Comprehensive downhole and core physical-property measurements at the AND-1B Drillsite, ANDRILL McMurdo Ice Shelf Project

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Summary As part of the ANDRILL McMurdo Ice Shelf (MIS) Project two comprehensive sets of geophysical data were collected on ice at the AND-1B drillsite. Whole-core physical properties were determined with high vertical resolution to a depth of 1285 mbsf. A multi-sensor-core-logger was used to determine bulk density, sonic velocity, magnetic susceptibility and electrical resistivity. After drilling, a set of downhole measurements was collected, which consisted of caliper, temperature, fluid conductivity, induction resistivity, magnetic susceptibility, natural gamma activity, acoustic televiewer, borehole deviation, and dipmeter. In addition, three vertical seismic profiles (VSP) were obtained. Physical properties were used for initial core characterization and on-site correlation with seismic modeling. Lithology and stratigraphic units are in good agreement with changes in the pattern of the physical properties. The resulting data are amenable to studies of cyclicity and climate, cementation and compaction history, heat flux and fluid flow, and structure and stress.

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Introduction

Geophysical logs obtained in a borehole provide vertically continuous, *in situ* records of a variety of physical properties that help characterize 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, are combined with and calibrated to laboratory measurements performed on cores to examine variability with respect to depth and, consequently, over time. Other logs, such as sonic velocity and density, can be used to construct synthetic seismograms to tie data derived from surface geophysical surveys to the core. Additional insights into the transport of heat and fluid through these deposits may be gained from the analysis of temperature and resistivity profiles of the borehole fluid (Buecker et al., 2001a; Blackman et al., 1987). 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 (Zemanek et al., 1970; Wilson and Paulsen, 2001; Morin and Wilkens, 2005).

Borehole seismic methods such as vertical seismic profiling (VSP) and Walk-away VSP (e.g., Hardage, 2000), in combination with sonic velocities measured on the core, can be used to link cored 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. Thus, linking new data from the AND-1B core and borehole to seismic lines will provide further calibration of regional seismic records of the Victoria Land Basin.

Whole-core physical properties such as wet bulk density, P-wave sonic velocity and magnetic susceptibility allow initial core characterization with a very high vertical resolution and can be used to define and interpret stratigraphy (Cape Roberts Science Team, 1998; 1999; 2000; Barrett et al., 2004) thereby providing a numerical link between lithology and sequences (Buecker et al., 2001b; Claps et al., 2000; Naish et al., 2001; Niessen and Jarrard, 1998; Niessen et al., 1998; Niessen et al., 2000). Magnetic susceptibility can be indicative of increased volcanism, for example, as derived from the McMurdo volcanic province (Niessen et al., 1998). Density and, in particular, sonic velocity have the potential to exhibit post-depositional alteration such as that induced by compaction and/or cementation (Jarrard et al., 2000; Niessen et al., 2000).

Whole-Core Measurements

Using a multi-sensor-core-logger (MSCL, GEOTEK Ltd., UK), measurements at the drillsite laboratory included non-destructive, near-continuous determinations of core temperature, core diameter, sonic (P-wave) travel time, gamma-ray attenuation, electrical conduction and magnetic susceptibility (raw data). Drilling at the AND-1 site revealed both soft sediments recovered as core in liners and consolidated and/or cemented rock core, which were logged in liners and on plastic carriers, respectively. The principle of logging cores in liners on a MSCL track is outlined in Weber et al. (1997) and Best and Gunn (1999). The principle of logging cores on carriers is described in detail in the CRP-2 Initial Report (Cape Roberts Science Team, 1999).

For each of these runs calibration sections (standard cylinders) were logged to calibrate and/or monitor data quality and to process the raw data for quantification of wet bulk density, sonic velocity, non-contact resistivity and magnetic susceptibility corrected for core and sensor geometry. Data acquisition and corrections, which were applied during drilling on ice and/or during the initial science-report phase (off ice), are described in detail in Niessen et al. (Terra Antartica, in press).

Downhole Measurements

Downhole measurements in the AND-1B drillhole were conducted in two separate phases between December 26, 2006 and January 8, 2007. In the initial phase, caliper, induction, magnetic susceptibility, acoustic televiewer, and dipmeter logs were obtained across the openhole section of the NQ hole extending from the base of the HQ pipe at 692 to 1018 mbsf. The bottom 266 m of the hole could not be reached with the wire line (limitation imposed by the length of the logging cable) and no downhole measurements were obtained across this lowermost section to 1285 mbsf. The caliper tool was calibrated using NQ and PQ drill bits at the drillsite, and the log provides a measure of average borehole diameter. Three separate multifunction tool logs were obtained from seafloor to maximum wire line 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.

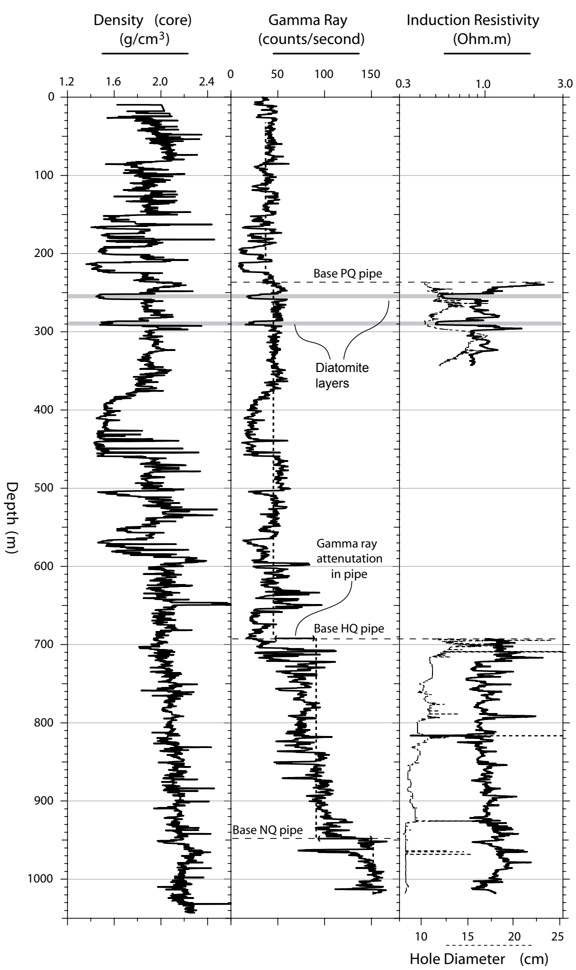

Figure 1. Overview of natural gamma radiation, induction resistivity, and caliper (borehole diameter) logs, plotted alongside density measured on core. Natural gamma and density are smoothed with a 20-cm running average. Note that the diatomite layers are well defined in the downhole logs and core physical properties. Natural gamma radiation is attenuated when measured through pipe, but still provides a valid record of formation radioactivity.

The second phase of the logging program was predicated upon the successful cutting and removal of the HQ drill pipe thereby leaving roughly 410 meters of open hole that was to extend to the base of the PQ pipe at about 237 mbsf. During the 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 became available for logging with the caliper, dipmeter, acoustic televiewer, induction, and magnetic susceptibility tools.

Two separate types of vertical seismic profiles were completed at AND-1B: (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 (75 m from the well head) while recording at each depth stage; (2) a Walk-away VSP was performed by stepping away from the well (30 m steps) with shots recorded in a fixed receiver array located approximately 265 mbsf. The procedure of VSP completed at AND-1B is described in more detail in Morin et al. (Terra Antartica, in press).

Preliminary Results and Discussion

On core AND-1B, a total of 74190 lines of physical property data were produced. These data allow a general characterization of the core material and provide a large potential for further analyses, which require a high vertical resolution. In addition to the core, a total of 5781 lines of physical property data were determined on standard calibration cylinders for monitoring core data quality. Because the core was drilled in four different diameters it is important to analyze the data of the standards for systematic offsets between the diameters as such offsets would also be present in the core data. Measurements on standards used for all core diameters vary in a certain range down-core but do not show systematic offsets at boundaries where the core diameter changed. Thus, the core data are not biased by different geometries related to core size. When compared with the total data range of

Vp and density in the core, the fluctuations observed on standards are negligibly small.

An overview of selected logs obtained in AND-1B is shown in Figure 1, where the caliper (hole diameter), induction resistivity, and natural gamma logs are presented alongside density measured on core (Morin et al.; Niessen et al., Terra Antartica, in press). All data have been adjusted to a common depth reference (meters below seafloor) for presentation and comparison, and gaps in the log data correspond to cased sections of the hole.

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. The density fluctuation is largely related to different porosity, which is controlled by grain size, compaction and cementation.

Features in the logs can be identified and correlated with lithostratigraphic features in the core. For example, logs from 237 to 343 mbsf indicate the presence of two prominent diatomite zones by 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. 1). Once the log response to lithology has been determined, more subtle lithologic variations may also be detected from the vertically continuous logs. In the logs shown in Figure 2 over a depth range of 700 to 740 mbsf, the natural gamma and resistivity logs are inversely correlated. In another Antarctic borehole (ODP Hole 1165B, offshore Prydz Bay), a similar anti-correlation was a result of silica cementation in terrigenous-poor layers (Williams and 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 sediment column may be illuminated.

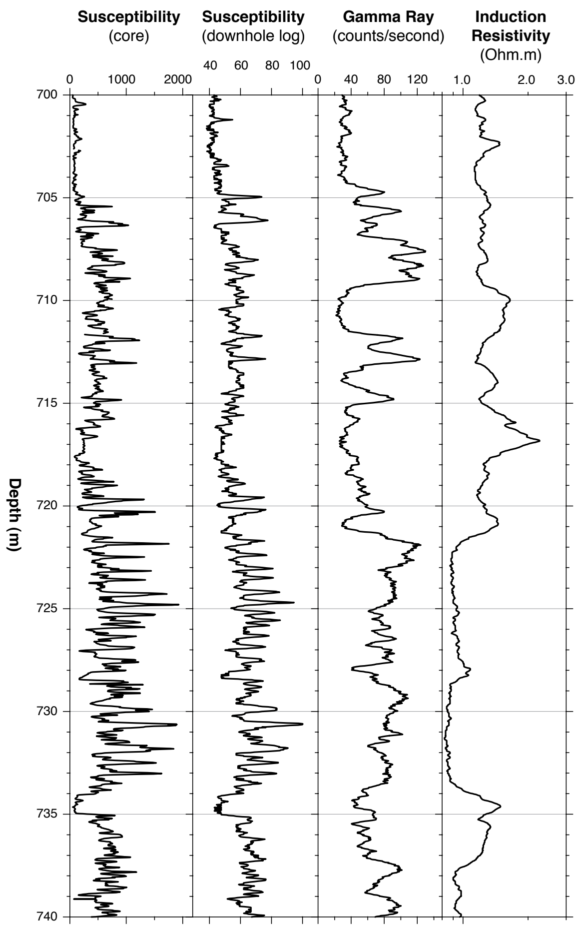

Figure 2. Data across the depth interval from 700-740 mbsf showing magnetic susceptibility, natural gamma radiation, and induction resistivity logs, alongside magnetic susceptibility determined from core. The clear similarity between log and core susceptibility helped to correct the log depths towards 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.

Across this same depth interval (700 to 740 mbsf), the logs display excellent correspondence between core and *in situ* magnetic susceptibility values (Fig. 2). In addition, for the entire depth range from 0 to 1285 mbsf, a linear regression was determined empirically by plotting the volume susceptibility measured on core plugs (sampled from the matrix of the AND-1B split core, G. Wilson et al., unpublished data) versus whole-core magnetic susceptibility measured at the same depth. The data set of 1034 points revealed a correlation coefficient of 0.984. The linear regression (Niessen et al., Terra Antartica, in press) can be used to calculate volume magnetic susceptibility on whole-core and borehole data.

Travel-time measured across the AND-1B core at a given depth interval for quantification of sonic velocity was used to calculate the vertical travel time in the core to the next deeper interval, thereby assuming isotropy of the materials on scales of a few centimeters. During the drilling phase, these travel times between depth intervals were compiled to a cumulative 2-way travel time to depth conversion in order to predict the depths of the target reflectors defined on the seismic profile.

The seismograms generated from the Standard VSP conducted during Phase 2 of downhole testing 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 and can be compared to whole-core velocity values (Niessen et al., Terra Antartica, in press). The two sets of data agree quite well, with uncertainty in identifying arrivals on seismic traces giving rise to an uneven VSP time-depth curve.

Summary

This extended abstract presents the first comprehensive data sets of geophysical measurements obtained on the ANDRILL MIS Project core and borehole (AND-1B), which are described in more detail in the AND-1B Initial Science Report (Naish et al., in press). Several geophysical logs, such as those displayed in Figures 1 and 2, 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 (Crane and Vachon, 1977), 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 orient 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.

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