Introduction to this special section: Borehole geophysics

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Borehole geophysics is essential for exploration, assessment, and production of Earth's resources, in addition to carrying out fundamental studies on the Earth itself. Borehole-based technology encompasses activities ranging from coring to measurements such as logging, VSP, crosswell profiling, and passive seismic monitoring. Each of these disiciplines has grown into an established branch of borehole geophysics. The idea behind all these measurements has been to obtain useful information about the geological environment that helps evaluate subsurface zones of interest. While cores yield information on specific sections of a borehole, logging focuses on continuous measurements of formation properties over extended depth intervals so that a more complete picture of the in-situ physical properties of different geological formations emerges. Instruments that measure different physical properties of rocks and fluids are lowered into boreholes to collect depth-continuous data, and these data are interpreted as a suite of log curves to take advantage of their synergistic nature and to make detailed determinations of rock and fluid properties adjacent to the borehole. One log measurement that is particularly useful for identifying formation boundaries and for indirect porosity measurement is the sonic log. This log is also commonly used by seismic interpreters to convert seismic two-way traveltime to depth and to generate synthetic seismograms. However, sonic measurements are not error-free because interval velocity measurements are influenced by washout zones, cycle skipping, tool sticking, and other effects. Such problems are alleviated by using velocity check-shot surveys to calibrate sonic logs. A check shot measures traveltime of a seismic pulse from a surface source to downhole receivers positioned at given depths, typically at intervals of 100–150 m. A check-shot-corrected log allows key formation boundaries known as a function of depth to be positioned on seismic sections and also specifies interval velocities between formations. Because check-shot surveys were the first technology that caused geophysicists to deploy seismic receivers in deep wellbores, they are the precursor of today's VSP technology.

Instead of measuring only downgoing traveltimes in a check-shot survey, Jolly, Levin and Lynn, and Clifford demonstrated in the 1950s that upgoing reflection wavefields and interbed multiple patterns could be analyzed if downhole receivers were positioned at closely spaced depth increments in a well to create data with a small depth sampling. These early 1950s papers demonstrated the concepts of today's VSP data-acquisition procedure and presented initial geological applications for VSP data. Interestingly, although these investigators established the principles of VSP during the 1950s, VSP did not become an immediate practice among American, European, and western hemisphere geophysicists. In contrast, Soviet geophysicists, led by Evsey Gal'perin, initiated aggressive VSP programs, and during the 1960s and 1970s, these eastern hemisphere colleagues demonstrated the rich amount of fundamental wave physics that can be studied with VSP data and expanded the value of VSP technology for evaluating geological problems. In the late 1970s, western hemisphere geophysicists finally became attracted to VSP, and there was a steady, worldwide growth of VSP technology in the 1980s that persists until today.

The VSP configuration in which a source is placed directly above a downhole receiver, called zero-offset VSP, yields data that are simple to process and ideal for correlation with surface-recorded seismic data. However, the desire to image the area around the borehole and to "see" far beyond a borehole led to different imaging configurations, like large-offset VSPs, walkaway VSPs, walk-around VSPs, and eventually 3D VSPs. In order to image the region between two wells, a variation of VSP geometry, called crosswell profiling, developed in which a source manipulated by wireline or coil tubing is positioned at closely spaced depth intervals in one well and receivers are placed at closely spaced intervals in a second well. By measuring seismic traveltimes and reflection/transmission amplitudes between these source and receiver stations, traveltime inversion can be done to determine velocity structure between the boreholes, and amplitude data can be used to image the interwell region.

In spite of its higher resolution and crisper images, the overall acceptance of VSPs in the industry has been limited for a variety of reasons. Two factors that have contributed to cautious use of VSP technology are the long data-acquisition times that are often encountered and unacceptable data-acquisition costs, with the latter sometimes including the standby cost of an expensive drill rig as data are recorded. In attempts to lower costs, ideas such as the reverse VSP, in which a source is downhole and large arrays of receivers are deployed on the surface, have been explored. Reverse VSP is still somewhat limited in popularity because of inadequate downhole source technology.

Advancements in data-processing methods, instrumentation, three-component geophones, and particularly downhole data digitization have brought significant improvements to VSP technology and provided new geological insights from VSPs, reverse VSPs, and crosswell seismic data that are useful for reservoir development, characterization, and performance evaluation. However, further work is needed to illustrate the value of VSP technology for depth registering surface-recorded P and S reflections, monitoring sequestered CO_2, evaluating geothermal systems, and imaging beneath shallow, complex geology that distorts images constructed from surface-recorded data.

Some papers in this special section focus on 3D VSP case studies and crosswell applications, and some deal with non-seismic borehole measurements (seismoelectric data and estimates of elastic moduli from drill cuttings) that complement conventional VSP data.

Burch et al. present a case study from Deimos Field in the Mississippi Canyon protraction area in the Gulf of Mexico. Some reservoirs of interest are between the Antares and Venus salt bodies and cannot be properly interpreted with towed-cable data. For Deimos Field, the imaging is poor. OBS data improved the imaging of these reflections, but even OBS data were not good enough to image key reservoir horizons near the Antares salt body. After initial finite-difference feasibility modeling (FDM), 3D VSP data were acquired in a development well, and subsequently processed and interpreted. The resulting image obtained after wave-equation migration using VTI anisotropy principles improved reflector positioning and continuity as indicated by FDM.

Müller et al., in a two-part paper, describe the acquisition, processing, interpretation and added value for two 3D VSP pilot projects. They demonstrate that a 126-level receiver array is crucial for imaging a greater lateral distance away from the borehole. The correlation of the final 3D VSP data with well synthetics, acoustic impedance inversion results, and other relevant data indicates the reliability of the high-resolution data. The added value comes in the form of more accurate images of the reservoir that not only show key stratigraphic features but enabled mapping of important faults not seen on surface seismic data. The authors suggest the 3D VSP technique is cost-effective and could be beneficial for time-lapse monitoring (4D) VSP surveys.

Using deterministic inversion of a high-resolution crosswell seismic survey, Ibrahim et al. obtain acoustic- and shear-wave images that provide insight into the internal geometry of a Niagaran reef in Michigan and match the geologic interpretation of the reef model quite well. The authors discuss reflector imaging for the usual configuration where sources and receivers are at depths shallower than the reflector, which provides a "from above" image, and a second reflector image called a "from below" image, in which the sources and receivers are below the reflector. They find that for reflectors corresponding to parts of the reef where gas saturation varies, reflection amplitudes are weaker on the from above image as compared with reflection amplitudes on the from below image. The authors attribute the lower amplitudes associated with shallower source/receiver stations to attenuation and scattering of the signal as it passes through the gas-charged region of the reef.

Mehta et al. extend the virtual source concept to crosswell geometries. Their virtual crosswell image matches the equivalent real crosswell image as well as do surface seismic data. The authors demonstrate that the separation of upgoing and downgoing wavefields through the use of 4-C sensors in a horizontal well improves virtual source data by suppressing overburden arrivals. Their methodology could encourage application of this technology to novel well geometries.

Glover and Jackson discuss the physics that connects transient electrical responses in rocks with the passage of seismic waves that cause pore-fluid movement. They use borehole measurements to verify this physics, and their side-by-side displays of vertical seismic profile (VSP) data and vertical seismoelectric profile (VSEP) data acquired in the same boreholes are impressive.

Abousleiman et al. present an interesting lab procedure in which atomic force microscopy (AFM) measurements are made on shale-gas drill cuttings to estimate shear and bulk moduli of rock units penetrated by a wellbore. AFM instruments are a new, emerging technology that allows experimentalists to measure rock properties down to the molecular level using tiny probes that physically contact a rock sample. By causing this probe to make small indentations in drill cuttings, the authors show how the properties of the applied force and the resulting indentation allow shear and bulk moduli of drilled rock to be calculated. These AFM measurements have the potential to calibrate dynamic estimates of elastic moduli calculated from VSP data in wells where operators collect drill cuttings but do not elect to retrieve core for laboratory measurements.

We hope readers find these papers as interesting and informative as we did while we created this special section. TLE

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