The ICDP Snake River Geothermal Drilling Project: Preliminary Overview of Borehole Geophysics

Douglas R. Schmitt[1], Lee M. Liberty[2], James E. Kessler[3], Jochem Kück[4], Randolph Kofman[1], Ross Bishop[1], John W. Shervais[3], James P. Evans[3], and Duane E. Champion[5]

[1]Institute for Geophysical Research, Dept. of Physics, University of Alberta, Edmonton
[2]Center for Geophysical Investigation of the Shallow Subsurface, Boise State University, Boise
[3]Department of Geology, Utah State University, Logan UT
[4]ICDP Operational Support Group, Deutsches GeoForschungZentrum GFZ, Potsdam
[5]United States Geological Survey, Menlo Park CA

Keywords

Snake River Plain, geophysical logging, vertical seismic profile, fractures, stress

ABSTRACT

Hotspot: The Snake River Geothermal Drilling Project was undertaken to better understand the geothermal systems in three locations across the Snake River Plain with varying geological and hydrological structure. An extensive series of standard and specialized geophysical logs were obtained in each of the wells. Hydrogen-index neutron and γ-γ density logs employing active sources were deployed through the drill string, and although not fully calibrated for such a situation do provide semi-quantitative information related to the 'stratigraphy' of the basalt flows and on the existence of alteration minerals. Electrical resistivity logs highlight the existence of some fracture and mineralized zones. Magnetic susceptibility together with the vector magnetic field measurements display substantial variations that, in combination with laboratory measurements, may provide a tool for tracking magnetic field reversals along the borehole. Full waveform sonic logs highlight the variations in compressional and shear velocity along the borehole. These, together with the high resolution borehole seismic measurements display changes with depth that are not yet understood. The borehole seismic measurements indicate that seismic arrivals are obtained at depth in the formations and that strong seismic reflections are produced at lithological contacts seen in the corresponding core logging. Finally, oriented ultrasonic borehole televiewer images were obtained over most of the wells and these correlate well with the nearly 6 km of core obtained. This good image log to core correlations, particularly with regards to drilling induced breakouts and tensile borehole and core fractures will allow for confident estimates of stress directions and or placing constraints on stress magnitudes. Such correlations will be used to orient in core orientation giving information useful in hydrological assessments, paleomagnetic dating, and structural volcanology.

I. Introduction

Hotspot – the Snake River Geothermal Drilling Project is an international scientific drilling program focussed on understanding the geological history, architecture, and current day geothermal regime of the Snake River Plain (SRP). This area is characterized high heat flow [e.g., *Blackwell*, 1989]and successive volcanism over the last 17 Ma [*Hanan et al.*, 2008; *Shervais et al.*, 2006] that terminates at the Yellowstone hotspot [*Smith and Braile*, 1994; *Waite et al.*, 2006]. As such, the combination of high geothermal potential together and intriguing geological issues makes the Snake River Plain an attractive target for scientific drilling as discussed in more detail by *Shervais et al* [2012] in this volume.

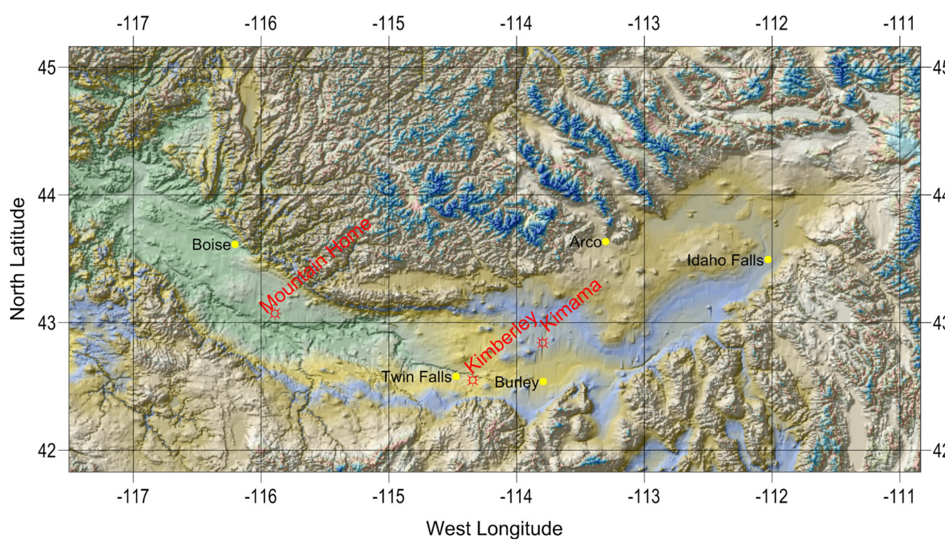

Figure 1. Shaded topographic map of the Snake River Plain showing the locations of the three sites of Kimama, Kimberley, and Mountain Home. Map created with data from the GEOTOPO data base.

This contribution provides an overview of the extensive geophysical logging and borehole seismic campaigns associated with the project. The lithologies and rationale for drilling each of the boreholes is cursorily reviewed. The geophysical work plans for each well are discussed and some of the initial findings from these are presented, the plans for ongoing work towards a final interpretation are discussed. As many readers are not familiar with the different geophysical logging tools, they are for convenience defined in a brief appendix.

II. Overview of Logging Programs

To date, three boreholes at sites near Kimama junction, the village of Kimberley near Twin Falls, and on the Mountain Home Air Force Base have been completed to depths each in excess of 1800 m. Each of these sites provides different examples of geothermal settings across the Snake River Plain (Figure 1). Below the lithology and the logging campaigns are overviewed and an example of some of the data obtained is provided.

i. Kimama

Kimama, completed at a final depth of 1912 m, is sited on the axis of the Snake River Plain that blanketed with thick overlapping basalts originating from a series of vents. The important Snake River Plain Aquifer [*Hubbell et al.*, 1997] underlies the site. The aquifer is in part recharged by flow of water from the mountains to the north with the general underground flow to the SE with significant discharge into the Snake River. The flow of these fluids cools the aquifer zone resulting in the conductive heat transport zone being at substantial depth. The general lithology at Kimama consists of primarily of basalt flows interbedded with weak, wind-blown sediments deposited during volcanic hiatuses.

Figure 2 gives a summary of the logs and the depth ranges over which they were obtained at Kimama. Geophysical hydrogen index (neutron), γ-γ dual density, natural γ, temperature and gyro deviation logs were obtained in October-November 2010 through the upper cased sections of both Kimama 1A and 1B [*Twining and Bartholomay*, 2011] by the U.S.G.S. to depths of about 300 m and 760 m, respectively. Neutron and γ-γ density logs were again obtained through the drill string by a commercial operator (Century Geophysical) in January, 2011. In the same campaign, open hole electrical, full wave form sonic, magnetic susceptibility, dipmeter, and and ultrasonic borehole televiewer data were collected through the NQ-diameter (76 mm) section of the hole. Collapse of the hole through the sediment interbeds and tool failures only allowed logs to be collected in the uppermost 200 m of the NQ section. Open hole logging of the HQ-diameter (96 mm) section was carried out in June, 2011 by the Operational Services Group of the International Continental Drilling Program. This included full BHTV, sonic, electrical resistivity, magnetic susceptibility, full vector magnetic field, and natural γ. At this time, zero-offset and walk-a-way vertical seismic profiles (VSP) were obtained. In this last campaign, the depth over which data could be obtained was limited by the separation at near 1145 m of the temporary liner. Restrictions along the borehole due to sediment interbedding did not allow the centralized BHTV and dipmeter tools to enter the entire HQ open hole section.

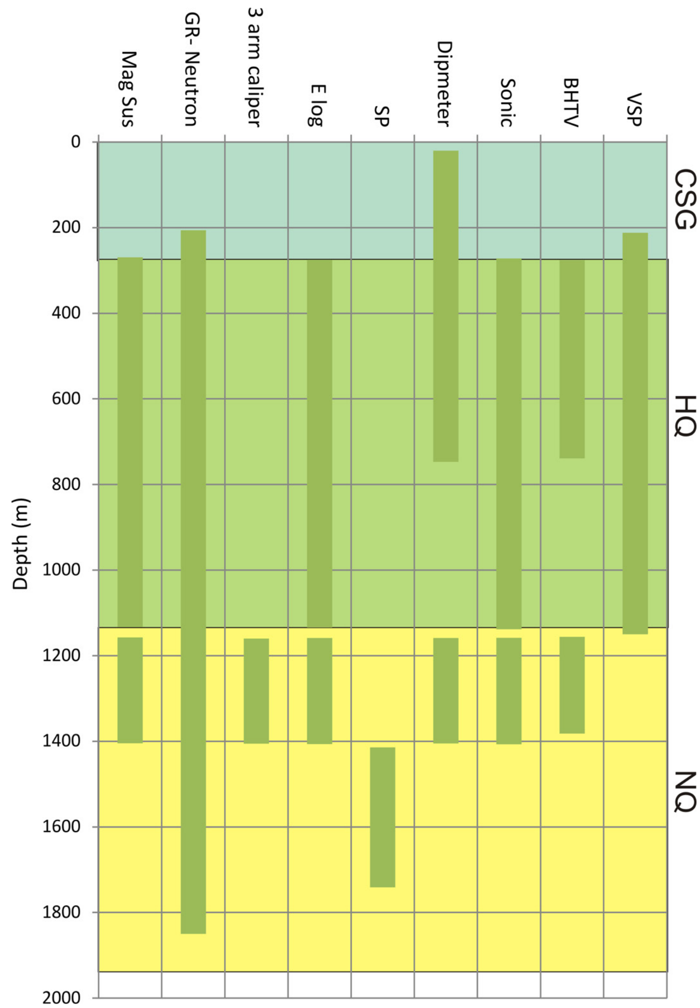

Figure 2. Summary of geophysical logging at Kimama. CSG, HQ, and NQ stand for depth sections of surface casing, HQ coring, and NQ coring, respectively.

An example of the processed zero-offset VSP called a corridor stack (Figure 3) is important for two reasons. First, this allows the true depth of surface seismic data to be properly calibrated. Second, the corridor stack highlights the zones of seismic reflectivity within the geological column. In Figure 3 from *Liberty et al* [2012] a number of horizontal events are seen in the corridor stack and these are correlated in a simple way against the gross lithologies. Strong events are produced at the two sediment interbeds seen in the core between 1200 m and 1400 m. Observing these in the borehole seismic data shows that substantial seismic energy does make it through the complex basalt flow packages.

ii. Kimberley

Kimberley is in the Twin Falls region that is already well known for its low enthalpy geothermal resources. Here, the ground waters are recharged in the mountains to the south, seeps deeper into the crust where it is heated, then upwells forming an artesian system [*Street and deTar*, 1987]. The lithology here does include a veneer of basalt and sediment interbeds above 430 m, but is then almost a completely rhyolite except for a few isolated and thin sediment zones to its total drilled depth of 1958 m.

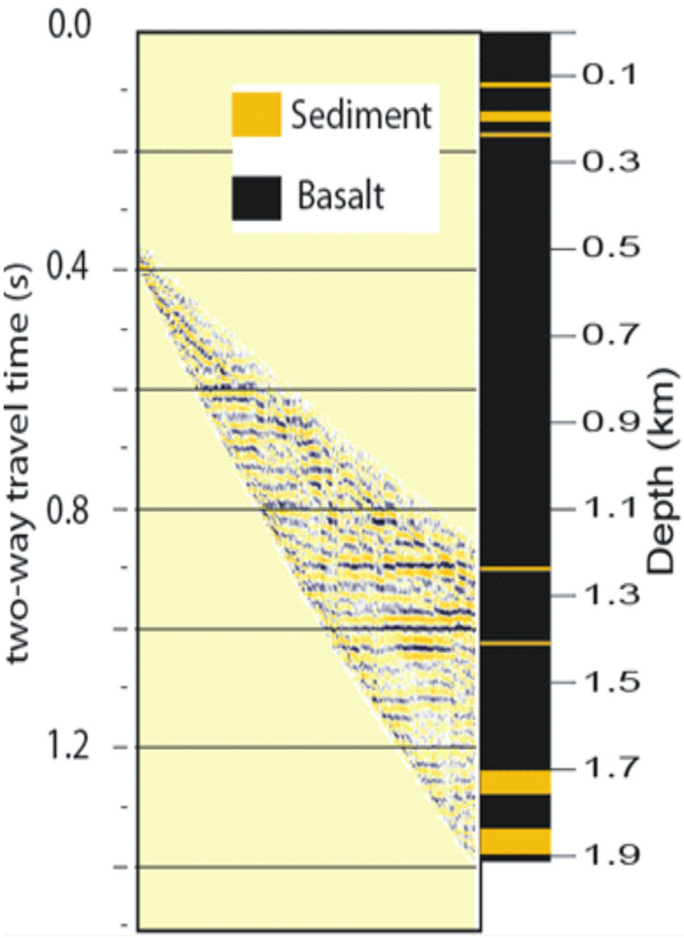

Figure 3. Final process 'corridor stack' obtained from the zero-offset VSP data acquired at Kimama. Strong seismic reflections are seen to be correlated with thin sediment interbeds.

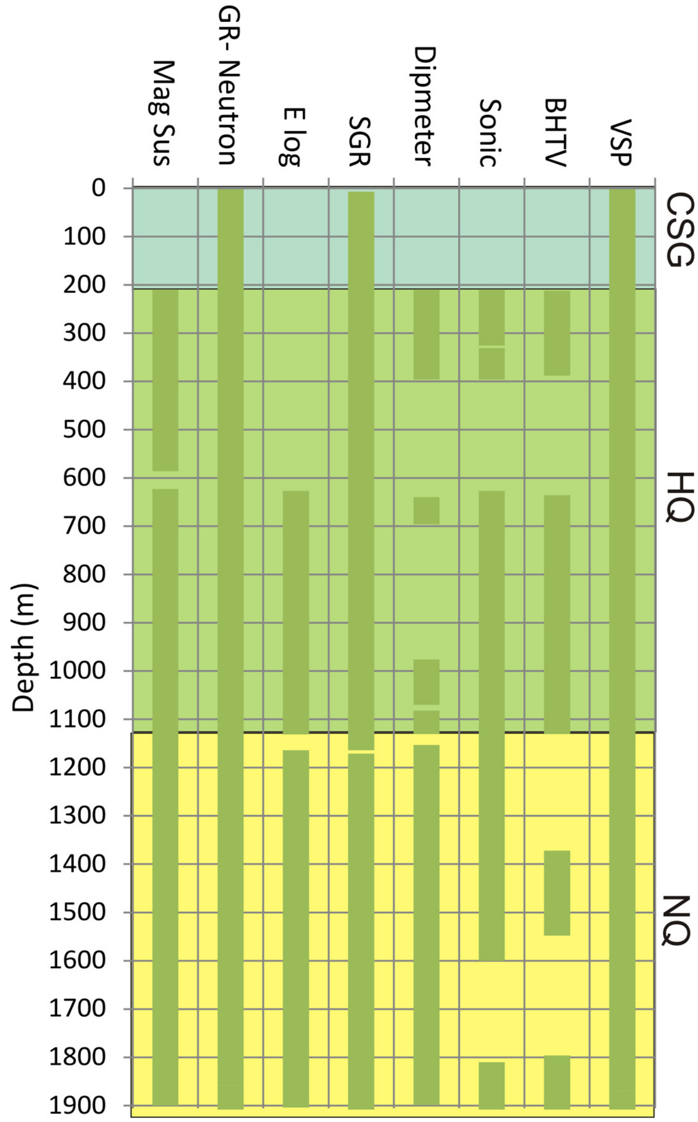

Figure 4. Summary of geophysical logging at Kimberley. CSG, HQ, and NQ stand for depth sections of surface casing, HQ coring, and NQ coring, respectively.

The logging and borehole seismic program was carried out in June, 2011 upon the completion of drilling and summarized in Figure 4. A commercial operator (Colog, Denver) was contracted to carry out neutron logging through the drill strings. Flow rate logging was attempted once the NQ drill string was removed but was unsuccessful on account of the viscous drilling fluids remaining in the borehole. The ICDP OSG then ran a full suite of tools. The lower sections of the borehole were drilled through a relatively homogeneous mass of rhyolite and this provided for a good quality borehole and, consequently, success with most of the logging operations.

The borehole seismic program was particularly ambitious. The program was fortunate to be able to use a Sercel Slimwave® seismic receiver system acquired by the GFZ-Potsdam and operated by the ICDP OSG. This system included 4 3-component geophone stations that allowed for relatively rapid acquisition along the entire depth of the borehole at a close spacing of 2.5 m.

Although hole conditions precluded obtaining BHTV images along the complete well, that which was acquired was of high quality. The BHTV log correlates well against the boxed core photos (Figure 5) through a ~0.6 m long section of the rhyolite core. This core material displays a series of open vugs that may also be seen in the corresponding BHTV images.

iii. Mountain Home

Geothermal resources in the Western Snake River Plain have been exploited for nearly 100 years, and as noted by *Shervais et al*. [2012, this volume] the main science driver for this well was to obtain new information about temperatures and fractures in order to evaluate the geothermal potential.

Drilling has so far been completed to 1821 m and the hole remains open awaiting additional temperature and geophysical logging. This stratigraphy at this site differs significantly in that over 600 m of lacustrine mudstones lie below about 215 m of basalt flows with minor sediment interbeds (much as at Kimama). These lake sediments provide a secondary scientific target as they potentially contain information on variations in climate in the region during the lifetime of the lake. These lake sediments too contain what appear a few thin basaltic sills. Beneath 850 m, the lithology consists primarily of basalt flows separated by sandstone, gravel, and ash deposits.

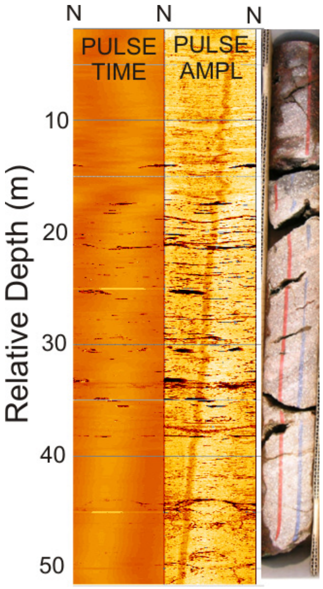

Figure 5. Comparison of BHTV pulse travel time and pulse amplitude images to boxed core photograph. The core length is approximately 0.6 m.

The fractures at Mountain Home are of particular interest because at 1745 m coring intersected an artesian fracture zone sufficiently pressurized to produce flow of hot water to the surface [*Armstrong et al.*, 2012; *Lachmar et al.*, 2012; *Nielson et al.*, 2012, this volume].

The initial logging and VSP campaign at Mountain Home was carried out in January, 2012 by the ICDP OSG. The spectral γ log (SGR) was obtained through the open NQ hole and nearly to the surface through the HQ and HWT drill strings. The higher temperatures at Mountain Home precluded use of the BHTV at the NQ depths. A zero offset VSP was acquired using an older analog downhole geophone system and the temperatures, too, limited the depths over which data could be obtained.

At this writing, the logging at Mountain Home remains incomplete and it is expected that neutron and high temperature BHTV logs will be obtained before the well is completed. Both of these are crucial given the large degree of alteration observed in the

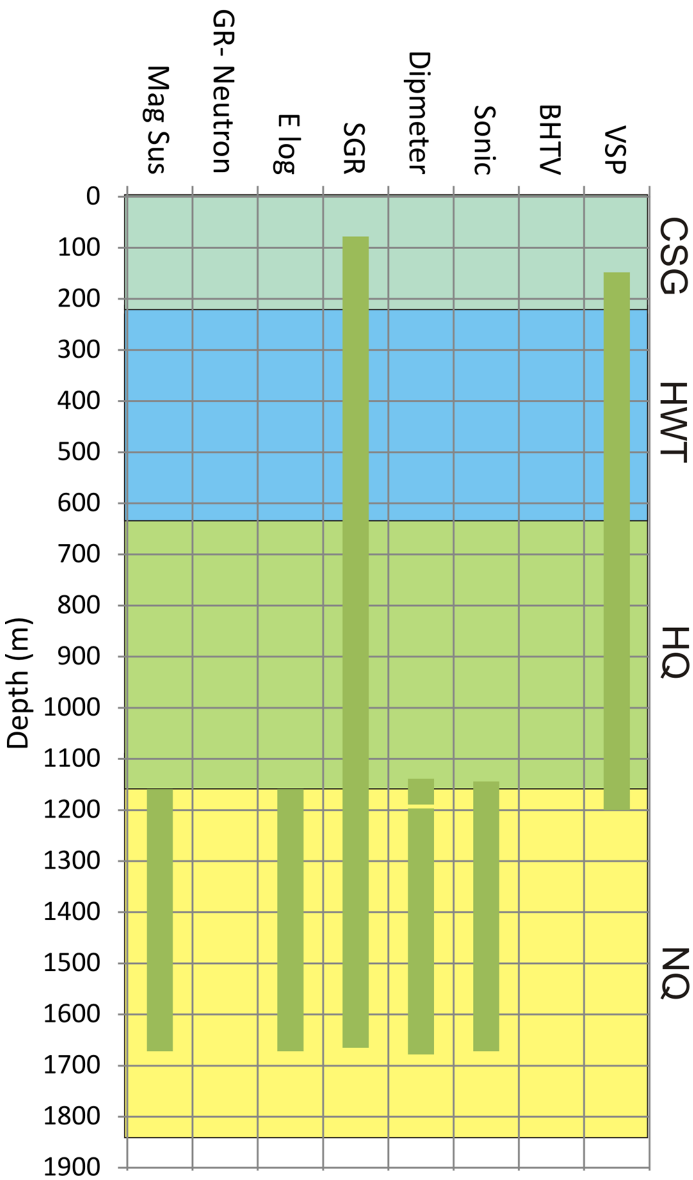

Figure 6. Summary of geophysical logging at Mountain Home. CSG, HWT, HQ, and NQ stand for depth sections of surface casing, PQ coring, HQ coring, and NQ coring, respectively.

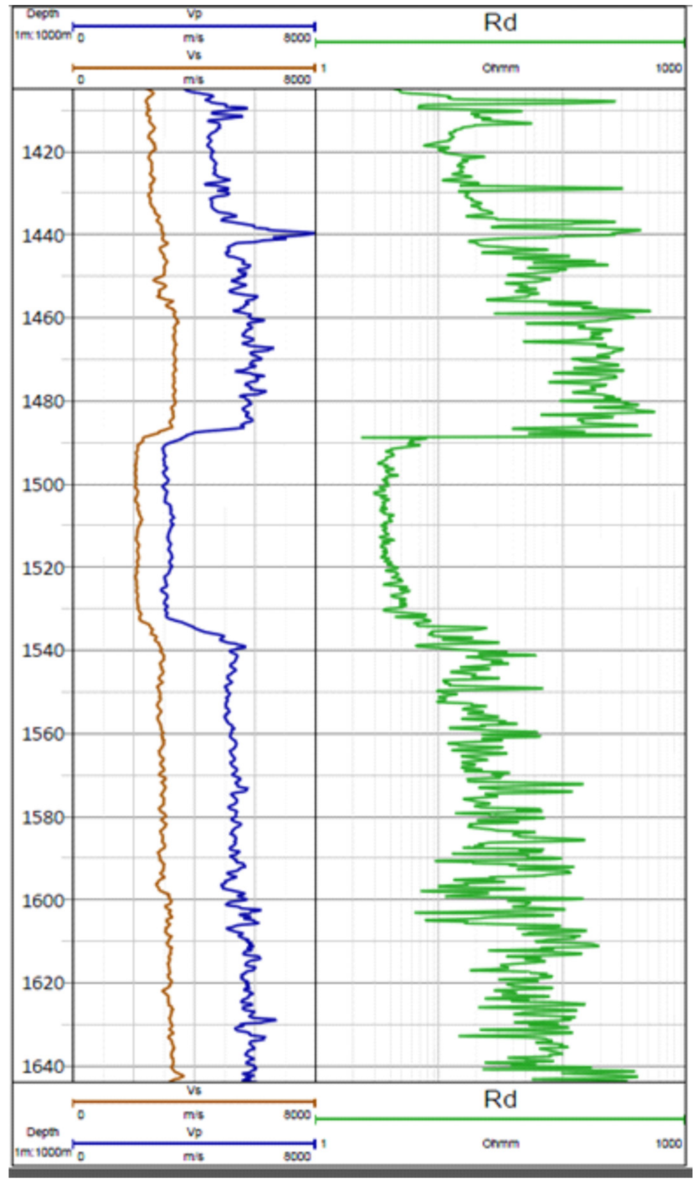

Figure 7. Correlations between the resistivity log (Rd) with the sonic Vp and Vs wavespeeds over a portion of the Mountain Home borehole.

core and because of the importance of understanding the fracture systems at depth. It will be important to attempt to acquire a high quality magnetic susceptibility log through the lake sediments as this will allow correlation to the cores scans now being carried out.

Figure 7 gives an interesting comparison between the P and S wave velocities and the electrical conductivity at Mountain Home. All three logs mimic each other's behaviour along the well. The large drop in resistivity between 1490 m to 1540 m depth is tracked by corresponding substantial decreases in the P and S wave velocity. The reason for this is not yet known but it may be related to alteration of the basalts as is seen in the retrieved core.

III. Summary

An extensive series of geophysical logs and borehole seismic experiments have been carried out at the Kimama and Kimbeley sites, and it is anticipated that higher temperature logging will occur at Mountain Home in the future. The logs have already been of use in locating sediment interbeds and even highlighting the finer scale structure of the basalt flows. Interpretation of the image logs is of the greatest priority in order to learn more about the natural fracture systems and the in situ states of stress. Further, the image logs will allow much of the core to be oriented; this information will be of use for refined paleomagnetic analyses and should find use in deducing the directions of the basalt flows and rhyolite deposition.

Acknowledgements

This work was sponsored by DOE award DE-EE0002848, by the International Continental Drilling Program, and by the National Science and Engineering Research Council of Canada through the Discovery grant of DRS. Logging was assisted by C. Carnein, M. Topfer, and M. Rey Abasolo from the OSG and R. Kofman and L. Duerksen from the Univ. of Alberta. Numerous students from Boise State Univ. and the Univ. of Alberta helped with the field seismic data acquisition.

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APPENDIX

Tool Descriptions

This appendix intends to provide a brief description only of the operation of such tools. The reader is directed to various texts on formation evaluation for additional information.

Hydrogen-Index (neutron): This log records the flux of scattered neutrons returning to the tool. The flux is highly dependent on the amount of H nuclei in the formation and as such responds to water and fluid hydrocarbons plus any H atoms locked in clays or alteration minerals.

γ-γ density log: The downhole tool illuminates the formation with γ-rays that are scattered by the electrons surrounding the atoms in the formation. As such, it provides an indirect measure of the density of electrons that correlates well with the mass density for most of the rock forming minerals.

Ultrasonic Borehole Televeiwer (BHTV): This is an instrument that provides an unwrapped image of the borehole wall rock that is oriented with respect to magnetic N. The tool contains a small ultrasonic transducer that both sends and receives a high frequency ultrasonic pulse reflected from the borehole wall. The transducer rotates around the borehole with hundreds of pulses per rotation; mapping with depth and azimuth of the travel times and the amplitudes of these returned pulses creates two images of the borehole wall.

Electrical Log (E-log): Here, the electrical log essentially measures the electrical resistivity of the formation.

Full Waveform Sonic Log (Sonic): This tool acquires sonic frequency (~10 kHz) acoustic pulse waveforms that travel from a transmitter down the borehole to two receivers. These waveforms are then interpreted to provide transit times, and hence velocities, of the compressional and the shear waves of the rocks.

Magnetic Susceptibility (Mag Sus): This tool provides a scalar measurement of the material's magnetic susceptibility. In rock this is mostly associated with the amount of magnetite. It is particularly useful for correlations in lake sediments as such amounts of magnetic minerals are sensitive to environmental conditions.

Natural γ and Spectral γ (SGR): Both of these logs measure the intensity of the natural γ-ray emissions from rocks. The strength of these emissions depends primarily on the Uranium, Thorium, and Potassium proportions. The SGR records the intensities over different γ-ray energy ranges and because U, Th, and K all emit different energies an estimate of their abundance in the rock can be made.

Dipmeter: In sedimentary formations this tool us used to estimate the dip of the layers using cross measurements of the electrical conductivity immediately at the borehole wall. In this project, the dipmeter mostly provides oriented caliper information and, locally, the hole azimuth and inclination.