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Project Images Crust, Collects Seismic Data in World's Largest Borehole

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An anomaly in our understanding of upper continental crustal structure is caused by conflicting observations from structural geologists and reflection seismologists. Near-surface structure in metamorphic terrain is frequently steeply dipping or vertical, but seismic reflection images display flat-lying reflectors below depths of a few kilometers. The seismic image of the topmost 2–3 km is usually blank. How can this be, when seismic reflections are supposed to represent primary geological structure?

Seismic measurements in and around a deep borehole could solve this dilemma. Surface seismic observations and physical samples collected from the hole by wireline logging, particularly by vertical seismic profiles (VSPs), could then be compared.

There are only two sites where hypotheses on crustal reflection sources can be tested against in situ geological and fluid samples. One of these sites, the Kola SG-3 superdeep well in the Kola Peninsula, northwest Russia, has been cored with more than 80% recovery. Investigation has yielded exciting evidence of current and past fluid flow, as well as physical property and logging data. However, until now it has lacked the deep crustal common-depth-point (CDP) seismic section required for correlation efforts. To remedy this gap in our knowledge, a major multinational experiment, incorporating truck-mounted vibrators, was performed during the winter of 1992 (Figure 1).

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A crucial factor about SG-3, apart from its depth of 12.2 km, is that the primary lithological layering of the Proterozoic supracrustal rocks dips at 40°–50° (Figure 2). Seismic reflections were observed from this layering both on high-resolution shallow surface data as well as on the previously recorded single component analogue-record VSPs. There are also flat-lying, lower-frequency reflections between 6 and 9 km depth, cross-cutting the Proterozoic/Archean lithologies (Figure 2).

Pavlenkova [1992] has reviewed the significance of the flat-lying reflectors. The depth range at which they occur corresponds roughly to the zones of porosity increase, velocity inversion, increase in *P* wave anisotropy and pressure, and the presence of circulating fluids. Furthermore, the essentially vertical variation in physical properties correlates well with discrete changes in metamorphic facies.

The SG-3 well provided an ideal opportunity to test hypotheses on several alternatives to primary lithological layering as the source of reflections. The alternative sources of crustal reflections include shear zones, fluids, and metamorphic facies changes, all of which are represented at the well. Seismic reflections are found both from dipping compositional layering which correlates with structure, and from horizontal zones, which are provisionally interpreted as horizontal, fluid-filled fractures.

Resourcefulness Saves Project

The principal aim of the project was to determine the reflection characteristics of the upper crystalline crust. Obtaining a whole-crustal image was a secondary priority.

Since crustal reflection surveys of the kind now commonplace in the west had never been undertaken at the SG-3 well, a multinational geophysical team was assembled to obtain the necessary surface and downhole seismic data. Reconnaissance site surveys were carried out by the summer of 1991. The northern branch of Environmental, Geological and Geophysical Investigation organized the field work in cooperation with the Universities of Bergen, Glasgow, and Wyoming.

The field work was carried out between early March and mid-May 1992. Normally, the late winter provides the best combination of calm weather conditions, hard ground, and enough daylight for seismic surveys. Unfortunately, however, the unusually mild winter of 1992 produced very deep snow but barely frozen ground.

First, a 38-km long crustal seismic reflection profile was recorded through the well in a direction at right angles to the regional strike. The surface and VSP data were recorded in three-component mode—ground motion in *x*, *y*, and *z* directions—to give the full wave field, permitting separation of *P* and *S* waves. A surface seismic survey was then

Fig. 1. Russian Caterpillar tractors are towing Bergen University's truck-mounted vibrators over the last hill on the CDP line. The SG-3 well tower lies 1 km to the north. This image is a still frame from a video of the project.

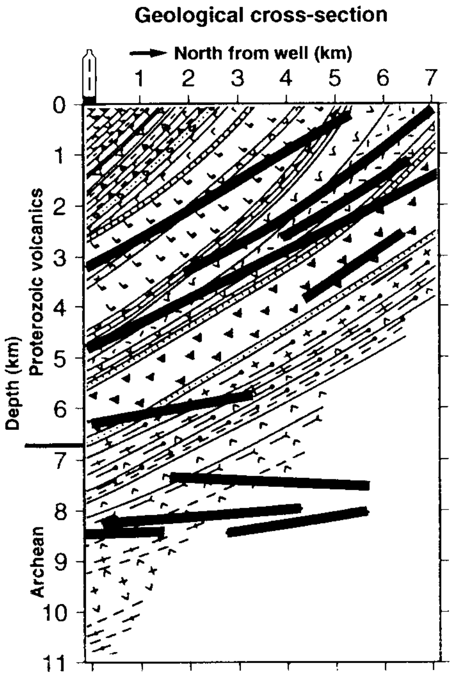

Fig. 2. Geological cross-section through SG-3, showing a variety of south-dipping lithologies. Bold solid lines indicate seismic reflectors interpreted from previous Russian experiments.

recorded in both three-component and three-dimensional formats.

The main line was shot from south to north, along a straight track. Away from the well the maximum lateral deviation of shots or receivers from a mean straight line was less than 300 m. The line could not be extended more than 3–4 km north of the well because of the proximity of the militarized border zone. South of this zone lie a number of east-west trending obstacles such as major roads, railroad tracks, and high-tension power lines, all of which may cause noise and degrade data.

Early plans to use dynamite as a source were ruled out due to logistical problems and cost, so four truck-mounted vibrators were used instead (Figure 1). Although truck-mounted vibrators are hardly ideal for the terrain, they are powerful. They are also equipped with control electronics compatible with the recording equipment being used to collect data. The trucks were each towed on the main line by tractors, and three ways of mounting the trucks on specially constructed skis were tried out. Due to mechanical breakdowns, the normal source turned out to be three out of the four vibrators. Once the convoy of source vehicles started on the line (Figure 1) there was no way to turn the vibrators around; this constrained the possible shot-receiver geometries.

Three 96-channel recording systems were set up to record the vibrations. Each system had its own spread in a 3 x 30 channel mode (Figure 3a) at 500-m channel spacing, giving a composite spread 4.5-km long. A recording cabin—or doghouse—with two systems sat between two spreads. Another doghouse triggered source-firing and the recording cycle of all three instruments. The vibrators, in an off-end configuration south of the cable, moved up 1.5 km as far as the south end of the most southerly spread vibrating every 50 m. This spread was then lifted and laid again in the north. Although each spread was made up of 120-channel roll-along Arctic cable sections in pristine condition, it was impossible to use it in a conventional roll-along mode, in which 12-24 channels are moved at a time, when combined with three-component recording and three separate recording systems.

While the CDP cable spread progressed toward the well from about 30 km south (Figure 3b), a separate 5-km long, 50-instrument Reftek remote instrument array was rolled toward the well at half the rate of the cable spread. The two spreads converged and overlapped near the well. The Refteks operated within time windows during the day.

To interface with the Refteks, the vibrators and geosource MDS-10 recording systems had to be started in absolute time. Thus total subsurface coverage was 60- to 70-fold. Because it was the first time that such instruments had been used to record such vast quantities of controlled source seismic data, many timing and internal noise problems had to be resolved. The data collected extend the range of CDP offsets to between 10 and 20 km (Figure 3b) and will eventually be merged with the shorter-offset CDP cable spread data.

Extensive wave tests were carried out to compare horizontal and vertical vibrations collected by acoustic detectors with single three-component cases. Even when the three strings had been properly planted and aligned, snow melting around the phones soon deteriorated the geometry. In the end, only the vertical component string buried in shallow holes in the snow was used, along with two horizontal components taken from one deeply buried three-component case.

Since the proposed east-west cross-line through the well was impossible to observe due to the weather conditions, a limited three-dimensional survey was carried out around the well instead. This three-dimensional, three-component coverage of a CDP area covers about 6 km^2 around the well, with offsets from 50 m to 5 km. Thus within each 50-m square area, three to four traces can be summed to improve the signal (Figure 3c). The result is a unique three-dimensional, three-component crustal reflection data set, complete with well control to 12 km. The aperture and density of the data are far too small for orthodox three-dimensional processing, but the data should permit a test of the hypothesis that there are horizontal reflectors at the well (Figure 2).

It was impossible to acquire the VSPs originally planned. The 12-km long logging cable was damaged beyond repair, so instead several 6-km deep, three-component VSPs were run at different offsets using a new Russian three-level, three-component tool that digitizes down-hole (2 m/s sample interval) onto a three-conductor cable. The VSP calibrates surface seismic data against the geologic data from the borehole. The Russian tool was used in a single-level mode at a level interval of 20 m, with a sweep of 12–120 Hz. Up to three vibrators per source point were used.

Positioning was based on a high-quality 1:50,000-scale topographic map enlarged to 1:10,000 scale. Three-dimensional global positioning satellite fixes were made at key locations. Absolute positioning is better than 20 m and relative positioning is 5 m or better, which is satisfactory for processing purposes.

Data Quality

The south end of the line, shot first, shows excellent data (Figure 4a). Lower crustal reflectivity and a Moho—the boundary surface that separates the Earth's crust from the mantle—at 12 s (40 km depth) could be seen on some raw shot gathers. Quality of the horizontal components is much lower than the vertical component, but presumed shear wave arrivals can be seen.

Because the Reftek data had never been used in this mode before, they required heavy low-level processing to apply time corrections. They also suffered from internal problems and 18 Hz and 50 Hz pickup from pumps at the well; however, good data are being recovered. The quality of the VSP data (Figure 4b) is excellent.

The complete wave field (in a three-component mode) was observed, and all raw data were preserved in unsummed, uncorrelated form. After demultiplexing, the surface seismic (CDP) data amounts to some 40 Gbar and the VSP data to about 2.5 Gbar. A great deal of data from the second-hand field tapes had been left in unheated, uninsulated doghouses overnight, during which the air temperature sometimes fell to -30°C. One operator's log sheet even records "Ice on tape!" However, the data on the corrupt tapes were successfully recovered by reading them back on a field recording system linked to a PC. More than 99% of the 10,000 shot records of the survey were saved.

Future Investigation

Because the data are preserved in both uncorrelated and unsummed form, filtering methods now being developed can later be

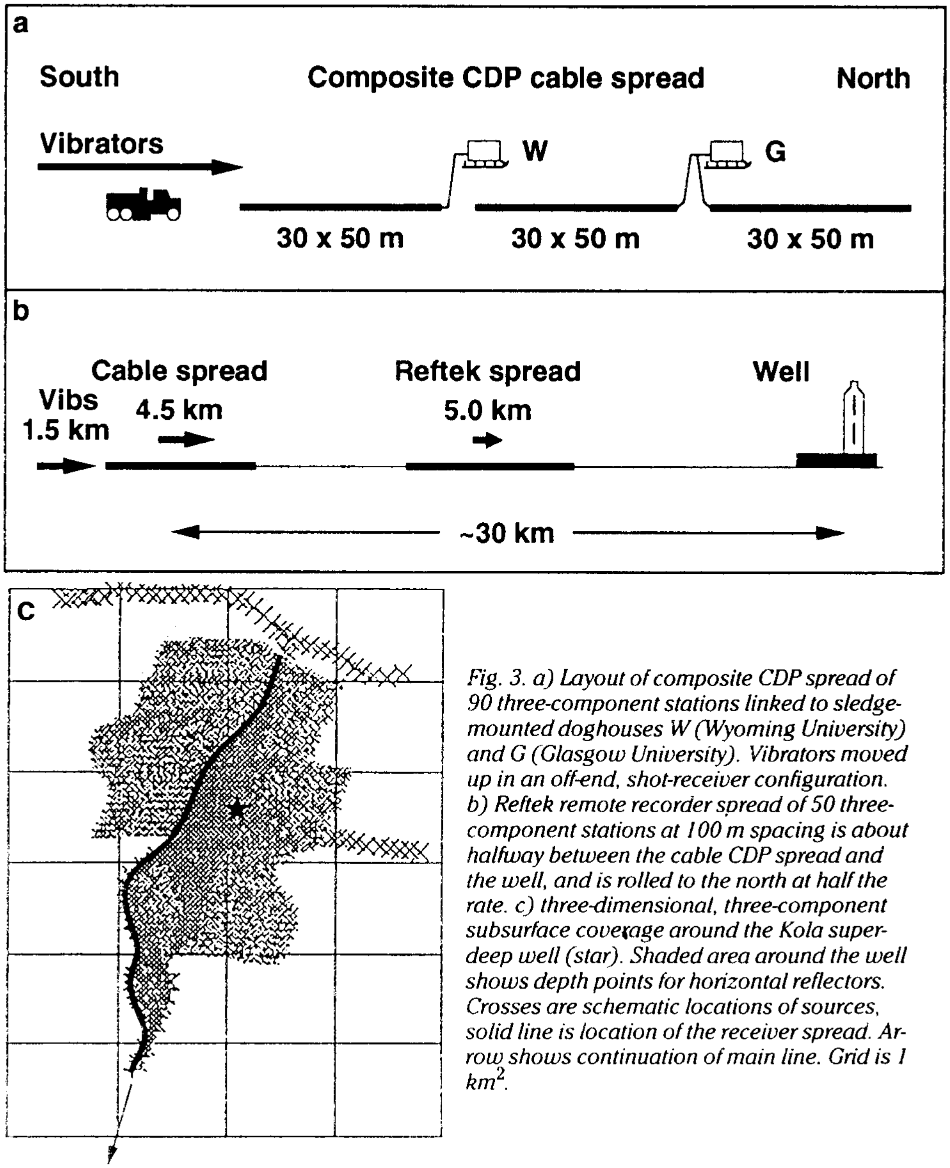

Fig. 3. a) Layout of composite CDP spread of 90 three-component stations linked to sledge-mounted doghouses W (Wyoming University) and G (Glasgow University). Vibrators moved up in an off-end, shot-receiver configuration. b) Reftek remote recorder spread of 50 three-component stations at 100 m spacing is about halfway between the cable CDP spread and the well, and is rolled to the north at half the rate. c) three-dimensional, three-component subsurface coverage around the Kola super-deep well (star). Shaded area around the well shows depth points for horizontal reflectors. Crosses are schematic locations of sources, solid line is location of the receiver spread. Arrow shows continuation of main line. Grid is 1 km^2.

applied to remove unwanted signals, such as the direct arrivals and the 18-Hz hum from machinery at the well site. Nonlinear effects of the vibroseis-Earth interaction, producing harmonics of the sweep, can also be analyzed, and perhaps removed.

Novel methods are also being applied to three-component data, treating (x,y,z) trace triplets as vector traces rather than within conventional vertical (z), inline (x) and crossline (y) gathers, the industry norm [*Tatham and McCormack*, 1991]. A new computer program simultaneously animates a ground motion and a trace-component display, while the data are rotated about any axis. The animation supplies a convincing three-dimensional illusion, and color coding and labeling permit identification of the time dimension. At the same time, the animated display can be dynamically switched through the trace gather so that adjacent vector traces can be compared.

Despite the political, weather, and funding problems, the acquisition phase of the experiment was successful. The seismic data obtained will address the conflict between the steep lithological dips seen at outcrop and the flat-lying reflectors commonly observed wherever deep seismic reflection profiles are shot. The primary lithological layering in both the Proterozoic volcanics and the Archaean is steeply dipping—but not, as in the KTB deep borehole in Germany, too steep and complex to image seismically. If we observe flat-lying, or low-dipping reflectors, as is usually the case with deep reflection profiling, then we can refute the hypothesis that such layering is due to lithological contrasts.

This unique data set should aid our understanding of the relative role of lithological layering, fractures, and fluids in giving rise to reflectors within the continental crust; for example, what is the structural control on fluid flow at mid-upper crustal depths, and the nature of the brittle-ductile transition? We should also be able to observe P wave and S wave anisotropy, and correlate them with the in situ stress that has been measured in the hole.

Going down beyond the reach of the drill, the experiment will help to define the nature of the Precambrian Moho, and whether Archean lower crustal structure is fundamentally different from younger crust, as is now being suggested after the reevaluation of seismological data [*Durrheim and Mooney*, 1991; *Mooney and Meissner*, 1992]. It also provides a crucial section of a crustal reflection transect across the Baltic Shield from the Gulf of Bothnia, where the BABEL data already exist [*BABEL Working Group*, 1993] to the Barents Sea. Completing the crustal transect should be relatively easy, since the remainder of it could be done entirely on roads. A short extension northward within Norway, combined with undershooting—shooting on one side and recording on the other side of an inaccessible area—of the no-go zone just north of the well, would also link into deep marine reflection data in the Barents Sea.

Although there are no plans to deepen SG-3 to 15 km, the well will be maintained as a natural laboratory for international cooperative experiments. Using the several super-deep holes, particularly SG-3, within the former Soviet Union for a variety of new down-hole experiments is a cost-effective way to support the new international continental deep drilling program currently in development.

Copies of a VHS video showing scenes of the operations at the SG-3 wellhead can be obtained from D. K. Smythe (e-mail dks@uk.ac.glasgow.geology).

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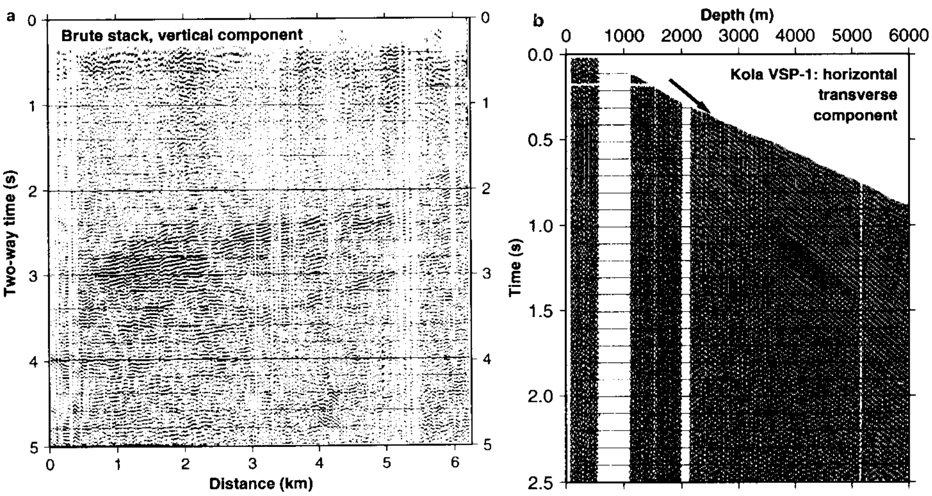

Fig. 4. a) Brute stack of vertical component data from the south end of the CDP line. Layering at 2–3 s two-way travel time is from Pechenga volcanics underlying Archean gneisses and migmatites that have been overthrust to the north. A single velocity function and simplified geometry were applied, but no static corrections or bad trace editing; raw data quality is therefore good. b) Example of a VSP section at short offset without wave field separation. Arrow indicates strong downgoing S waves generated by mode conversion at about 2800 m depth.

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