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# Downhole Measurements in the AND-1B Borehole, ANDRILL McMurdo Ice Shelf Project, Antarctica

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**Abstract** - A comprehensive set of downhole measurements was collected in the AND-1B drillhole as part of the on-ice scientific programme defined for the McMurdo Ice Shelf (MIS) Project. Geophysical logs were recorded over two operation phases and consisted of calliper, temperature, fluid conductivity, induction resistivity, magnetic susceptibility, natural gamma activity, acoustic televiewer, borehole deviation, and dipmeter. In addition, two standard vertical seismic profiles (VSP) and one walk-away VSP were obtained. Radioactive logs (porosity and density) were not run because of unstable borehole conditions. Although the total depth of the hole is 1285 metres below seafloor (mbsf), the depth range for *in situ* measurements was limited by the length of the wireline (1018 mbsf) and by the nullification of some geophysical logs due to the presence of steel casing. A depth correction was derived to account for systematic discrepancies in depth between downhole measurements and cores; consequently, log responses can be directly compared to core properties. The resulting data are amenable to studies of cyclicity and climate, heat flux and fluid flow, and structure and stress. When integrated with physical properties and fractures measured on the core, this information should play a significant role in addressing many of the scientific objectives of the ANDRILL programme.

## INTRODUCTION

Geophysical logs obtained in a borehole provide vertically continuous, *in situ* records of a variety of physical properties that help characterise the surrounding rocks (*e.g.* Ellis 1987; Hearst et al. 2000). Logs that respond to rock mineralogy, porosity or fabric, such as natural gamma activity, electrical resistivity, and magnetic susceptibility, may be combined with and calibrated to laboratory measurements performed on cores to examine variability with respect to depth and, consequently, over time. Sonic velocity and density logs can be used to construct synthetic seismograms to tie data derived from surface seismic reflection profiles to the core. Additional insights into the transport of heat and fluid through these rocks may be gained from the analysis of temperature and resistivity profiles of the borehole fluid. Information on structure and stress conditions may also be obtained by combining the detailed examination of fractures in cores with magnetically oriented acoustic televiewer images of the borehole wall to investigate stress-induced features in the rocks and relate these to the local stress field.

Borehole seismic methods such as vertical seismic profiling (VSP) and walk-away VSP (*e.g.* Hardage 2000) can be used to link borehole stratigraphy to seismic reflection data. Specifically, VSP provides (1) down-going travel-time data that can be used to determine velocities and to serve as a basis for comparison with downhole sonic and core measurements, (2) up-going reflections that can be used to tie directly into on-ice seismic reflection data, and (3) information about strata below the bottom of the well.

These applications address many of ANDRILL's scientific objectives (Naish et al. this volume), and the downhole measurements programme for the AND-1B hole was an integral part of the scientific activities outlined in the *Scientific Logistics Implementation Plan for the ANDRILL McMurdo Ice Shelf Project* (SLIP; Naish et al. 2006). The original logging plan called for nine separate tools to be deployed in AND-1B, some across the entire span of the well and others across only the open-hole portions of both the NQ and the HQ sections of the borehole once drill pipes were removed. These tools measure natural gamma activity, borehole fluid temperature and conductivity (multifunction tool), electrical resistivity, compressional and shear sonic velocities, porosity, density, borehole diameter, magnetic susceptibility, structural dip, and acoustic borehole imaging. The data acquisition system used to run the full-waveform sonic tool blew a transistor and could not be repaired. Moreover, the two sondes housing radioactive sources, the neutron porosity and gamma-gamma density tools, were not run because of the risk of them becoming stuck in the unstable and unpredictable hole. Thus, with these three eliminated from the geophysical logging programme, a total of six logging tools were deployed in this hole in addition to the hydrophone array required for the VSP experiments. Their descriptions and design specifications are listed in table 1.

## SUMMARY OF DOWNHOLE MEASUREMENT OPERATIONS

Downhole measurements were conducted in two separate phases, and a detailed timeline of these operations performed in the AND-1B drillhole between 26 December 2006 and 8 January 2007 is presented in tables 2 & 3 and illustrated in figure 1. In the initial phase, calliper, induction, magnetic susceptibility, acoustic televiewer, and dipmeter logs were obtained across the open-hole section of the NQ hole extending from the base of the HQ pipe at 692 to 1018 mbsf. This maximum depth is the limitation imposed by the length of the logging cable and does not correspond to the total depth of the hole (1285 mbsf). Thus, the bottom 266 metres (m) of the hole could not be reached with the wireline and no downhole measurements were obtained across this lowermost section. Three separate multifunction tool logs were obtained from seafloor to maximum wireline depth. These repeat logs provide continuous profiles of natural gamma activity, temperature, and fluid conductivity across a 1018 m depth range. They also serve to monitor the thermal recovery of the well over a period of five days as it approached equilibrium formation temperature.

The second phase of the logging programme was predicated upon the successful cutting and removal of the HQ drill pipe roughly 30 to 50 m above its base where it had been cemented into place, thereby leaving roughly 410 m of open hole that was to extend to the base of the PQ pipe at about 237 mbsf. However, the HQ pipe was jammed in the hole somewhere between 343 and 525 mbsf, and the lower section could not be pulled out of the hole. During the drill-pipe cutting operations, the HQ pipe below 525 mbsf fell a further 57 m down into the over-gauge NQ hole. A 106 m section (237–343 mbsf) and a 58 m section (525–583 mbsf) that had previously been cased were now available for logging with the calliper, dipmeter, acoustic televiewer, induction, and magnetic susceptibility tools (Fig. 1). Logging plans with tools that require an open hole for their measurements, such as the dipmeter and the acoustic televiewer, were encumbered by the failure to remove most of the HQ drill pipe and were further limited by the inability of the wireline to reach total depth. As a result, these logs were recorded across only about one third of the entire borehole.

Two separate types of vertical seismic profiles were completed at AND-1B and are schematically illustrated in figure 2. (1) A standard VSP was performed by stepping up the well at 30 m intervals with a 5-channel, 30 m hydrophone array and one explosive source placed 80 m from the well head while recording

*Tab. 1* - Downhole tools successfully deployed and their design specifications.

| | |
|---|---|
| **4-arm calliper** | |
| Manufacturer | Century Geophysical Corporation |
| Model | 9065 |
| Specifications | Diameter range: 5.1 to 76.2cm. Accuracy: ±0.38 cm |
| **Multifunction** | |
| Manufacturer | Century Geophysical Corporation |
| Model | 8144 |
| Specifications | Natural gamma activity |
| | Range: 0–10 000 API units. Accuracy: ±5% |
| | 16N and 64N normal resistivity |
| | Range: 0–2000 ohm-metres. Accuracy: ±5% |
| | Temperature |
| | Range: 0 - 70°C. Accuracy: ±5% |
| | Fluid resistivity |
| | Range: 1–100 ohmmetres. Accuracy: ±5% |
| | Spontaneous potential |
| | Range: -400 to + 400mv. Accuracy: ±5% |
| **Acoustic televiewer** | |
| Manufacturer | Advanced Logic Technology (ALT) |
| Model | ABI40 |
| Specifications | 1.4 MHz transducer, 1.5 x 1.53mm beamwidth |
| | Borehole diameter: 45–600mm depending on fluid |
| | Magnetometer |
| | Accuracy: ±0.5° inclination, ±1.5° azimuth |
| **data acquisition** | |
| Manufacturer | Mount Sopris Instrument Corporation |
| Model | MGX-II console |
| **Induction** | |
| Manufacturer | Century Geophysical Corporation |
| Model | 9512 |
| Specifications | Conductivity |
| | Range: 5 – 3000 mmho/m. Accuracy: ±5% |
| | Natural gamma |
| | Range: 0 – 10 000 API units. Accuracy: ±5% |
| **Magnetic Susceptibility** | |
| Manufacturer | Century Geophysical Corporation |
| Model | 9620 |
| Specifications | Magnetic susceptibility |
| | Range: 0–90 000 cgs. Accuracy: ±5% |
| | Natural gamma |
| | Range: 0–10 000 API units. Accuracy:±5% |
| | X-Y inclinometers |
| | Range: 0-90°. Accuracy: ±0.5° |
| | Azimuth |
| | Range: 0-360°. Accuracy: ±2° |
| **Dipmeter** | |
| Manufacturer | Century Geophysical Corporation |
| Model | 9411 |
| Specifications | Micro resistance |
| | Range: 0–10 000 ua. Accuracy: ±5% |
| | Natural gamma |
| | Range: 0–10 000 API units. Accuracy:±5% |
| | X and Y calliper |
| | Range: 6.4–30.5cm. Accuracy: ±0.5cm |
| | X-Y inclinometers |
| | Range: 0-90°. Accuracy: ±0.5° |
| | Azimuth |
| | Range: 0-360°. Accuracy: ±2° |
| **data acquisition** | |
| Manufacturer | Century Geophysical Corporation |
| Model | System VI console |
| **VSP Hydrophone Array** | |
| Manufacturer | Z-Seis |
| Model | 5-channel (6m spacing) |
| Specifications | Range 100Hz - 4kHz |
| **Seismograph** | |
| Manufacturer | Bison |
| Model | 9024 |
| Specifications | 24 Channel Instantaneous Floating Point |

*Tab. 2* - Timeline summary for Phase 1, AND-1B downhole measurements.

| Start time | End time | **PHASE -1** |
|---|---|---|
| **26 Dec 2006**<br>19:30 | **27 Dec**<br>03:00 | **Calliper log** – reached bridge at 865mbsf. Logging up at 5m/min to HQ pipe. |
| | | Mount Sopris data acquisition box failure (fuse). |
| | | Cable adapter problem with internal socket rotated. |
| 11:30 | 19:00 | Run in the hole with sinker bar to find/clear bridges |
| 21:00 | **28 Dec**<br>08:00 | Run in the NQ pipe to below lowest bridge. |
| 10:00 | 13:50 | Attempt calliper log but no data due to tool malfunction. |
| 13:50 | 20:20 | **Multifunction log** - seafloor to max cable depth. Logging down at 5m/min. |
| 20:20 | **29 Dec**<br>00:45 | **Calliper log** – no bridges in the 60m of lowermost open hole below NQ pipe. Logging up at 5m/min. |
| 00:45 | 06:45 | **Multifunction log** - seafloor to max cable depth. 2nd run to get temperature equilibration. Logging down at 5m/min. |
| 08:00 | 18:00 | **Standard Vertical Seismic Profile (VSP)** |
| | | Pull NQ pipe to base of HQ pipe |
| 23:00 | **30 Dec**<br>03:30 | **Calliper log** - successfully reach max wireline depth. Logging up at 5m/min to base of HQ pipe. |
| 03:30 | 11:30 | Pull NQ pipe out of the hole |
| 14:30 | 22:50 | **Acoustic televiewer log** – from base of HQ pipe to max cable length. Logging down at 1.5 – 2.0m/min. |
| | | Attempt to use sonic tool unsuccessful – requires the failed data acquisition system. |
| **31 Dec**<br>08:00 | 12:20 | **Induction log** - from max wireline length to base of HQ pipe. Logging up at 5m/min. |
| 12:30 | 18:00 | **Magnetic susceptibility log.** Good data from base of HQ pipe to max cable length (except magnetometer data below 880mbsf). Logging down at 5m/min. |
| | | Attempt to run sonic tool again with back-up data acquisition system, but unsuccessful. |
| 19:00 | **1 Jan 2007**<br>03:20 | **Dipmeter log** – from max wireline length to HQ pipe. Logging up at 3m/min. |
| 04:00 | 08:00 | **Multifunction log** – from seafloor to bridge at 822mbsf. 3rd run to get temperature equilibration. Logging down at 5m/min. |
| | | End of Phase-1 logging |

at each depth stage (Fig. 2a). (2) A walk-away VSP (Fig. 2b) was performed by stepping away from the well (30 m steps) with shots recorded in a fixed receiver array located approximately 265 mbsf. This two-sided survey consisted of two 900 m walk-aways run in different directions from the drill site.

A shot depth of 18 m below the ice surface was used for most of the surveys. Shots were recorded as 6-channel SEG2 format on a seismograph and later transcribed to SEGY. The sample rate (1 ms) and record length (5.0 s) were kept constant for all experiments. The explosive source consisted of Anzomex P boosters (395 g) and shots comprising 8 boosters (3160 g) were used for the walk-away spread. A smaller number of boosters were used as the source for the standard VSP.

The standard VSP was undertaken in two phases (Fig. 1; Tabs. 2 & 3). In Phase 1, a VSP was successfully completed from 1018 mbsf to the seafloor. This interval included the open-hole section from the base of the HQ pipe (692 mbsf) to the maximum wireline depth. The part of the VSP record run in casing was contaminated with tube wave noise and wave trains dominated by arrivals having a velocity

*Tab. 3* - Timeline summary for Phase 2, AND-1B downhole measurements.

| Start time | End time | **PHASE-2** |
|---|---|---|
| **6 Jan 2007**<br>13:00 | 19:00 | **Calliper log** – reached bridge at 822mbsf. Logging up at 5m/min to base of HQ pipe and then in HQ open hole |
| | | Discover bottom HQ pipe lower than previously determined. |
| | | Repeat calliper log in lower section at 5m/min |
| 19:30 | 22:30 | **Induction log** – from base of PQ to 345mbsf. Logging down at 5m/min. |
| 23:00 | **7 Jan**<br>03:00 | **Magnetic susceptibility log** – from base of PQ to 345mbsf. Logging down at 5m/min, with good magnetometer readings. Also run across section where HQ pipe has fallen into NQ open hole to confirm presence of metal. |
| 04:00 | 12:00 | Pull out remaining HQ pipe |
| 12:30 | 18:00 | **Acoustic televiewer log** – attempt logging down from base of PQ but tool doesn't descend because of ledge in open hole. Raise tool to surface, set centralizers to smaller diameter, and try again. Logging down from base of PQ to 345mbsf at 1.5m/min. Continue lowering tool to find open gap in casing and log from 586 to 528mbsf. |
| 18:30 | 19:30 | Attempt has been made to repair data acquisition system for sonic tool. Try sonic tool again, but not responding. |
| 21:00 | **8 Jan**<br>05:00 | **Dipmeter log** – from 586 to 528mbsf (gap in HQ pipe) and from 345 to 292mbsf. Logging up at 2.5m/min. Numerous intermittent tool failures in upper portion requiring stopping and starting with new data file. |
| 06:00 | 16:00 | **Walk-away and StandardVertical Seismic Profiles** |
| | | End of Phase-2 logging |

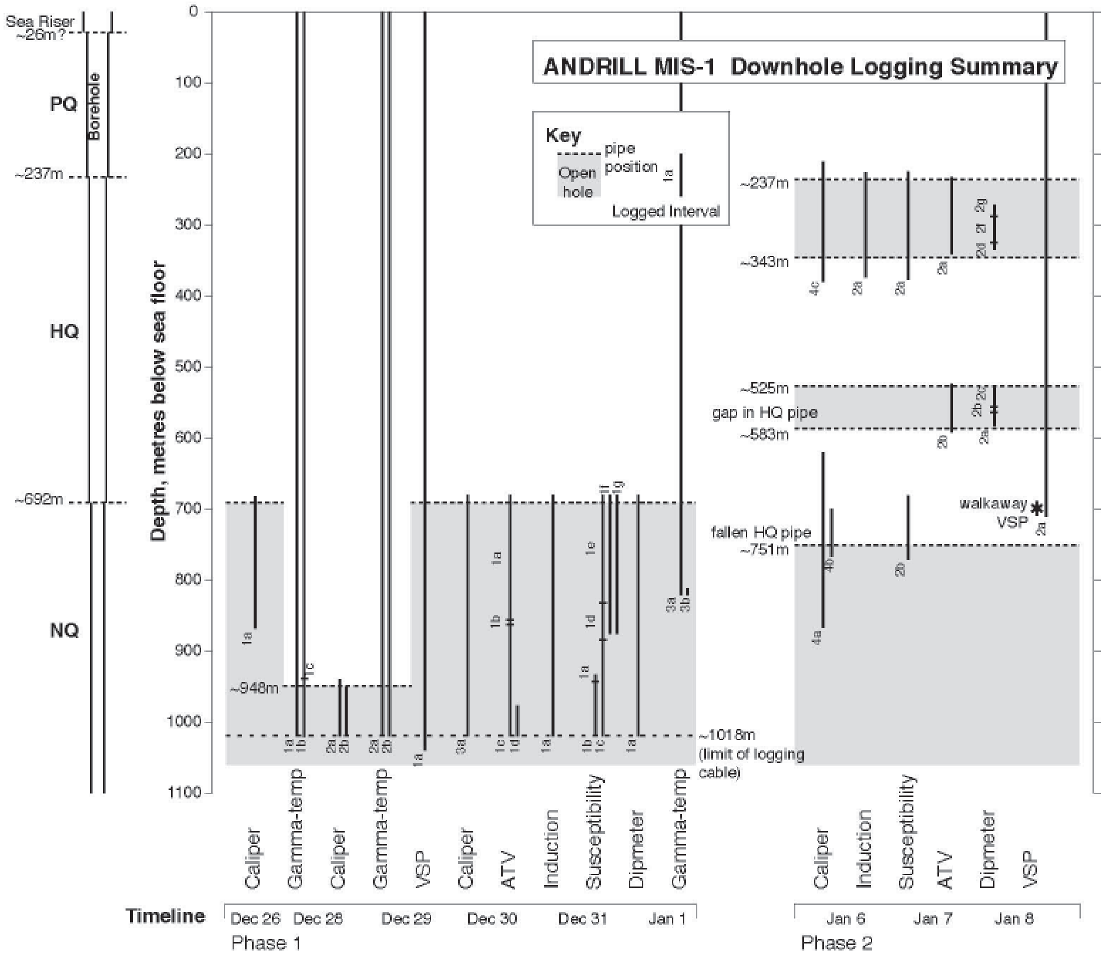


*Fig. 1* – Graphical summary of the downhole measurements operations in hole AND-1B. The length of logged intervals was restricted by the length of wireline and by difficulties removing HQ pipe from the hole. Nevertheless, a broad suite of measurements was obtained from the open-hole intervals, and natural gamma radiation and temperature logs, as well as a standard VSP experiment, cover the entire interval from 0 to 1018 mbsf.

of the steel casing (~4000 m/s). During Phase 2 of the downhole measurements programme, the VSP was repeated over the interval from 446 mbsf to the seafloor. For this experiment, the amount of cable noise was reduced by allowing the hydrophone cable to stand for approximately 15 minutes between steps. The open hole available for Phase 2 was from 237 to about 343 mbsf (about 106 m).

## LOGGING DEPTH CORRECTION

Initially, there was a large offset between the driller's depth values and the downhole log depth values, ranging from 10 m at the seafloor to 25 m offset at the base of the logged section. The offset was determined by correlation of features in the core and downhole log physical property data (Fig. 3). For the 700 to 1000 mbsf interval, magnetic susceptibility was measured on both core and log, and common features could easily be correlated. For the 0 to 1000 m interval, the same lithological features appeared in both density records measured on core (Niessen et al. this volume) and the natural gamma radiation downhole log; for example, diatomites appear as having low density and low natural gamma activity. The offsets increase linearly with depth, and thus a linear correction to the downhole logging depths was applied: a 1.6% depth expansion. This brought the downhole logs into line with the core data to within ±1 m (as shown in Figs. 4 & 5), and enables core and log data to be more easily compared and integrated.

The final correction is determined to be,

$$y = 1.016x + c - d$$

where $y$ = corrected log depth, $x$ = original log depth, $c$ = -5.6 m for most of the logs (but different values, ranging from -4.6 for induction resistivity during Phase 1 to -7.6 for magnetic susceptibility during Phase 2, are required for some logs), and d = 940 m, the water depth required to convert the reference point from rig floor to seafloor. The depth offsets are probably due to a combination of several effects: cable stretch, pipe stretch, and a possible slight inaccuracy in the circumference of the encoder wheel from which cable depth is read.

## DOWNHOLE MEASUREMENTS AND SCIENTIFIC APPLICATIONS

An overview of selected logs obtained in AND-1B is shown in figure 4, where the calliper (hole

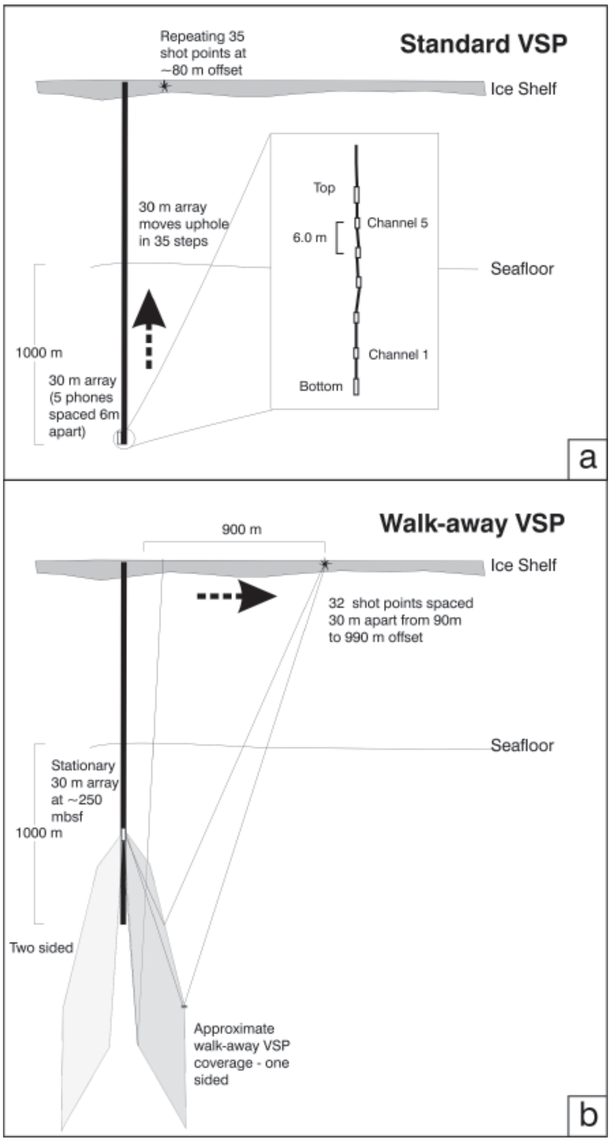


*Fig. 2* – Illustration of a) standard vertical seismic profile (VSP) and b) walk-away VSP experiments.

diameter), induction resistivity, and natural gamma logs are presented alongside density measured on core (Niessen et al. this volume). All data have been adjusted to a common depth reference (metres below seafloor) for presentation and comparison, and gaps in the log data correspond to cased sections of the hole.

The calliper tool was calibrated using NQ and PQ drill bits at the drill site, and the log provides a measure of average borehole diameter. The resistivity log represents the electrical properties of the surrounding rocks, and results are related to porosity, pore-fluid conductivity, and mineralogy. Natural gamma activity as recorded with the multifunction tool depends on the concentration of radioisotopes of potassium, uranium, and thorium in the formation and reflects, for example, the concentration of clay and other potassium-bearing minerals. The magnetic susceptibility of sediments is controlled by the concentration of magnetite and other magnetic minerals; magnetite is part of the terrigenous sediment fraction and may dissolve in silica-rich pore waters.

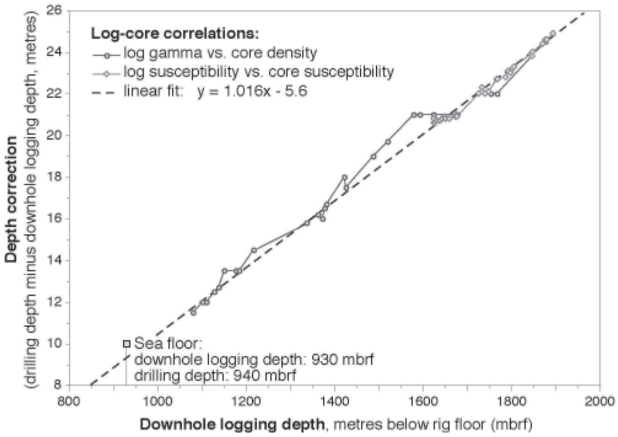


*Fig. 3* – Depth offsets between core and log data. The linear fit represents the correction applied to bring the logs into line with the core data, to within 1 m.

Features in the logs can be identified and correlated with lithostratigraphic features in the core. For example, logs in the 237–343 mbsf interval indicate the presence of two prominent diatomite zones by

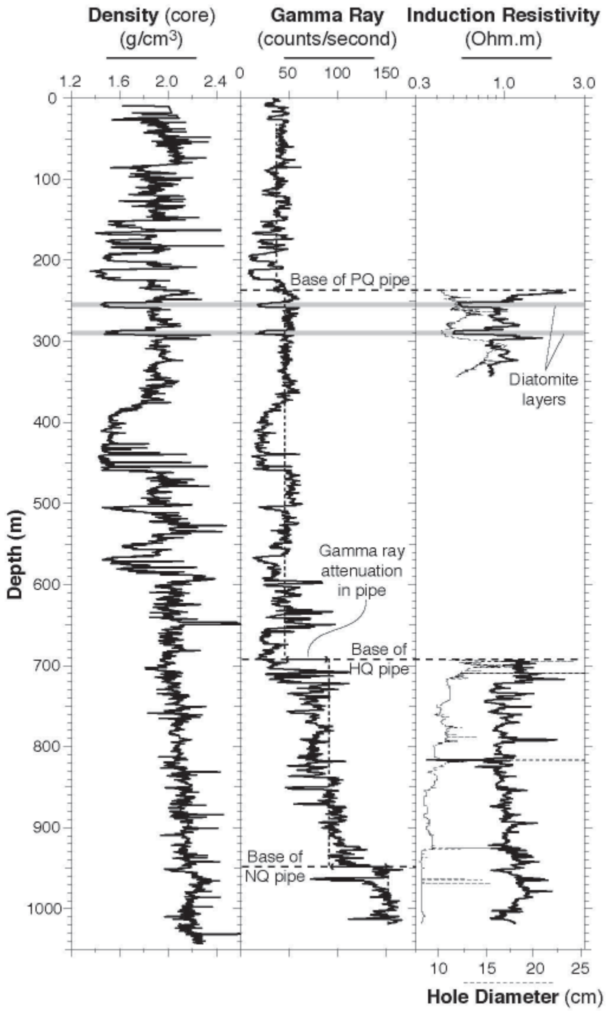


*Fig. 4* – Overview of natural gamma radiation, induction resistivity, and calliper (borehole diameter) logs, plotted alongside density measured on core (from Niessen et al. this volume). Natural gamma and density are smoothed with a 20 cm running average. Note that the diatomite layers are well defined in the downhole logs and core physical properties. Natural gamma radiation is attenuated when measured through pipe, but still provides a valid record of formation radioactivity.

means of common responses from the natural gamma, resistivity, and density tools; all three of these logs shift markedly to lower values when encountering diatomite (Fig. 4). Once the log response to lithology has been determined, more subtle lithologic variations may also be detected from the vertically continuous logs. The logs shown in figure 5 over a depth range of 700 to 740 mbsf display excellent correspondence between core (Niessen et al., this volume) and *in situ* magnetic susceptibility values. Across this same interval, the natural gamma and resistivity logs are inversely correlated. In another Antarctic borehole (Ocean Drilling Program [ODP] Hole 1165B, offshore Prydz Bay), a similar anti-correlation was a result of silica cementation in terrigenous-poor layers (Williams & Handwerger 2005), but as the 700 to 740 mbsf interval is part of a volcaniclastic unit, a different explanation is required here. When combined with the magnetic susceptibility logs, which have a different signature again, further aspects of lithologic variation through the rock column may be illuminated.

The sequence of three temperature profiles collected over a five-day period is presented in figure 6. These reflect thermal conditions initially disturbed due to drilling operations and circulation of drilling mud, but gradually equilibrating such that the fluid temperature measured in the borehole approaches the local geothermal gradient. The thermal conductivities of the rocks were not measured directly but can be estimated using mixing models (*e.g.* Crane and Vachon 1977) based upon porosity and mineralogy. In this case, the density values determined from core combined with other lithologic information can be used to predict rock thermal conductivity. With the background geothermal gradient determined from the temperature equilibration record and the rock thermal conductivity estimated from other physical properties, a value of heat flow for this site may be computed and compared with other values reported for the region (*i.e.* Blackman et al. 1987; Bücker et al. 2001).

Structural information was obtained from the acoustic televiewer and the dipmeter logs run in the open-hole sections of AND-1B. The televiewer (ATV) provides a magnetically oriented image of the borehole wall from which features such as bedding planes, fractures, and clasts can be identified and their orientations determined (Zemanek et al. 1970). Borehole images were of fairly good quality in zones where borehole rugosity was not excessive and diameter was close to gauge; an example is shown in figure 7 across a 4 m section. Images such as these that contain distinctive features can be used to orient core. The resulting information may also be

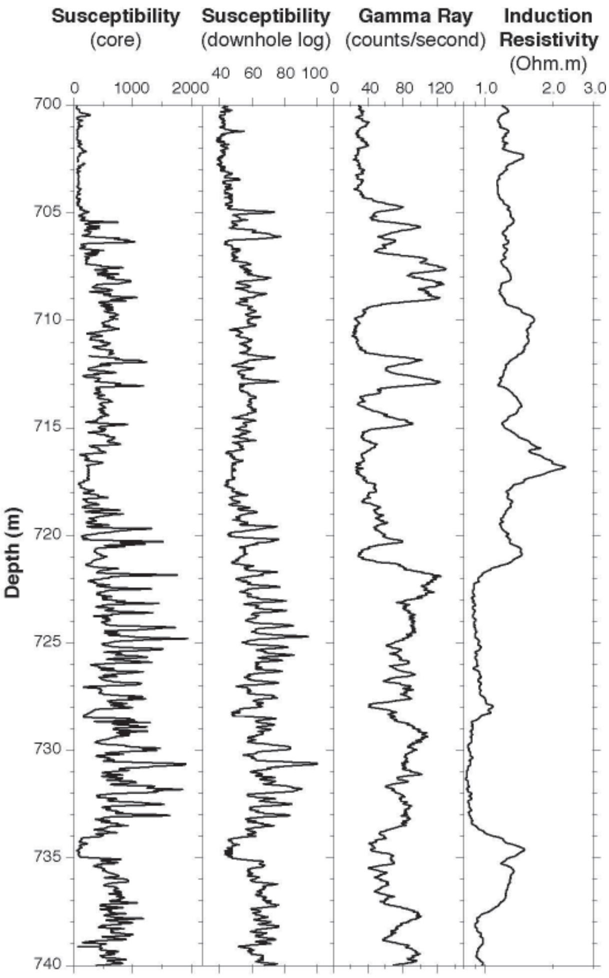


*Fig. 5* – An example across the depth interval from 700 to 740mbsf showing magnetic susceptibility, natural gamma radiation, and induction resistivity logs, alongside magnetic susceptibility determined from core (from Niessen et al. this volume). The clear similarities between log and core susceptibility helped correct the log depths towards the core depth scale. Features in the susceptibility, natural gamma, and resistivity logs can be interpreted in terms of terrigenous content, clay content, degree of cementation, and other lithological parameters.

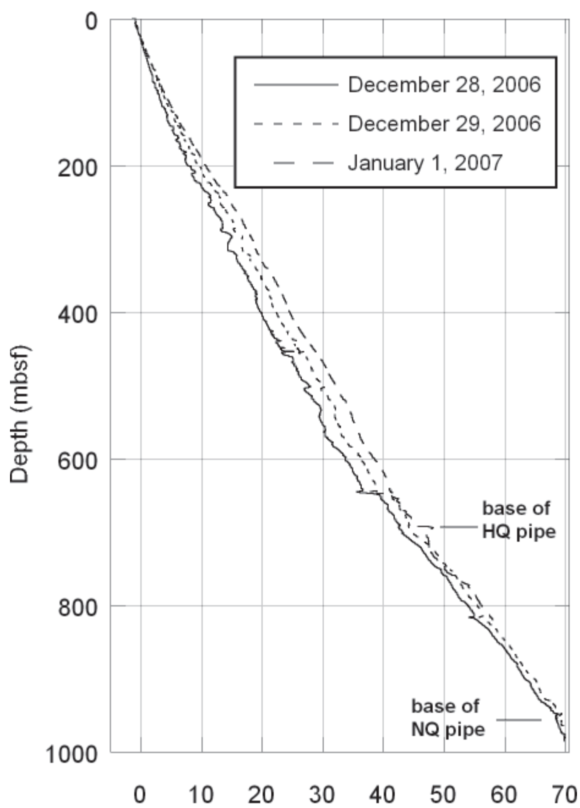


*Fig. 6* – Series of three temperature logs recorded over a five-day period depicting thermal recovery after disturbance from drilling and mud circulation.

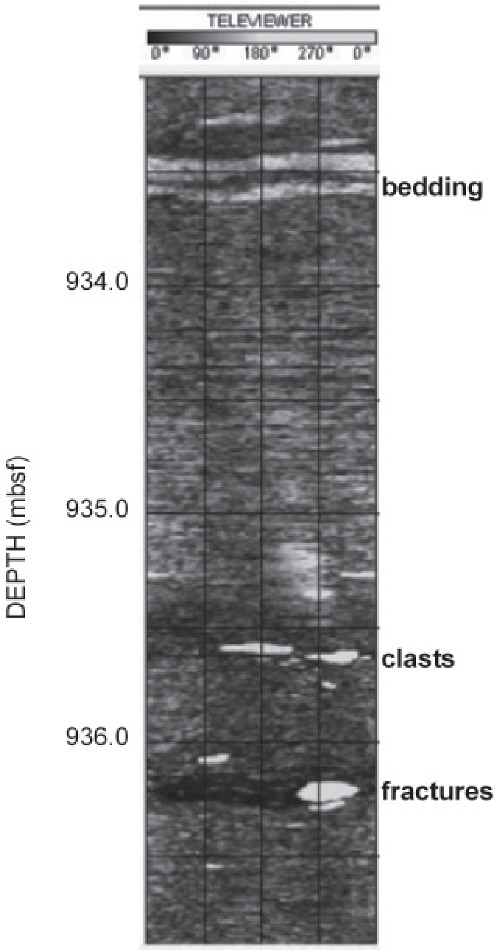


*Fig. 7* – Acoustic televiewer image of borehole wall across a 4 m interval showing low-angle fractures and bedding planes.

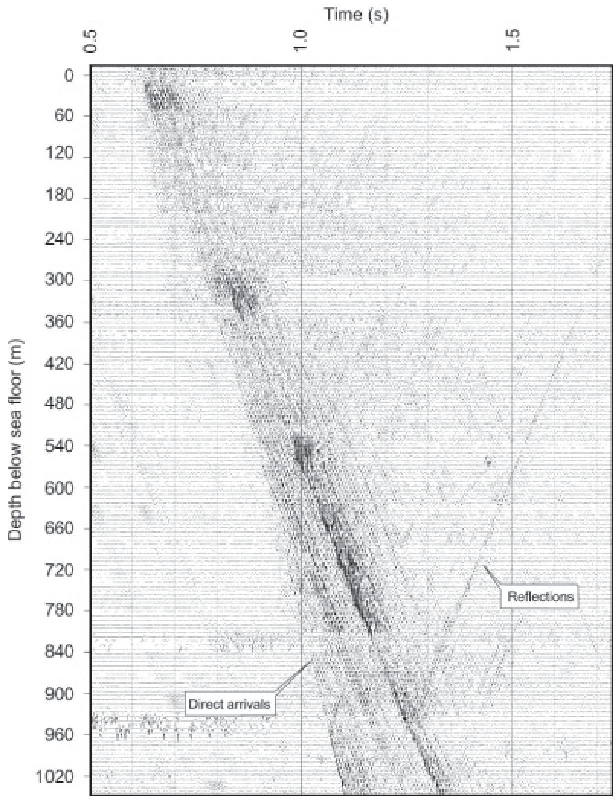


*Fig. 9* – Raw seismograms from the standard VSP experiment completed during Phase 1 of the downhole measurements program. Clear direct arrivals and reflections are observed in the raw data. The depth of the geophone receiver array has been corrected.

examined closely to match stress-induced features observed in cores with *in situ* images of the borehole wall in order to obtain new insight into the magnitude and orientation of the local stress field (*i.e.* Wilson & Paulsen 2001).

The dipmeter is equipped with four pads containing imbedded electrodes that slide against the borehole wall while logging to yield fine-scale, high-resolution records of electrical properties. The four resulting profiles may be processed and analysed to determine the strike and dip of bedding planes, which adds to our general understanding of geologic structure at this site (*i.e.* Jarrard et al. 2000). Both the televiewer and the dipmeter tools are equipped with a magnetometer and inclinometers, and orientation data may also be processed to construct the spatial trajectory of the borehole. Because the drill bit is continually being prodded up-dip by the fractures it encounters, borehole deviation is typically oriented perpendicular to the strike of fracture planes (Morin & Wilkens 2005) and provides a large-scale view of the general basin structure. A polar deviation diagram of the borehole drifting towards the west-northwest below the base of the HQ pipe is presented in figure 8. The information represented in this figure should be consistent with fracture data determined from core and from borehole images.

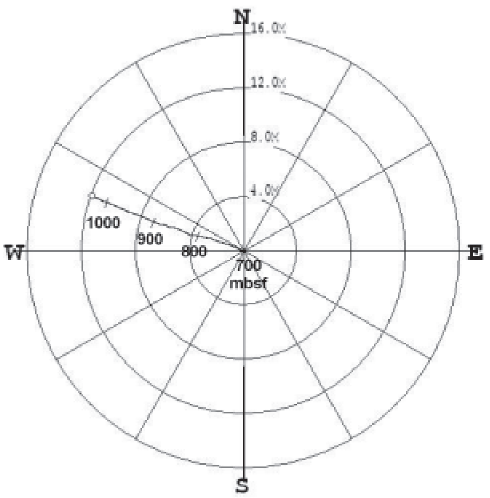


*Fig. 8* – Polar diagram of borehole deviation from base of HQ pipe at 692 mbsf to maximum length of wireline. Plot depicts a consistent trend toward the west-northwest across 324 m of the open hole section of the NQ hole with an average slant angle of 2.2°.

The seismograms generated from the standard VSP conducted during Phase 2 of downhole testing are illustrated in figure 9. These records display clear first arrivals and reflections that correspond to lithostratigraphic boundaries. Picked first or direct arrival times can be used to derive a time-depth conversion curve in order to map the seismic reflection section to depth (Fig. 10) and can be compared to whole-core velocity values (Niessen et al. this volume). The two sets of data shown in figure 10 agree markedly well, with uncertainty in identifying

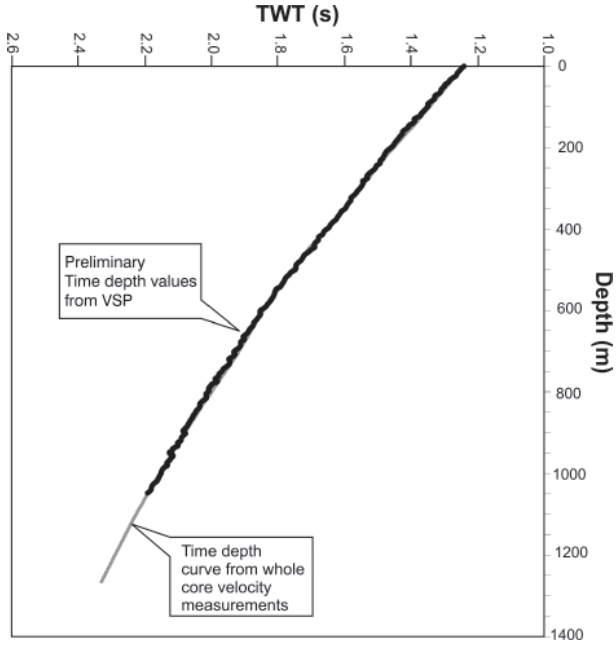


*Fig. 10* – Two-way travel time (TWT-seconds) versus depth (metres below seafloor) curves derived from whole core velocity measurements (Niessen et al. this volume) and picked first arrivals on VSP seismograms shown in figure 9.

arrivals on seismic traces giving rise to an uneven VSP time-depth curve.

## DISCUSSION

The downhole measurements obtained during this project offer numerous opportunities for scientific investigation. Several geophysical logs, such as those displayed in figures 4 and 5, respond primarily to lithologic characteristics and should be helpful in identifying both large-scale and subtle downhole variations in lithology. These high-resolution records should also correlate with measurements of physical properties to fill gaps and cross-calibrate the measurements. Because the logs are continuous and numerical (rather than descriptive), they lend themselves to spectral analysis, which may reveal depositional patterns and characteristic climatic periodicities. The successive temperature logs can be extrapolated to equilibrium conditions and the resulting geothermal gradient, when combined with estimates of rock thermal conductivity determined from core physical properties, can be used to compute the local heat flux at this site.

Magnetically oriented data obtained from the televiewer and dipmeter logs can be used to construct stereographic plots of planar features intersecting the borehole, to reorientate core and describe stress-induced features, and to help develop a structural model of the subsurface that complements our understanding of the local stress regime. This structural information may be expanded and refined with VSP results that integrate lithostratigraphic details with core and log data over a larger scale. This collection of downhole measurements should allow scientists to successfully pursue many of ANDRILL's scientific goals.

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