Lithostratigraphy from downhole logs in Hole AND-1B, Antarctica

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ABSTRACT

The ANDRILL (Antarctic Drilling Project) McMurdo Ice Shelf (MIS) project drilled 1285 m of sediment in Hole AND-1B, representing the past 12 m.y. of glacial history. Downhole geophysical logs were acquired to a depth of 1018 mbsf (meters below seafloor), and are complementary to data acquired from the core. The natural gamma radiation (NGR) and magnetic susceptibility logs are particularly useful for understanding lithological and paleoenvironmental change at ANDRILL McMurdo Ice Shelf Hole AND-1B. NGR logs cover the entire interval from the seafloor to 1018 mbsf, and magnetic susceptibility and other logs covered the open hole intervals between 692 and 1018 mbsf and 237–342 mbsf. In the upper part of AND-1B, clear alternations between low and high NGR values distinguish between diatomite (lacking minerals containing naturally radioactive K, U, and Th) and diamictite (containing K-bearing clays, K-feldspar, mica, and heavy minerals). In the lower open hole logged section, NGR and magnetic susceptibility can also distinguish claystones (rich in K-bearing clay minerals, relatively low in magnetite) and diamictites (relatively high in magnetite). Sandstones can be distinguished by their high resistivity values in AND-1B. On the basis of these three downhole logs, diamicitic, claystones, and sandstones can be predicted correctly for 74% of the 692–1018 mbsf interval. The logs were then used to predict facies for the 6% of this interval that was unrecovered by coring. Given the understanding of the physical property characteristics of different facies, it is also possible to identify subtle changes in lithology from the properties measured on core in that downhole tools measure a larger rock mass than the core, and that rock mass is under in situ conditions and not influenced by any expansion or cracking when brought to the surface. Core recovery at AND-1B was excellent, averaging ~98%, but some intervals were less well recovered, such as the less well-consolidated material from 0 to 26 mbsf (meters below seafloor), and deeper in the hole between 692 and 1018 mbsf, where 6% of the stratigraphic section is missing from the cores. Downhole log data provide the principal information from the unrecovered intervals.

INTRODUCTION

After completion of coring in the AND-1B borehole (McMurdo Ice Shelf, western Ross Sea, Antarctica, Fig. 1), logging instruments were lowered down into the hole to take in situ measurements of the petrophysical properties of the surrounding rocks. The resulting downhole logs include natural gamma radiation (NGR), magnetic susceptibility, electrical resistivity, borehole diameter, borehole fluid temperature, and acoustic images of the borehole wall (Morin et al., 2007, 2010). Elsewhere in the Ross Sea area, similar downhole data have been used to better understand lithostratigraphy, faults and structure, and heat flow (ANDRILL [Antarctic Drilling Project] Southern McMurdo Sound Site AND-2A; Wonik et al., 2008, and Cape Roberts Sites CRP-2 and CRP-3; Bücker et al., 2000, 2001; Claps et al., 2000; Brink et al., 2000) Downhole log data are widely used in industry and in other scientific drilling programs, such as the Ocean Drilling Program (Goldberg, 1997). Here we interpret lithology from downhole logs and core measurements from ANDRILL Hole AND-1B.

At AND-1B, measurements available only from downhole logs include NGR, fluid temperature, and oriented borehole acoustic images. Magnetic susceptibility and electrical resistivity were measured both downhole and on the core (Niessen et al., 2007a), though the core resistivity data are problematic. Downhole log data differ from measurements of similar rock

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in clay minerals, micas, and potassium feldspar; thorium is found in clay minerals and heavy minerals; and uranium is found in heavy minerals and glauconite. Biogenic material such as diatom opal has no K, Th, or U, so sediments rich in diatoms have relatively low NGR. Magnetic susceptibility depends on the concentration of magnetic minerals in a sample, in particular magnetite, as it has the strongest magnetic susceptibility of the major rock-forming minerals. Magnetic minerals, eroded from rocks on the Antarctic continent, are found in the terrigenous fraction of the sediment.

METHODS

Downhole measurement operations at the AND-1B borehole took place in two phases, from 26 December 2006 to 1 January 2007, and 6–8 January 2007, as described in the ANDRILL McMurdo Ice Shelf initial reports (Morin et al., 2007; Falconer et al., 2007). In the first phase, the innermost of the nested drill pipes, NQ pipe (NQ = 70 mm outer diameter, standard diamond core drilling size; Q indicates Boart Longyear’s Q wireline core retrieval system; Table 1) was removed to leave the lower part of the hole, below 692 mbsf, open for logging. Before the second phase, only part of the HQ pipe (89 mm) could be removed from the hole, leaving the 237–343 mbsf interval for open hole logging (Fig. 2). The PQ pipe (114 mm) remained in the hole between the seafloor and 237 mbsf. However, three full passes of downhole measurements of NGR and temperature cover the entire interval to 1018 mbsf, because the attenuation of the natural gamma signal by the pipe can be corrected for (see following). The open hole intervals are covered by magnetic susceptibility, induction resistivity, caliper, dipmeter, borehole televiewer, and vertical seismic profile (Morin et al., 2007).

NGR was measured every 2 cm using a Century Geophysical Corporation Multifunction tool, model 8144, with a manufacturer’s stated accuracy of ±5%. The magnetic susceptibility tool, Century Geophysical Corporation model 9620, measured magnetic susceptibility every 2 cm in the range 0–90000 cgs with an accuracy of ±5%. Electrical resistivity was measured with a Century Geophysical Corporation Induction tool, model 9512, every 2 cm, with a conductivity range of ~0.3–200 ohm-m.

The original logging depth values were first adjusted to change the reference depth for the downhole logs from the rig floor to the seafloor (940 m below rig floor), and then linearly stretched to correct a depth miscalibration in the original logged depths (corrected depth = 1.016 × original depth), to bring the downhole data to within 1 m of the data measured on the cores (see Morin et al., 2007). To bring the log data still closer into line with the core data, features in the log data were matched to the equivalent features in the core measurement. The core depth scale is used here for the common standard because all the other core data are referenced to it, although we note that in some instances (like intervals of incomplete core recovery), the downhole log depth scale may be superior. Features in the magnetic susceptibility records were matched from log to core, and features in the NGR data were matched to those in the potassium XRF-CS data (Rh tube, 10 kV, average step size 6 cm; for details, see Pompilio et al., 2007). Generally, there was an abundance of distinctive features in the core and log data that allowed for robust depth matching, but there was more uncertainty where features were indistinct.

Magnetic susceptibility was linearly corrected for drift of the measurement over time. The core magnetic susceptibility data were linearly resampled at 2 cm spacing (close to the average spacing) and smoothed with a 20 cm window. The depth-matched NGR logs were smoothed with a 20 cm boxcar window (on the order of the measurement resolution; the detector crystal in the tool is 10.2 cm long), and were then corrected for the attenuation of the gamma ray signal through the drill pipes (Fig. 2; Table 1) (Morin et al., 2007). The attenuation for each pipe was determined as follows: for NQ pipe (the narrowest of the four nested pipes), the same intervals were logged for NGR (with the multifunction tool) both through the NQ pipe and after the NQ pipe had been pulled out of the hole. The ratio of the averaged NGR values gives the attenuation: 77% of the NGR is transmitted through the NQ pipe. Similarly, the interval 237–343 mbsf was logged both before and after removal of the HQ pipe, showing that 71% of NGR is transmitted. The PQ pipe and the sea riser pipe were present throughout logging, so the attenuation is estimated from the thickness of the pipe wall, calibrated to the attenuation through NQ pipe. PQ pipe lets 69.5% of the NGR through, and the sea riser lets 63% through. Three of the NGR logs were stacked to give a composite NGR log for 0–1018 mbsf with better signal-to-noise ratio.
than the individual NGR logs (because more gamma ray counts accumulate when the total measurement time is longer).

The NGR signal is composed of contributions from K, U, and Th, and each of these elements is contained in different components of the sediment. Although some downhole NGR tools are equipped to measure the energy spectra of the NGR, from which the individual K, U, and Th components can be derived, very few of these tools fit in a 70-mm-diameter borehole, and those that do necessarily have small detectors that need long NGR count times to resolve the elemental components. Therefore, we use potassium data from the XRF-CS (Pompilio et al., 2007; Monien et al., 2010) to supplement the downhole NGR data. In this paper, we use the potassium XRF counts, corrected for air (in any gap between the detector and the core surface), but not water, because the measurements to which it is compared (NGR and magnetic susceptibility) are also bulk measurements.

A synthetic log of the contributions of U and Th was derived by subtracting the K data from the NGR signal.
the NGR log. To do this, the K units (XRF counts per second, cps) were empirically calibrated to equivalent NGR units (cps) by linearly adjusting the K values so that maximum K value did not exceed (in general) the equivalent NGR value, because K would never contribute more than 100% to the NGR (Figs. 3 and 4). The resulting empirical formula for the U + Th contributions to NGR is $U + Th = NGR - (K/60)$. In most sedimentary formations, Th has a similar response to K because both are typically controlled by the clay content, so in typical log analysis, Th is grouped with K. However, because there was no spectral gamma radiation measurement, it is not possible here to separate the U from the Th signal. The contrasting pattern between the K and U + Th data demonstrates that Th in clays does not dominate the AND-1B U + Th signal.

**DESCRIPTION OF THE DOWNHOLE LOGS**

NGR varies downhole between 20 and 200 cps (Fig. 2). The NGR log maintains quite uniform values over tens of meters, punctuated by drops to lower values, and less frequent jumps to higher values. Several 10-m-scale drops to low NGR values occur in the 100–600 mbsf interval (e.g., 212–224 mbsf). There is no smooth compaction trend (NGR values increasing with depth) over the full 0–1018 mbsf interval. In the 760–1018 mbsf interval, there is an ~25% increase in NGR values that is only partially explained by compaction, because the dry bulk density increases by only ~6% over the same interval (Niessen et al., 2007b), indicating that lithology is the main control on the NGR values. The highest NGR values are found in the top 16.5 m of the hole.

The patterns and amplitudes in the magnetic susceptibility log agree well with susceptibility measurements made on the core in the lower open hole interval, 692–1018 mbsf (after corrections for drift and baseline of the log data) (Fig. 2). The values are approximately log-normally distributed, so the logarithm of the susceptibility data is presented in the cross-plot figures (e.g., Fig. 3). Isolated spikes to higher values are probably due to the influence of highly magnetized igneous clasts. Magnetic susceptibility generally correlates with clast content (Figs. 4 and 5). Logged magnetic susceptibility did not give valid results for the upper section (238–343 mbsf); values in diatomite were higher than those in diamictite, contrary to the core magnetic susceptibility and to the expected magnetic mineralogy in diatomite, and are not plotted. In the lower open hole interval, patterns in core and log magnetic susceptibility match well (Fig. 2), so we suspect tool error in this upper run. The core magnetic susceptibility follows the same broad pattern as NGR and bulk density, i.e., high values (high magnetite input) in the diamicrites, and lower values in the diatomite.

The resistivity logs show a slight increase in average values from the upper open hole section (238–343 mbsf) down to the lower open hole section (692–1018 mbsf) (Fig. 2), probably reflecting increased compaction and lithification with burial. Additional controls on resistivity include differential porosity between facies, clay content, and fluid salinity. The log has 1-m-scale to 10-m-scale low-amplitude variation, interrupted by jumps to higher values (maximum of 2 ohm-m) in the lower logged section.

**Downhole Log Interpretation, 83–588 mbsf**

In the upper part of the AND-1B borehole, the 83–590 mbsf interval is dominated by diatomite-diamictite alternations (AND-1B lithological facies were described in Krissek et al., 2007; McKay et al., 2009; this facies grouping is contrasted to the diatomite-open-water facies, because the depositional environment of the subice diamicite facies is unlikely to have been favorable for magnetotactic bacteria. Wet bulk density is lower in diatomite because the diatoms hold intragranular porosity and are made of opal (density 2.1–2.2 g/cm$^3$) rather than other major rock-forming minerals (typical density ~2.6–2.7 g/cm$^3$) (Niessen et al., 2007a).

The petrophysical characteristics of the different lithological facies can be seen quantitatively in cross-plots (Fig. 3). Facies with similar properties plot close together, while other facies with differing properties plot in different fields. Thus, petrophysical facies may be assigned according to which field in the cross-plots each data point (representing a 10 cm stratigraphic interval) plots. In most instances, the petrophysical facies at a certain depth corresponds to the lithological facies (since one is derived from the other), but some fraction does not. Contrasts between the two types of facies suggest subtleties, patterns, and refinements to the initial lithological facies assignments, as discussed in the following (Figs. 4 and 5).

The diatomite lithological facies are divided into facies 1a, with <10% terrigenous content, and facies 1b, with 10%–50% terrigenous content (Krissek et al., 2007). Geophysical properties can also be used to gauge the terrigenous content of the diatomites, and to distinguish between addition of clay minerals and addition of heavy minerals and magnetite. For example, within the Early Pliocene upper long diatomite interval (377–439 mbsf, ca. 3.6–3.4 Ma; Naish et al., 2009), on-ice lithostratigraphy identified a relatively terrigenous-rich (facies 1b) interval between 411 and 431 mbsf (Fig. 5). This interval corresponds to slightly higher values in the U + Th log, but not noticeably higher values in the K or magnetic susceptibility logs, indicating the probable presence of terrigenous heavy minerals, but not much contribution of clay minerals. This is in contrast to the overlying interval, 382–402 mbsf, that has quite high K values, but low values in the derived U + Th log, indicating that clay minerals form the terrigenous component in this interval (identified as facies 1a from lithostratigraphy).

As a second example, each of the three diatomite intervals in Figure 4 starts with more terrigenous material at their base (facies 1a), overlain by cleaner diatomite (facies 1b). This is

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**TABLE 1. NATURAL GAMMA RADIATION ATTENUATION THROUGH THE DRILL PIPES**

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Outer diameter (mm)</th>
<th>Pipe wall thickness (mm)</th>
<th>NGR transmitted (%), calculated empirically</th>
<th>NGR transmitted (%), calculated by wall thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea riser</td>
<td>152.4</td>
<td>7.72</td>
<td>–</td>
<td>62.9</td>
</tr>
<tr>
<td>PQ</td>
<td>114.3</td>
<td>6.35</td>
<td>–</td>
<td>69.5</td>
</tr>
<tr>
<td>HQ</td>
<td>88.9</td>
<td>5.55</td>
<td>71.2</td>
<td>73.3</td>
</tr>
<tr>
<td>NQ</td>
<td>69.9</td>
<td>4.8</td>
<td>77.0</td>
<td>77.0</td>
</tr>
</tbody>
</table>

Note: NGR—natural gamma radiation; PQ, HQ, NQ—standard core drilling sizes; – indicates not enough data to calculate.
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Figure 3. Cross-plots. (A) Potassium (X-ray fluorescence core scan) versus natural gamma radiation (NGR, counts per second, cps) (downhole log). (B) NGR (downhole log) versus magnetic susceptibility (susc.; core) for 83–588 m below sea-floor. The data from each 10 cm depth interval are color coded according to lithofacies (Krissek et al., 2007). The average (circles) and standard deviation (bars) are plotted for each lithofacies. The figure illustrates that diatomites, and to a certain extent clay-rich facies, may be distinguished using petrophysical properties. Here, petrophysical facies 1b is diatomite above the dotted line [NGR > (–33.5 × susc.) + 90].
Figure 4. Geophysical logs and core data from 200 to 350 m below seafloor (mbsf), covering the upper open hole logged interval of AND-1B, compared to lithology (Krissek et al., 2007); GSE—glacial surface of erosion. Natural gamma radiation (NGR, counts per second, cps) and resistivity are downhole logs; K (X-ray fluorescence, XRF), bulk density, and clast content are core data; and U + Th is a combination of both downhole log and core data. Ice-distal diatomite lithofacies 1a (yellow) and 1b (dark yellow), and mudstone lithofacies 2 (gray) are compared to the equivalent petrophysical facies, derived from the NGR, potassium, and magnetic susceptibility (susc.) data (Fig. 3). Petrophysical facies 2 (claystone rich) is taken to be high K, low susceptibility (K > 1.8 x susc.) in non-diatomite intervals. The petrophysical facies provide details of the transitions from ice-covered to ice-free conditions at AND-1B: each of the three diatomite intervals in this plot is underlain by clay-rich petrophysical facies, and the basal part of the diatomites have significant terrigenous component, grading up into cleaner diatomite. Clast data are described in Pompilio et al. (2007), and density data by Niessen et al. (2007).
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Figure 5. Geophysical logs and core data from 350 to 500 meters below seafloor (mbsf), covering the long diatomite interval (376–459 mbsf), compared to lithology (Krissek et al., 2007). Natural gamma radiation (NGR, counts per second, cps) is downhole log data; K (X-ray fluorescence, XRF), bulk density, and clast content are core data; and U + Th is a combination of both downhole log and core data. Ice-distal diatomite lithofacies 1a (yellow) and 1b (dark yellow), and mudstone lithofacies 2 (gray) are compared to the equivalent petrophysical facies, derived from the NGR, potassium, and magnetic susceptibility data (Figs. 3 and 4). The terrigenous-rich part (411–431 mbsf) of the long diatomite interval is less terrigenous rich, according to the petrophysical facies. Short-term changes in diatomite terrigenous content are recorded in the NGR and magnetic susceptibility data.
recognized in the lithostratigraphy, but appears to be more extensive in this petrophysically based interpretation.

Another instance where the petrophysical properties can help refine the lithostratigraphy is in the clay mineral content of the diamictite facies. Mudstone facies are characterized by relatively high K and low susceptibility, but a significant part of the diamictite lithofacies also plots within this clay-rich field (Fig. 3A). We interpret these diamictites to be relatively low in clasts (indicated by the low susceptibility values) and higher in clay minerals (indicated by the higher K contents). K is observed to correlate with aluminum in conventional XRF analyses (Monien et al., 2010), supporting the inference that the K is a good indicator of clay mineral content. Clay-rich diamictites tend to appear just below the diatomite facies, suggesting gradation and transition to reduced ice conditions prior to diatomite deposition, for example 236–225 mbsf (Fig. 4) and 467–463 mbsf (Fig. 5).

There is only one gap in the core recovery in the 83–588 mbsf section, a 2 m interval from 293.5 to 295.5 mbsf, just below a diatomite interval. The NGR and resistivity logs indicate that this short interval is not diatomite, but do not provide enough data to distinguish between diamictite and siltstones.

NGR, Condensed Interval, 439–440 mbsf

The 1 m interval of coarse mixed sediments at 439–440 mbsf represents a hiatus, condensed sedimentation, or mild erosion that did not remove the soft underlying diatomites, and lasted from ca. 4.3 to ca. 3.6 Ma (Naish et al., 2009; Wilson et al., 2007). In some sedimentary environments uranium accumulates during hiatuses, for example, at hardgrounds in carbonate slope deposits (Williams and Pirmez, 1999), and therefore a thin layer of elevated uranium levels can sometimes mark the presence of a hiatus. At AND-1B, this interval has a NGR peak but no potassium peak (Fig. 5), meaning that the NGR peak is composed mostly of contributions from U and Th. Although the U + Th values (~80 cps in NGR equivalent units) are in the high range for AND-1B, there are other intervals, in diamictite and volcaniclastic sediments, also having such high values, with no indication of hiatus. This interval is composed mostly of volcanic material, which has high U and Th values (facies 11, Fig. 3). Thus the NGR log is not able to assist in distinguishing whether this interval is a hiatus or is an erosive boundary. Its origin is interesting, because nonerosion of the soft underlying diatomites would suggest that thick ice sheets did not cover the site during this long interval; this would fit with the prediction of open-marine conditions during this part of the Early Pliocene at the AND-1B Site from ice sheet modeling (Pollard and DeConto, 2009).

**Downhole Log Interpretation, 760–1018 mbsf**

The lower of the two open hole logged sections differs from the upper logged interval in that there are no diatomites, which dominated the geochemical and geophysical signal in the upper part of the hole. The interval 760–1018 mbsf is composed of mudstone, diamictite, silts, and sandstone, and is part of the motif 3 lithofacies association (Krissek et al., 2007; McKay et al., 2009). There is clear lithological control on the geophysical properties in this interval, particularly the contrast between the mudstones (highlighted in gray in Fig. 2) and the diamictites.

Mudstones (facies 2) and mudstones with dispersed or common (<5%) clasts (facies 4) are ice-distal facies. They are characterized by relatively low susceptibility values (typically below ~100 × 10^-5 SI units) (Figs. 6 and 7). Magnetic

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![Image of the geophysical properties in the interval 760–1018 mbsf.](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/8/1/127/3341329/127.pdf)
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Figure 7. Cross-plots. (A) X-ray fluorescence (XRF) potassium versus magnetic susceptibility (uncalibrated) (downhole log). (B) Electrical resistivity (downhole log) versus magnetic susceptibility (susc.; core), for 692–1018 m below seafloor in AND-1B. The data from each 10 cm depth interval are color coded according to lithofacies (Krissek et al., 2007). The mean (circles) and standard deviation (bars) are plotted for each lithofacies. Empirically derived dashed lines divide fields containing mostly clay-rich facies, diamictites, and sand-rich facies (see text), and are used to define petrophysical facies (v1 in Fig. 8): claystone where K > 3.6 × susc.; diamictite where K < 3.6 × susc. and K > 1.8 × susc.; and sandstones where K < 1.8 × susc.
susceptibility correlates quite well with the clast count (Fig. 8), and is high in the diamictite and sandy facies, indicating that magnetic minerals in the coarse terrigenous fraction control the magnetic susceptibility log.

The mudstone facies have high K contents compared to the diamictite and sandy facies (Figs. 7 and 8) because they contain more K-bearing clay minerals, such as illite and smectite (Giorgetti et al., 2009). The NGR log also has high values in the mudstone facies, as expected, since the NGR includes contributions from K, U, and Th. But, unlike K, the NGR values remain high in the diamictite facies (Fig. 8). Therefore, the diamictites contain almost enough U and Th to compensate for their lesser clay content. U and Th are probably contained in (small amounts of) heavy minerals in the terrigenous fraction.

Sandstone (facies 6) and conglomerate (facies 7) produce the highest susceptibility values seen in the logs (e.g., 962.5–964.5 mbsf), though not all sandstones have high susceptibility. These facies often have low K values (which also lowers the overall NGR values), indicating that they have low levels of clay minerals and are generally not arkosic. The U + Th content appears to remain similar to levels in diamictite. Notably, occurrences of sandstone and conglomerate are nearly always marked by jumps to higher values in the resistivity log (Figs. 7 and 8). We speculate that greater levels of cementation in this facies would block pore throats and therefore the current path in the pore fluid, increasing electrical resistance (otherwise, clean sands would be expected to have a lower resistivity, because of sorting). In addition, low clay mineral concentrations in the sandy facies contribute to the higher resistivity, because the surface conduction provided by the clay minerals is reduced. Since the sandstone facies are generally also characterized by higher density and acoustic velocity (Niesen et al., 2007a), these sand beds probably contribute to the reflections observed in the seismic sections in the McMurdo Sound area (Naish et al., 2007).

Interstratified mudstone and sandstone (facies 3), as a mixed facies, has susceptibility, K, and NGR values intermediate between sandstone and mudstone. The values are in the same range as those for diamictite, and unfortunately it is therefore not possible to distinguish proglacial facies 3 from the subglacial diamictite facies using these three petrophysical data sets alone.

The observations and inferences here constitute an understanding of the expected log response from a particular lithology; this sets the stage for the converse, i.e., predicting a lithology from a particular set of log responses. Changes in the geophysical log values may indicate subtle variation in lithologies that are not always straightforward to describe from initial visual inspection of the core. For example, the low potassium and high magnetic susceptibility between 869.5 and 872 mbsf suggests the lithology to be a clean siltstone or sandstone, rather than a mostly mudstone facies (Fig. 8); the high potassium values at 943–944 mbsf indicate high clay levels in the diamictite; and the steady decrease of clay content from 1003 mbsf to 970 mbsf indicates a gradual lithological transition from proglacial to subglacial lithologies.

**Intervals Unrecovered by Coring**

Although core recovery in the ANDRILL AND-1B borehole was excellent, in the interval 760–1020 mbsf, ~6% (15 m) of the stratigraphy was unrecovered, and downhole logs (and drilling data) provide the only information to fill these gaps (highlighted by arrows in Fig. 8).

A variety of methods can be used to infer lithologies from petrophysical data, and here we apply two of the simpler methods, introduced above, and described in more detail in the following. The first is to assign petrophysical facies to fields in the cross-plots that characterize individual lithological facies (Figs. 6 and 7). The second method is inversion of the petrophysical data, based on the assumption that all the lithologies are mixtures of end-member lithologies (e.g., Doveton, 1994; Robinson and Williams, 2008). Further ways to extract lithological meaning from the petrophysical logs are factor analysis and cluster analysis (e.g., Monien et al., 2010). These methods have the advantage of being less empirical than the two methods presented in this paper, and of combining a greater number of petrophysical and geochemical data sets. The methods employed here have the advantage of being based on the observed relationships between lithological facies and the petrophysical data.

For the first method, we plotted the different lithofacies on cross-plots of NGR, K, magnetic susceptibility, and resistivity (Figs. 6 and 7). Because different lithofacies have typical log responses, groups of similar lithofacies tend to plot together in the same fields. Here, three facies groups are distinguished: clay-rich rocks (lithofacies 2 and 4); diamictite and mixed sediment (lithofacies 3, 9, and 10); and coarse, sorted rocks, like sandstones and conglomerates (lithofacies 6 and 7). Dotted lines were placed approximately midway between the average value for each lithofacies group to divide the cross-plot into fields (Figs. 6 and 7). The predicted petrophysical facies group is then assigned depending on which field the log values plot. This process is a manual version of multiple discriminant analysis. First, all depth intervals with detrended resistivity values >1.3 ohm·m were assigned to the sandstone petrophysical facies (Fig. 7B), because resistivity distinguishes sandstone more readily than the other logs. Then the remaining samples were assigned petrophysical facies according to the fields in Figure 7A (version 1 of the analysis, based on K and magnetic susceptibility) and Figure 6 (version 2 of the analysis, using NGR and magnetic susceptibility). The version 2 analysis, based only on downhole log data, enables petrophysical facies to be predicted for the unrecovered intervals. In version 1, which relies on XRF-CS K data, the facies group is correctly predicted for 77% of the section, and in version 2, the facies group is correctly predicted for 74% of the section (Figs. 6, 7, and 8). In particular, the diamictites and mudstones below 950 mbsf are satisfactorily identified, and most (but not all) of the sandstone beds are identified correctly.

The second method employed here is petrophysical inversion (e.g., Doveton, 1994; Robinson and Williams, 2008). This method involves specifying a compositional model with a limited number of components, in this case clay-rich mudstones, diamictite, and sandstone and/or conglomerate, all of which have known log responses (Fig. 6). End-member log values for each of the three components were chosen and inverted to proportions of the three lithological components. The three equations to be solved assume a linear relationship between the value recorded by the log and the relative contributions to that value by the lithological component. This operation was done in Microsoft Excel, using the “ = MINVERSE(ARRAY)” command; see Table 2. Where the proportions were calculated to be <0% or >100%, they were truncated. Note that using lithology types as component end members leads to some conflicting results (e.g., diamictite contains clay), and it rarely results in a single predicted lithology for any one depth interval. However, it provides a guide to the missing lithology, information that is otherwise absent.

The end-member values were iteratively adjusted (manually) to improve the match to the known lithostratigraphy. The end-member values given in Table 2 and Figure 6 produce a reasonable match, but are not the only solution; rather, they are a representative example. The results are presented in Figure 8, in the petrophysical inversion column. In general, the results match the lithology well, particularly in the 840–1018 mbsf interval. Downhole changes
Lithostratigraphy from downhole logs in Hole AND-1B, Antarctica

Figure 8. Geophysical logs and core data from 750 to 1020 meters below seafloor (mbsf) depth in AND-1B, covering the lower open hole logged interval, with petrophysical facies prediction compared to lithological facies. Petrophysical facies are derived from (v1) potassium (XRF—X-ray fluorescence), magnetic susceptibility (suscept.; log), and resistivity (log) (Figs. 7A, 7B) and (v2) natural gamma radiation (NGR, counts per second, cps), magnetic susceptibility (uncalibrated), and resistivity (all downhole logs, Figs. 6 and 7B). GSE—glacial surface of erosion. Facies are color coded according to the keys in Figures 6 and 7. Petrophysical inversion (see text) reduces the data to a mix of three end members (corresponding to the three petrophysical facies) and offers information on, for example, the varying clay content of diamictites.
within facies are apparent in this analysis, for example the clay content of the diamictites, and the trend to decreasing clay content from 978 to 1003 mbsf. A summary of the interpreted lithology in the main gaps in core recovery is given in Table 3.

Potential problematic issues with these analyses include mixed facies and subtle nonlithological trends in the petrophysical data. For example, the diamictite with a minor volcanic component at the top of the interval (759–774 mbsf) is identified as claystone in the petrophysical facies, because the magnetic susceptibility values are relatively low for diamictite, but the difference from typical diamictite values may be due to the admixture of volcanic material in this interval. Because of possible differential compaction and cementation among the facies, a correction could not be reliably applied to the unrecovered intervals, and the original wet bulk NGR and susceptibility data were used here.

**Downhole Log Interpretation, 588–759 mbsf (Volcaniclastic Interval)**

In the volcaniclastic unit (588–759 mbsf; Krissek et al., 2007), the logged geophysical data can be used to give information on lithological trends and features that are difficult to quantify from visual inspection of the core. For example, in the 705–740 mbsf interval (Fig. 9), magnetic susceptibility has a series of high-amplitude decimeter- to meter-scale peaks that appear to be associated with coarse-fine lithological alternations in some intervals (e.g., 723–728 mbsf). These alternations may be related to individual turbidites redepositing volcanic material, triggered by episodic volcanic activity (Pompilio et al., 2007). However, this relation does not appear to hold for the underlying interval, 728–734 mbsf, where high-susceptibility beds are not reflected in the lithostratigraphy. Magnetic susceptibility does not follow the iron content (from XRF-CS data), indicating that magnetite is not the principal iron-bearing mineral in this interval, perhaps related to the diagenetic growth of pyrite (Di Roberto et al., 2010). There is no great change in the source of these volcanic-rich claystones and sandstones, suggesting that the original magnetic mineralogy might be somewhat homogeneous, and that dissolution of the magnetic minerals has played a role in shaping the susceptibility profile. The NGR log follows the potassium content of the volcanic unit, suggesting that the U and Th contribution is minor or at a steady level here (Fig. 9). This is curious, given that in the motif I sequence (83–588 mbsf), volcanic facies have high U + Th (Fig. 3). Higher NGR and K values mark layers where K-rich volcanic components (e.g., lapilli tuffs) dominate over the siliciclastic component (Di Roberto et al., 2010). In addition, potassium is preferentially mobilized during alteration, thus drops to lower K and NGR values probably mark intervals that are more altered than the intervening material. The lowest magnetic susceptibility values (734–735, 728–728.3, and 716–718 mbsf) correspond to low-K beds, indicating that the magnetite has also been altered in these beds. In summary, while not straightforward to interpret, the gamma ray, potassium, and susceptibility logs reveal details of the volcanic stratigraphy that are not readily apparent from the initial visual core analysis.

**CONCLUSIONS**

Downhole petrophysical logs provide lithostratigraphic information from the AND-1B borehole. NGR logs cover 0–1018 mbsf, while magnetic susceptibility and electrical resistivity logs cover the Late Miocene open hole interval, 692–1018 mbsf. Together with data measured on the core (potassium and magnetic susceptibility), we establish the petrophysical characteristics of each of the 10 facies introduced by Krissek et al. (2007) and McKay et al. (2009). For example, low NGR values characterize diatomite facies, low magnetic susceptibility and high potassium characterize clay facies, and high resistivity characterizes sandstones. Then, given these petrophysical characteristics, the lithostratigraphy can be refined, and variability within facies can be found. Diatomite facies have distinct variations in clay and terrigenous contents that sometimes show differences from the subdivision of the diatomite facies described from lithological analysis of the core. For example, the lowermost parts of most of the Pliocene diatomite intervals have a transitional zone with more terrigenous material. In the diamictite facies, higher clay content often precedes lithological transition to diatomites. In the volcaniclastic interval (588–759 mbsf), altered beds can be readily identified by reductions in potassium and magnetic susceptibility. The NGR data covering the ca. 4.3–3.6 Ma hiatus at 440 mbsf are consistent with the previous interpretation of nonerosive open-marine conditions during this part of the Early Pliocene. Although core recovery was very high, 6% of the lower open hole interval (692–1018 mbsf) was unrecovered. We use the downhole data to infer petrophysical facies for the gaps, and complete the stratigraphy in this Late Miocene interval. In this way, downhole logs provide important support for the visual stratigraphic logs and contribute to the overall understanding of the paleoenvironment at the AND-1B drill site.

**TABLE 2. LOG VALUES USED IN THE THREE-LITHOLOGY PETROPHYSICAL INVERSION MODEL**

<table>
<thead>
<tr>
<th>Log measurement</th>
<th>Petrophysical facies</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic susceptibility (uncalibrated units, log scale)</td>
<td>diamictite</td>
<td>claystone</td>
</tr>
<tr>
<td>Natural gamma radiation (counts/s)</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Electrical resistivity* (Ohm-m)</td>
<td>135</td>
<td>140</td>
</tr>
</tbody>
</table>

*After long-wavelength trend shown in Figure 8 was removed.

**TABLE 3. LITHOLOGICAL FACIES IN UNRECOVERED INTERVALS**

<table>
<thead>
<tr>
<th>Interval (meters below seafloor, mbsf)</th>
<th>Length (m)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>782.37–780.79</td>
<td>1.58</td>
<td>Diamictite in the lower part of the interval is overlain by mudstone with clasts at 781.5 mbsf.</td>
</tr>
<tr>
<td>789.80–786.41</td>
<td>3.39</td>
<td>Mostly diamictite, with a mudstone interval from 786.6 to 787.3 mbsf.</td>
</tr>
<tr>
<td>819.18–816.91</td>
<td>2.27</td>
<td>There is a 1-m-thick washed out fracture or fault at the top of this interval, dipping 60° to the north (Morin et al., 2010). Lithologically, high natural gamma radiation and low magnetic susceptibility indicate that claystone composes most of this interval. Sandstone is probably present from 808.8 to 808.5 mbsf.</td>
</tr>
<tr>
<td>879.19–877.00</td>
<td>2.19</td>
<td>Moderately high magnetic susceptibility indicates this interval is probably diamictite. Diamictite in the lower part of the interval is overlain by sandstone from 895.2 mbsf.</td>
</tr>
<tr>
<td>897.94–894.76</td>
<td>3.18</td>
<td></td>
</tr>
</tbody>
</table>

*Note: Interpreted from petrophysical facies based on downhole logs, and from the neighboring lithological facies (see Fig. 8).
Figure 9. Example from the lower part of the volcaniclastic interval, 705–740 m below seafloor. More stratigraphic detail is apparent in the downhole logs (natural gamma radiation, NGR, magnetic susceptibility, suscept.; uncal. is uncalibrated), core magnetic susceptibility, and X-ray fluorescence (XRF, counts per second, cps) core scanning data (e.g., K, Fe, Ti) than in the visually described lithology (see text), owing to the dark, fine-grained nature of the rocks. Chemical alteration such as redistribution of potassium and pyritization likely plays a main role in controlling the geophysical and geochemical stratigraphy.
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