Lithostratigraphy determined from downhole logs in the AND-2A borehole, southern Victoria Land Basin, McMurdo Sound, Antarctica

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ABSTRACT

During the 2007–2008 austral spring season, the ANDRILL (Antarctic Drilling project) Southern McMurdo Sound Project recovered an 1138-m-long core, representing the last 20 m.y. of glacial history. An extensive downhole logging program was successfully carried out. Due to drill hole conditions, logs were collected in several passes from the total depth at 1138.54 m below seafloor (mbsf) to 230 mbsf. After data correction, several statistical methods, such as factor analysis, cluster analysis, box-and-whisker diagrams, and cross-plots, were applied. The aim of these analyses was to use detailed interpretation of the downhole logs to obtain a description of the lithologies and their specific physical properties that is independent of the core descriptions.

The sediments were grouped into the three main facies, diamictite, mudstone and/or siltstone, and sandstone, and the physical properties of each were determined. Notable findings include the high natural radioactivity values in sandstone and the high and low magnetic susceptibility values in mudstone and/or siltstone and in sandstone. A modified lithology cluster column was produced on the basis of the downhole logs and statistical analyses. It was possible to use the uranium content in the downhole logs to determine hiatuses and thus more accurately place the estimated hiatuses. Using analyses from current literature (geochemistry, clasts, and clay minerals) in combination with the downhole logs (cluster analysis), the depths 225 mbsf, 650 mbsf, 775 mbsf, and 900 mbsf were identified as boundaries of change in sediment composition, provenance, and/or environmental conditions. The main use of log interpretation is the exact definition of lithological boundaries and the modification of the paleoenvironmental interpretation.

INTRODUCTION

ANDRILL (Antarctic Drilling project) is a multinational program with the objective of recovering stratigraphic intervals for use in interpreting Antarctica’s climatic, glacial, and tectonic history over the past 50 m.y. The key motivation stems from a lack of knowledge of the complex role the Antarctic cryosphere (ice sheets, ice shelves, and sea ice) plays in the global climate system. Understanding the history of ice-volume variation and associated physical changes in the Antarctic region is critical for assessing the interaction of ice sheets with other elements of the Earth system, such as ocean, atmosphere, lithosphere, and biosphere. Accurate assessment of the scale and rapidity of changes affecting large ice masses is of vital importance because ice-volume variations lead to changing global sea levels, affect Earth’s albedo, and influence the latitudinal gradient of the Southern Hemisphere; these factors in turn affect heat transport via atmospheric and oceanic circulation. They also influence the distribution of ice shelves and seasonal sea ice, which is considered to have a key role in the formation of cold bottom waters that drive global ocean circulation (Naish et al., 2007).

During the ANDRILL Southern McMurdo Sound Project, an 1138-m-deep borehole (AND-2A) was drilled in austral spring 2007–2008. The AND-2A drilling platform was located on 8.5-m-thick sea ice above a 380-m-thick water column in an ice-proximal position in the southern part of McMurdo Sound, ~30 km west of McMurdo Station (77°45.5’S; 165°16.6’E).

The Southern McMurdo Sound is bounded by the Transantarctic Mountains to the west and by the Ross Ice Shelf and several islands to the south (Fig. 1). Numerous glaciers (Koettlitz, Blue, Ferrar, and Mackay) discharge into the McMurdo Sound or feed the Ross Ice Shelf. The Southern McMurdo Sound is surrounded by terrains preserving a variety of lithologies. Neogene alkalic volcanic rocks, mainly basanites of the McMurdo Volcanic Group, characterize the geology to the south and east of the AND-2A drill site. In contrast, the Transantarctic Mountains to the west consist of a crystalline basement of late Precambrian to early Paleozoic granites (Granite Harbour Intrusive Complex) and mainly amphibolite-grade metamorphic rocks (Skelton Group, Koettlitz Group) that crop out over wide areas (Haskell et al., 1965; Warren, 1969; Laird and Bradshaw, 1982; Tingey, 1991). In the western part of the Transantarctic Mountains, sedimentary rocks, mainly sandstones, quartzites, and siltstones of the Devonian to Triassic Beacon Supergroup, overlie the basement rocks. Sills and dikes of the Jurassic Ferrar Dolerite intruded both basement and sedimentary strata. Neogene volcanic cinder cones are scattered between Koettlitz and Ferrar Glaciers. Quaternary sediments overlie the bedrock in areas near the coast as well as at Brown Peninsula and in the Dry Valleys.

After completion of the coring of a section of the AND-2A borehole, logging instruments were lowered down into the hole to take in situ measurements of the petrophysical properties of the surrounding rocks. Elsewhere in the Ross Sea area, downhole data have been used to better understand lithostratigraphy, faults, structure, and heat flow (AND-1B borehole, McMurdo Ice Shelf: e.g., Williams et al., 2012; Morin et al., 2010; Cape Roberts Sites CRP-2 and CRP-3: e.g., Bücker et al., 2000, 2001; Claps et al., 2000; Brink et al., 2000; ANDRILL Southern McMurdo Sound Site AND-2A: Wonik et al., 2008–2009; Schröder et al., 2011).

The main purpose of this paper is to provide important new constraints on lithostratigraphy (Pliocene–Pleistocene sediment composition...
and paleoenvironment) that have general bearing for understanding the climatic evolution of the Victoria Land Basin within the West Antarctic Rift. This new information derived from the interpretation of downhole logging data will help to achieve the objectives of the ANDRILL project listed here.

Other studies based on further downhole logging data (ultrasonic borehole imager, geochemical logging, and vertical seismic profile, VSP) are ongoing; those results are not presented here (e.g., hydraulic fracturing stress measurements were carried out in the lowermost part of the AND-2A borehole to obtain information about the stress field; Schmitt et al., 2012). The ultrasonic borehole imager logs before and after the fracturing operations allow us to locate the induced hydraulic fractures.

METHODS

Downhole Logging

Downhole logging allows continuous, high-resolution data to be collected within the borehole. The downhole data differ from measurements of similar rock properties made on core samples in that downhole logs are based on a larger rock mass than the core, and that rock mass is under in situ conditions and not influenced by expansion or cracking that occurs when cores are brought to the surface (e.g., Williams et al., 2012). However, the drilling process also affects the quality of the borehole logs. Downhole measurements can be divided into radiative methods (density, neutron porosity, spectral gamma ray including natural radioactivity, and content of several elements such as potassium, thorium, and uranium), acoustic methods (sonic velocity), magnetic methods (magnetic susceptibility), electrical methods (resistivity), and other methods (borehole diameter). (For detailed descriptions of the methods applied, see Rider and Kennedy, 2011; Ellis and Singer, 2007; Fricke and Schön, 1999; and Serra, 1984.)

Downhole measurements were conducted in five phases between drilling operations in November and December 2007 (described in detail in Wonik et al., 2008–2009). During all phases, a conductor pipe was held in place from 0 to 230 m below seafloor (mbsf). To prevent the borehole walls from caving in, the drill string was kept in place down to a certain depth in all phases but the fifth. In the first phase, the string was lifted to 410 mbsf. Downhole measurements were executed from 640 mbsf to 400 mbsf in an open borehole. At 640 mbsf a bridge was hit and consequently no measuring was conducted down to the bottom of the hole. After removing the bridge, the string was drawn up to 640 mbsf, leaving the 640–1012 mbsf interval for openhole logging. In the third phase, the total depth of 1138 mbsf was reached. In phases three and four, the drill string was left downhole to 1000 mbsf. During the fifth phase, the drill string was pulled out completely and downhole measurements were executed only within the conductor pipe between seafloor and 230 mbsf.

The following wireline logs were successfully recorded at the AND-2A borehole: natural radioactivity (gamma ray, GR) comprising the contents of potassium (K), thorium (Th), and uranium (U), density (DENS), neutron porosity (NPOR), p-wave velocity (vp), magnetic susceptibility (SUSC), borehole diameter (caliper, CALI), and dipmeter; these abbreviations are used herein to refer to the borehole logging parameters. Summarizing, continuous downhole measurements were executed for DENS (0–998 mbsf) and GR (0–983 mbsf) in a mostly open borehole (Fig. 2). The unit for GR logging is the API (American Petroleum Institute) unit, defined in a reference well in the grounds of the University of Houston, Texas (Rider and Kennedy, 2011). The logs did not include certain intervals that were either inaccessible due to bridging or shielded by the drill string (Wonik et al., 2008–2009). NPOR data are nearly complete except for the interval from 225 mbsf to 400 mbsf. All data of the upper 230 mbsf were recorded through casing, and thus are corrected. NPOR measures only relative porosity values, so porosity units (p.u.) are used. The vp and SUSC were logged between 400 mbsf and 1051 mbsf. Furthermore, CALI was measured between 610 mbsf and 1134 mbsf only. A resistivity tool and its backup both failed to operate, so resistivity data were not collected (Wonik et al., 2008–2009).

Data Quality and Correction

Borehole quality is determined by the vertical and horizontal deviation of the borehole, and the condition of the borehole wall. The deviation of AND-2A was derived using the logging and processing software GeoBase (Antares). The borehole has an inclination of ~2.0°–2.5°.
hiatuses

Figure 2. Geophysical measurements in borehole AND-2A for the depth range 0–1000 m below seafloor (mbsf). Parameters: natural radioactivity (gamma ray, GR), potassium (K), thorium (Th), uranium (U), neutron porosity (NPOR) in porosity units (p.u.), density (DENS), p-wave velocity (vp), magnetic susceptibility (SUSC), the element ratios Th/U (Th/U) and Th/K (Th/K), and the borehole diameter (caliper, CALI). At the right side of U the depths of the inferred hiatuses are marked in red.
to the southeast. Log quality and reliability are judged to be excellent for almost all tools over the entire length of the hole. We base this conclusion on (1) a smooth borehole diameter log without intervals of great washouts, (2) internal consistency for several tools (e.g., three different types of borehole diameter measurement), (3) repeatability as observed on some repeated runs in short intervals, and (4) the great similarity with core logging data (DENS, vp, and SUSC) (Dunbar et al., 2008–2009; Wonik et al., 2008–2009).

During logging, the lower edge of the drilling platform was defined as the reference point for depth measurements. For the sake of comparability, the core depth is used as reference system for all further purposes. The tidal heave of the drilling platform, which amounts several meters, was corrected. The overall depth accuracy of the downhole logs is very good. Comparisons with the core logs showed only a few discrepancies between the downhole log depths and core log depths. The necessary adjustment of log depths to match the values in these areas was carried out using the software Geobase on the basis of prominent features such as minimum and maximum values in the downhole logs. The core depths are used as the standard below since all geological and mineralogical data refer to them.

The borehole diameter (CALI) is considerably widened in the section 770–810 mbsf and, consequently, data from this section may be subject to inaccuracies.

Multivariate Statistics

The various physical properties are not necessarily independent of each other. For example, DENS and NPOR are closely linked. To reduce the influence of these dependencies and obtain a set of parameters with no linear interdependencies, a factor analysis was carried out prior to cluster analysis. (For further details regarding factor analysis and multivariate statistics, cf. Brown, 1998; Davis, 2002; Backhaus et al., 2010.) The parameters thus obtained are termed factors and are associated with the original physical properties by factor loadings. It is assumed that a factor loading $>0.5$ means that the factor is significant for the property concerned. The factors determined can explain most of the variance in the data, thus reducing the size of the data set without losing information.

Factor Analysis

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Box-and-Whisker Diagram

Box-and-whisker diagrams are used to illustrate the distribution of a set of statistical data. They are calculated to illustrate the differences in the physical properties of the lithologies at different depths.

Physical Properties of Cluster Lithologies

The mean values of each lithology are calculated from the logging data and the different lithologies are also plotted in cross-plots. This is done to quantify the lithologies and often provides evidence of empirical relationships, because similar facies plot close together (Rider and Kennedy, 2011).

Data Availability

For the logging data of drill hole AND-2A, see Wonik et al. (2009).

RESULTS

The downhole logs are described and interpreted here to obtain new findings to supplement those from sediment stratigraphy of the drill cores (Fielding et al., 2008); these concern hiatuses, clay minerals, physical properties of the sediments, and borehole washouts.

Description of Downhole Logs

The main downhole logs, GR, DENS, and SUSC, are described for the logging range 0–1000 mbsf. This description seeks to characterize the borehole data (Fig. 2), including the minimum and maximum values. GR varies between 25 API and 140 API. The highest GR values are found in the depth sections 775–810 mbsf and 920–970 mbsf; the lowest are observed in the 400–550 mbsf section. Some U anomalies can be found, e.g., at 270 mbsf, 285 mbsf, 330 mbsf, 370 mbsf, 505 mbsf, 610 mbsf, and 620 mbsf. In the interval 400–600 mbsf some fining-upward and coarsening-upward sequences are reflected by an increase or decrease in the GR signal (Wonik et al., 2008–2009). Naturally radioactive elements tend to have a far greater concentration in shales than in other sedimentary lithologies (e.g., see Ellis and Singer, 2007; Rider and Kennedy, 2011).

The DENS values vary between 2.0 g/cm$^3$ and 3.0 g/cm$^3$. The lowest values are in the depth sections 280–315 mbsf, 535–550 mbsf, and 600–650 mbsf; the highest are in the sections 195–230 mbsf and 910–925 mbsf. These high DENS values (to 3.0 g/cm$^3$) occur in thin layers or clasts and might be an indicator for a significant proportion of mafic minerals at these depths. NPOR varies considerably over a range of 0–40 p.u. As would be expected, it exhibits a negative correlation with the DENS curve. Compaction of the sediments essentially increases with depth. Some sections deviating from the normal compaction trend were found at the depths 235–265 mbsf and 580–605 mbsf. The lithologies in these bedding sequences consist of diamictite with some sandstone in the upper sequence, and diamictite and sandstone with some mudstone and/or siltstone in the lower sequence.
Hiatuses

Hiatuses can be determined from U content, which is associated with secondary components. Typically, U exhibits irregular, high peaks corresponding to its uneven distribution. These peaks are linked with condensed sequences or unconformities where a long time is represented by little deposition (Rider and Kennedy, 2011). However, uranium may become enriched due to factors such as organic material, suboxic deposition, and volcanic clasts, thus distorting the interpretation. To verify the observations, it is necessary to determine the sediment ages in absolute values. Based on these findings, peaks of high U content (>4 ppm) were identified (Fig. 2) and compared with the age model described by Acton et al. (2008–2009) and modified by the ANDRILL SMS Science Team (2010). The following five examples show that a link exists between U content and the hiatuses in sediment deposition, thus allowing an accurate determination of the depths of these hiatuses.

1. The hiatus at 38 mbsf (Acton et al., 2008–2009) is confirmed by a considerable increase in U content, though at a depth of 35 mbsf. The reason for this difference in depth is probably an uncorrected depth shift between the core and downhole logs.

2. Acton et al. (2008–2009) pointed out that one or more of these breaks in the record are located between 50 mbsf and 122.86 mbsf, but could not delineate precise locations for the hiatuses within this interval. Based on increased U content values, these hiatuses can be placed at 66 mbsf and 79 mbsf.

3. An additional hiatus is located at 224.82 mbsf; this break could be accommodated on multiple erosional and/or nondepositional surfaces that occur between 145 mbsf and 224.82 mbsf, but at present this is an interval without age constraints (Acton et al., 2008–2009). The peak in U content occurs at 185 mbsf.

4. According to Acton et al. (2008–2009), one or more hiatuses occur within lithostratigraphic unit 5 (224.82–296.34 mbsf) or at 296.34 mbsf. Two peaks in U content place these hiatuses at 272 mbsf and 284 mbsf.

5. Acton et al. (2008–2009) described how below 296.34 mbsf, sedimentation was relatively continuous; even so, short hiatuses (less than a few thousand years) undoubtedly occur, but are beyond the resolution of chronostratigraphic age constraints. Confirming this assumption, sections of low thickness with high U contents are located at 368 mbsf, 503 mbsf, 611 mbsf, and 621 mbsf.

Factor Logs

The three principal factors were selected, which together account for 78% of the variance. The third factor, having an eigenvalue of 0.98, would not, in accordance with the Kaiser criterion, normally be extracted (Backhaus et al., 2010). However, because the eigenvalue is very close to 1 and the factor thus contains a sufficiently high proportion of the variance, it is appropriate to use it for the further calculations.

GR forms the factor 1 log together with the contents of Th and K (Table 1). According to Rider and Kennedy (2011), GR is mainly related to lithology and grain size. All factor loadings are positive and >0.8; thus, the underlying physical or chemical properties show a positive correlation. The illite content from the core logs (Franke and Ehrmann, 2010) is plotted alongside the factor 1 log, showing a good correlation between illite and factor 1 in the clay-rich section (790–900 mbsf) (Fig. 3).

As expected, the factor loadings of factor 2 for DENS and NPOR are opposite in sign. Thus, this factor mainly responds to the compaction or cementation of sediments. Confirming this, over long sections factor 2 shows a good correlation with Ca counts from the XRF core scanner logs (Hoffmann et al., 2012) and thus correlates with the carbonate cementation of the sediments. This indicates that the core is carbonate cemented over more than half of its length, independent of lithology.

The K/U ratio correlates well with the factor 3 log, particularly in the areas of low clay content (400–780 mbsf and 950–1000 mbsf). The K/U ratio often indicates the type of clay minerals present (Rider and Kennedy, 2011). This ratio reflects the K-rich McMurdo volcanics and K-feldspar-rich sections in the borehole. Factor 3 reflects the sediment provenance by changing ratios of the radiogenic elements. In the clay-rich sequence (790–900 mbsf), the K/U values are observed to increase with depth (such as at 880–900 mbsf) in several instances. These increases indicate transitions from smectite to illite (Macfarlane et al., 1988).

Characterization of the Main Facies with Cluster Analysis

Cluster analysis was carried out only for the depth range 400–1000 mbsf, because a sufficiently extensive data set of borehole parameters is available only below 400 mbsf. If the cluster analysis is carried out for the entire depth range and the cluster lithology column is compared with the core lithology column of Fielding et al. (2008), very little correlation is found between the two columns over the entire depth. It is therefore necessary to perform a more specific cluster analysis on a small scale. In order to assign the different facies as exactly as possible, 6 depth intervals were established within the 400–1000 mbsf range, each 100 m in length. Cluster analysis was carried out for each interval and a cluster lithology column was created (Fig. 4). Thus, the same clusters are found within each 100 m cluster interval.

Determination of the Main Facies

According to Fielding et al. (2008), 13 lithofacies are identified on the basis of grain size distribution, bedding relationships, sedimentary structures, fossil content, and other characteristics: (1) calcareous mudstone, (2) fine sandstone and mudstone with clasts, (3) fine sandstone and mudstone, (4) sandstone, (5) muddy sandstone or sandy mudstone with clasts, (6) fine sandstone and siltstone with diamicite, (7) stratified diamicite, (8) massive diamicite, (9) conglomerate and sandstone, (10) lava, (11) volcanic breccia, (12) lapilli tuff, and (13) volcanic breccia and sandstone. Further environmental interpretation was given by Fielding et al. (2011) and Passchier et al. (2011). The proportion of volcanic sediments and diatomites in the sequences is very low (<5%) and is ignored in the following log interpretation. Franke and Ehrmann (2010) pointed out that the sedimentary succession comprises mainly diamicitics, sandstones, and mudstones. The 13 lithofacies are grouped here into the 3 main facies, diamicite, sandstone, and mudstone.
and mudstone and/or siltstone, because only end-member lithologies can be determined and delimited from the downhole logs. Confirming this, Naish et al. (2007) described that, unlike core AND-1B, which is characterized by two dominant lithologies (diamictite and diatomite) with strongly contrasting physical properties, the AND-2A core is dominated (~75%) by a single lithology, diamictite.

Physical Properties of the Main Facies

The quality of the separation of the three main facies is illustrated in the cross-plot GR against SUSC (Fig. 5). The GR values are comparatively high in mudstone and/or siltstone, medium in diamictite, and low in sandstone. However, the absolute values, with an average of 89 API for sandstone, are very high (Table 2); this may be caused by clay mineral content in the matrix. The SUSC values are low in diamictite, whereas both low and high values were measured in sandstone and mudstone and/or siltstone. The physical properties of the three main facies were calculated for cluster analysis from the six depth ranges (Table 2) and combined for the overall interval (400–1000 mbsf). A differentiation of mudstone and siltstone is not possible, because siltstone has only slightly lower GR values than mudstone.

DISCUSSION

Interpretation of Downhole Logs

The statistical method of cluster analysis was applied to the geophysical measurements in the AND-2A borehole and a cluster lithology column was created (Fig. 6). The cluster analysis for the overall depth range yielded no detailed results and was thus replaced by a cluster analysis in six 100 m intervals. Throughout the depth range, the physical properties of the lithologies vary due to cementation (Fig. 3). The characteristic physical properties of the three main facies (diamictite, mudstone and/or siltstone, and sandstone) were determined. Volcanic sediments cannot be determined from the cluster analysis due to the low bedding thickness. Diamictite is characterized by medium GR and DENS values, and low values for SUSC. Mudstone and siltstone have generally high GR and low DENS values. Their SUSC values are both low and high. In contrast, the sandstones tend to have low GR and high DENS values, while their SUSC values are, as in mudstone and/or siltstone, both low and high. Because a very high core recovery of 98% was achieved, it was possible to carry out an extensive comparison of the core lithology column with the cluster lithology column.
Figure 4. Construction of the cluster lithology column using the example of the 700–800 mbsf (meters below seafloor) depth range. The cluster analysis was carried out on the basis of the downhole logs natural radioactivity (gamma ray, GR; API—American Petroleum Institute units), neutron porosity (NPOR), density (DENS), thorium/potassium ratio (Th/K), and magnetic susceptibility (SUSC). The cross-plot GR against DENS is an example to show how the clusters relate to the original measurements. A lithology is assigned to each of the five clusters from comparison with cross-plots and the core lithology (Fielding et al., 2008). The result is the cluster lithology column.
Comparison of Core and Cluster Lithologies

The mean depth shift between the calculated cluster lithology and the core lithology determined by Fielding et al. (2008) amounts to as much as 4 m, in which the cluster lithology is deeper than the core lithology. Overall, both lithology columns are very similar in the lithologies identified, as a comparison of the (percentage) proportions of the main facies shows (Table 3; Fig. 6).

On a detailed level, two cases of different determination of lithologies are observed. (1) In a sediment package the sediment composition is quite similar, but their distribution of depth and quantity differs; e.g., the core lithology in the depth section 600–650 m is mainly composed of sandstones with interlayers of mudstone and/or siltstone, and minor amounts of volcanic sediments. In contrast, the cluster lithology comprises interlayers of sandstone, mudstone and/or siltstone, and diamictites. (2) Sediment layers of the core lithology were recognized as a different lithology in the clusters, e.g., sandstone and/or conglomerate (716–719 m) or mudstone (707–709.5 m) of the core description were determined as diamictite in the clusters.

Cementation of Lithology

The physical properties in the three main facies exhibit sometimes considerable changes with increasing depth (Fig. 6). In diamictite, GR shows no trend of change with increasing depth, while DENS increases with depth. This may be explained by compaction and the different grain matrix distribution. In mudstone and/or siltstone, the GR values decrease slightly with increasing depth. This is probably due to the lower proportion of mudstone or a different clay mineral composition. The DENS values are low and increase a little in just the lowest two sequences as a result of compaction. Sandstone is characterized by heavy variation in GR values with no depth trend. The high GR values may be explained by the occurrence of clay minerals or of other radioactive minerals in the sandstone. The DENS values increase continuously with depth. An exception is the lowest sequence, which has lower DENS; this may be explained by a lower degree of cementation.

Fielding et al. (2008) described how an initial analysis of diagenesis in the core revealed that the principal diagenetic phenomena are carbonate cementation, authigenic pyrite formation, and alteration of volcanic glass (devitrification, hydration, and zeolitization). This diagenetic overprint affects all lithologies and the entire depth range. Consequently, there is a good match between Ca-rich lithologies determined from factor 2 and calcium content (Fig. 3) on the one hand, and enhanced DENS values (Fig. 6) on the other. This applies for the following lithological sediment packages: diamictites D3, D4, and D6 and sandstones S4 and S5. However, not all lithologies at all depths are influenced to the same degree. Instead, cemented zones occur over various lithologies. Sections that deviate from the normal compaction trend may be derived from the DENS values and are characterized by different lithology compositions. Local processes, such as cementation, thus appear to have a bearing on these DENS changes.

Sandstone has varying proportions both of clay and of carbonate cement (characterized by low GR and enhanced DENS; Fig. 6). The negative correlation between GR and DENS shows the higher the clay content, the lower the DENS, and therefore the degree of cementation is less in these sections.

Interpretation of Susceptibility

The varying SUSC levels in the three main facies are discussed in the following. According to Coflet (2005), all magnetic properties are significant. These may include magnetic grain size distribution, the concentration of magnetic minerals, and different types of magnetization. SUSC in sedimentary rocks exhibits an increase when moving from clay-free to clayey rock types (Henkel and Guzman, 1977). However, Thompson and Oldfield (1986) asserted that the SUSC values of sand and clay are very similar and depend heavily on the depositional

![Figure 5. Cross-plot of natural radioactivity (GR—gamma ray; API—American Petroleum Institute units) against magnetic susceptibility (SUSC) plotted separately for the three main facies (mudstone, diamictite, and sandstone) with averages and standard deviations. Six sections with homogeneous cluster lithologies were used for the lithologies.](image-url)
Figure 6. Cluster lithology and core lithology (Fielding et al., 2008) columns with the main borehole logging parameters of natural radioactivity (GR—gamma ray; API—American Petroleum Institute units), density (DENS), and magnetic susceptibility (SUSC). The ages determined by Acton et al. (2008–2009) and the ANDRILL SMS Science Team (2010) and the determined hiatuses (marked by red rectangle) are given. Six sequences with lithological homogeneous composition were identified for each of the three main facies: diamictite sequences D1–D6, mudstone and/or siltstone facies M1–M6, and sandstone facies S1–S6. Box-and-whisker diagrams showing the parameters GR, DENS, and SUSC were calculated for each sequence and each lithology. They indicate the data range and the distribution of values. The rectangle marks the range enclosing 50% of the data (25th and 75th percentiles). The median of the distribution is indicated by a horizontal line in the box. The two lines extending from the box represent the 5th and 95th percentiles of the values, the whiskers.
conditions. The SUSC content of the parent rock may change considerably as a result of weathering processes and the associated conversion of materials (Henkel and Guzman, 1977). Pure diagenesis in terms of sediment consolidation has little or no effect on SUSC values (C. Rolf, 2012, personal commun.), but have changes in redox conditions such as pyritization (destruction of magnetite).

In borehole AND-2A, the SUSC values may be subdivided into a group of low values and a group of high values. Diamictite exhibits low SUSC values. Mudstone and/or siltstone and sandstone show low and high values. No trend of SUSC values associated with increasing depth can be observed in any lithology. However, the characteristics described here, the interpretation of SUSC is difficult, because no unambiguous link can be found between SUSC values and provenance or mineral weathering.

Isolated susceptibility spikes with higher values are probably due to the influence of highly magnetized clasts; according to Dunbar et al. (2008–2009), SUSC correlates with clast content: very low values are observed in some diamictites and large clasts. A comparison between the number of clasts from Fielding et al. (2008) and the SUSC values shows that a high number of clasts (in diamictite and sandstone) are observed where SUSC is high. However, where SUSC is low, both high numbers (in diamictite) and low numbers of clasts (in sandstone and mudstone) are present. There are intervals of magnetite dissolution in many Antarctic marine sediments (e.g., Florindo et al., 2003), but dissolution would not affect magnetite embedded in clasts. A possible explanation for intervals with high SUSC is that these indicate a relatively high supply of volcanic sediment to the core (Dunbar et al., 2008–2009). Overall the susceptibility character of the AND-2A facies differs from the character at AND-1B, where mudstone has a significantly lower susceptibility than diamictite. A reason for this cannot be given; nevertheless, both in areas of high SUSC and at SUSC peaks the proportion of volcanic ash is only high in half of all cases.

### Determination of Provenance

In the literature, borehole AND-2A has been divided into sections with the aim of identifying provenances. According to the clay mineral investigations by Franke and Ehrmann (2010), the main provenances of the sediments in borehole AND-2A are the Transantarctic Mountains, Beacon Supergroup, and McMurdo Volcanic Group. In addition, the glaciers of southern Victoria Land (Mulock-Skelton, Carlyn-Darwin, Koettlitz, and Blue Glaciers) are regarded as the most likely sources for the gravel-fraction basement clasts, as concluded from the investigations by Sandroni and Talarico (2011). Petrological and geochronological data of volcanic clasts (Panier et al., 2008–2009; Di Vincenzo et al., 2010) indicate that their main sources are the volcanic centers of the Erebus Volcanic Province and the area around Mount Morning (Talarico and Sandroni, 2011). The cluster analysis (400–1000 mbsf) shows a subdivision of the borehole into four sections in terms of their lithological compositions (boundaries at 650 mbsf, 775 mbsf, and 900 mbsf). Indirect information from the quantity ratios of Th/K yields no further findings. Franke and Ehrmann (2010) divided the borehole into three sections based on smectite contents (boundaries at 225 mbsf and 440 mbsf). Hoffmann et al. (2012) also divided the borehole into three sections; however, their boundaries, based on geochemistry, are at 225 mbsf and 665 mbsf. The division according to clasts by Talarico and Sandroni (2011) was only applied to the lower depth range (700–1000 mbsf) and shows two boundaries (at 778 mbsf and 905 mbsf). Further boundaries were determined by Passchier et al. (2011) at 645 mbsf, 795 mbsf, 900 mbsf, and 935 mbsf, on the basis of sediment composition and sedimentary facies distribution. In summary, boundaries can be established at 650 mbsf, 775 mbsf, and 900 mbsf, and they imply changes of the depositional environment and the ice sheet.

### CONCLUSIONS

To determine the depths of hiatuses using the uranium content was a good approach; other disciplines could only give greater intervals for the depths of hiatuses. Based on downhole logging data, hiatuses can be determined at 35 mbsf, 66 mbsf, 79 mbsf, 185 mbsf, 272 mbsf, 284 mbsf, 368 mbsf, 503 mbsf, 611 mbsf, and 621 mbsf.

The high content of information available from downhole logging data can be also seen after interpreting the results of a factor analysis. For the interval 400–1000 mbsf, 3 principal factors were selected: factor 1 (loaded by GR, Th, and K) correlates with illite in the clay-rich sections; factor 2 (DENS and NPOR) responds to compaction or cementation of sediments; and factor 3 (SUSC and U) reflects the sediment provenance by changing ratios of radiogenic elements.

A further advantage of log analysis is the ability to construct an independent lithological profile based only on physical properties. A cluster analysis determined the lithology for the interval 400–1000 mbsf; the 3 main facies are diamictite, sandstone, and mudstone and/or siltstone, and their physical properties exhibit significant changes with increasing depth. It is remarkable that cemented zones occur over various lithologies. The correlation between cluster and core lithologies is good, but on a detailed level some modifications of sediment composition must be made: one is the lithological distribution of depth and quantity and another concerns sediment layers, which differ in the lithological determination between cores and cluster analysis.

The values of SUSC are subdivided into one group with low values (diamictite) and another group with both high and low values (mudstone and/or siltstone and sandstone). Within all lithologies, no trend of SUSC values associated with increasing depth is observed.

The main provenances of the sediments were determined by cluster analysis and their lithological compositions; the boundaries of sediment provenances were determined at 225 mbsf, 650 mbsf, 775 mbsf, and 900 mbsf.

Some remarkable results could be achieved from the downhole logging data of AND-2A borehole, although the boundary conditions for interpretation were far from ideal: (1) there is no great variability in the lithology of the AND-2A core; (2) the cementation occurred over various lithologies and changes significantly the physical parameters of each lithology. All results presented herein show the benefit of downhole logging for the overall understanding of the ANDRILL geological setting.

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### Table 3. Quantitative Distribution of the Three Main Facies in the Cluster and Core Lithologies

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Cluster lithology</th>
<th>Core lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thickness (m)</td>
<td>Content (%)</td>
</tr>
<tr>
<td>diamicrite</td>
<td>259</td>
<td>44</td>
</tr>
<tr>
<td>mudstone and/or siltstone</td>
<td>173</td>
<td>30</td>
</tr>
<tr>
<td>sandstone</td>
<td>151</td>
<td>26</td>
</tr>
</tbody>
</table>

*Note: Facies after Fielding et al. (2008).*
Lithostratigraphy from downhole logs in the AND-2A borehole, Antarctica

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