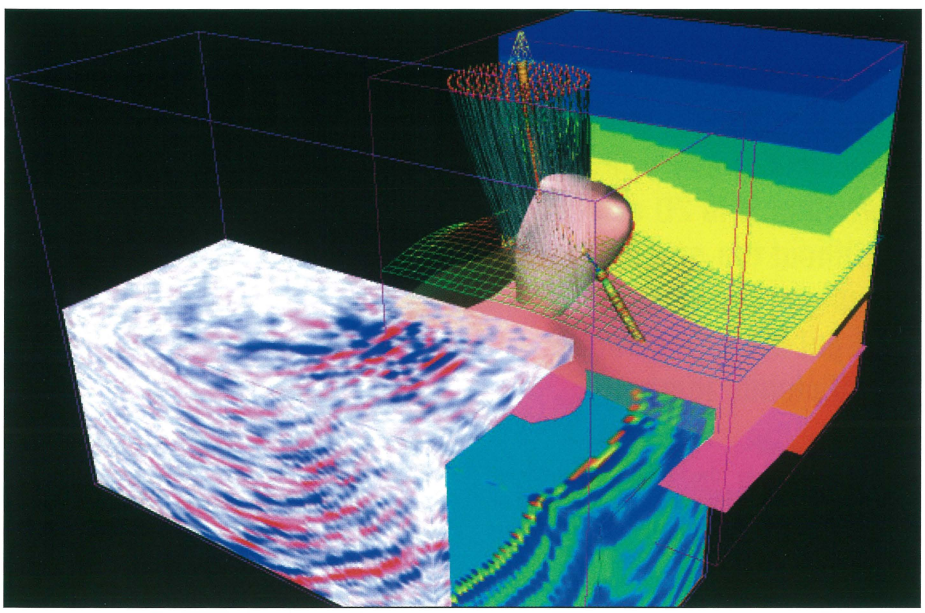

Fig. 5. 3D VSP presentation display showing two 3D VSP volumes.

allows the *VS3* system to efficiently prepare large datasets for the 3D VSP imaging process. During the data processing stage, *VSFusion* geophysicists carefully analyse and process all three geophone components. Using all three components ensures that the full seismic vector response that was recorded is available for imaging. Depending upon the objective (i.e. P-wave or S-wave imaging), the data is carefully processed to obtain an upcoming wavefield dataset that is ready for 3C 3D imaging.

While the VSP data is being processed on the *Geocluster* system, the actual survey geometry coordinates of the sources and receivers, as well as the actual waveform travel time information is quickly transferred to the *VS3* modelling sub-system. 3D travel time tomography modelling is done to compare the actual VSP travel time data with the synthetic times computed through the initial 3D velocity model, and to update the velocity model accordingly. Utilising the travel time information helps to produce the most accurate velocity model possible with the available information. As 3D VSP migration applications are generally depth imaging algorithms that utilise a velocity model to guide the imaging process, building an accurate geologic velocity model is an extremely important part of the process.

The heart of any 3D VSP processing system is the 3D migration imaging application. In order to take advantage of the full waveform response recorded from a three component downhole receiver, all of this data must be migrated. Current VSP industry migrations will image either only one geophone component, or if they are able to use multiple components, will image each 3C sample non-directionally. Non-directional imaging means that each data sample is distributed evenly along the 3D diffraction spheroid. Events are therefore mis-positioned spatially within the migrated data volume, causing a great deal of ambiguity when trying to interpret the data.

To solve this problem, *VSFusion* has developed the industry's first directional vector 3C 3D VSP migration. After careful pre-processing to remove all unwanted wave modes, each 3C data sample is analysed within the 3C 3D vector migration and is distributed only to its proper spatial and azimuthal position. Unlike conventional 3D VSP migrations, utilising all three geophone components directionally allows the full amplitude response of the image point to be recovered. In addition to migrating vector data properly, the *VSFusion* migration also contains an azimuth-dip filter that allows unwanted signal to be attenuated for a specified bedding dip, and azimuthal direction. This feature can limit the aperture allowed during the imaging, and is especially helpful in tuning the image in areas of structural complexity.

After running the 3D VSP migration, the output image volume is then transferred to the *VS3* 3D Viewer/Presentation module. The *VS3* presentation module can display the 3D VSP image data and overlay the velocity model and all well/survey parameters. Other 3D seismic data volumes, such as a 3D surface seismic volume, or an overlapping 3DVSP volume can be simultaneously displayed. According to Mark Newman, *VSFusion* Asia Pacific Area Manager, "The VS3 3D Viewer/Presentation module is a key component in the 3D VSP process. Being able to view the migrated data volume in 3D space allows us to evaluate the quality of the 3D image and to see how well our velocity model matches the migrated data. If required, changes to the velocity model can be made and the data re-migrated. In addition to being an easy to use visualisation tool, we can present the 3D VSP image to our customer in many ways to assist in the interpretation of the results. "

The *VSFusion VS3* system is in place and contains all of the tools necessary for optimal 3D VSP processing in a single integrated system. Quick data turn around, full waveform vector imaging, and 3D data presentation combine to make the 3DVSP survey a practical technology for enhanced subsurface understanding. For additional information, you are invited to visit www.vsfusion.com. ■