Preliminary Integrated Chronostratigraphy of the AND-2A Core, ANDRILL Southern McMurdo Sound Project, Antarctica

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Abstract - We use all available chronostratigraphic constraints – biostratigraphy, magnetostratigraphy, radiocarbon dates, strontium-isotope stratigraphy, and correlation of compositional and physical properties to well-dated global or regional records – to construct a preliminary age model for ANDRILL SMS Project’s AND-2A drillcore (77°45.488’S, 165°16.605’E, 383.57 m water depth). These diverse chronostratigraphic constraints are consistent with each other and are distributed throughout the 1138.54 m-thick section, resulting in a well-constrained age model. The sedimentary succession comprises a thick early and middle Miocene section below 224.82 mbsf and a condensed middle/late Miocene to Recent section above this. The youngest sediments are Brunhes age (<0.781 Ma), as confirmed by a radiocarbon age of 0.691±0.049 Ma at 10.23 mbsf and the occurrence of sediments that have normal magnetic polarity down to ~31.1 mbsf, which is interpreted to be the Brunhes/Matuyama reversal (0.781 Ma). The upper section is punctuated by disconformities resulting from both discontinuous deposition and periods of extensive erosion typical of sedimentary environments at the margin of a dynamic ice sheet. Additional breaks in the section may be due to the influence of tectonic processes. The age model incorporates several major hiatuses but their precise depths are still somewhat uncertain, as there are a large number of erosional surfaces identified within the stratigraphic section. One or more hiatuses, which represent a total 7 to 8 million years of time missing from the sedimentary record, occur between ~25 mbsf and the base of Lithostratigraphic Unit (LSU) 3 at 122.86 mbsf. Similarly, between about 145 mbsf and the base of LSU 4 at 224.82 mbsf, one or more hiatuses occur on which another 2 to 3 million years of the sedimentary record is missing. Support for the presence of these hiatuses comes from a diatom assemblage that constrains the age of the core from 44 to 50 mbsf to 2.06-2.84 Ma, two radiocarbon dates (11.4 Ma) and a Sr-isotope date (11.7 Ma) that indicate the interval from 127 to 145 mbsf was deposited between 11.4 and 11.7 Ma, and three diatom occurrence datums from between 225.38 and 278.55 mbsf that constrain the age of this upper part of Lithostratigraphic Unit (LSU) 5 to 14.29 - 15.89 Ma. Below the boundary between LSU 5 and 6 sedimentation was relatively continuous and rapid and the age model is well-constrained by 9 diatom datums, seven 40Ar/39Ar dates, one Sr-isotope date, and 19 magnetozones. Even so, short hiatuses (less than a few hundred thousand years) undoubtedly occur but are beyond the resolution of current chronostratigraphic age constraints. Diatom first and last occurrence datums provide particularly good age control from the top of LSU 6 down to 771.5 mbsf (in LSU 10), where the First Occurrence (FO) of Thalassiosira praefraga (18.85 Ma) is observed. The diatom datums ages are supported by radiocarbon dates of 17.30±0.31 Ma at 640.14 mbsf (in LSU 9) and 18.15±0.35 and 17.93±0.40 Ma for samples from 709.15 and 709.18 mbsf (in LSU 10), respectively, and 18.71±0.33 Ma for a sample from 831.67 mbsf (in LSU 11). The sediments from 783.69 mbsf to the base of the hole comprise two thick normal polarity magnetozones that bound a thinner reversed polarity magnetozone (958.59 - 985.64 mbsf). This polarity sequence most likely encompasses Chrons C5En, C5Er, and C6n (18.056 - 19.772 Ma) or slightly older given uncertainties in this section of the geomagnetic polarity timescale, but could be also be Chrons C6n, C6r, and C6An.1n (18.748 - 20.213 Ma). Either polarity sequence is compatible with the 40Ar/39Ar age of 20.01±0.35 Ma obtained from single-grain analyses of alkali feldspar from a depth of 1093.02 mbsf, although the younger interpretation allows a better fit with chronostratigraphic data up-core. Given this age model, the mean sedimentation rate is about 18 cm/k.y. from the top of LSU 6 to the base of the hole.
INTRODUCTION

ANDRILL's Southern McMurdo Sound (SMS) Project cored Hole AND-2A (77°45.488'S, 165°16.605'E, ~383.57 m water depth) to a total depth of 1138.54 mbsf and recovered over a kilometer of core (Fig. 1). The goal of this chronostratigraphy report is to integrate all age information available as of September 2008 into a coherent age model for the AND-2A core. Currently, the age model incorporates data from biostratigraphy and magnetostratigraphy studies, radioisotopic dating of volcaniclastic sediments and tephras, $^{87}$Sr/$^{86}$Sr dating of micro- and macrofossils, and correlation of compositional and physical properties to well-dated global or regional records. This age model provides a basis for studying the timing and rates of geologic, climatic, and tectonic events recorded in the core, and for comparing them with other records from around the world. Because new age constraints are still being obtained as part of the 'Science Documentation' phase of the ANDRILL-SMS Project, the age model is considered to be preliminary. A revised age model will be constructed in the future that uses the data presented here and incorporates new age information from the Science Documentation phase. Important age constraints may come from any of the many disciplines involved in the ANDRILL-SMS Project and, hence, the age model is necessarily a group effort that will continue to evolve.

CHRONOSTRATIGRAPHIC DATA

Primary chronostratigraphic constraints available at present include marine diatom datums and radioisotopic dates, which together are relatively evenly distributed throughout the stratigraphic section (Tab. 1). The independently derived ages provided by these two methods agree well with each other. Magnetic polarity zones (magnetozones) complement and aid in refining the age constraints particularly in Lithostratigraphic Units (LSU) 8 through 14, which span from 436.18 mbsf to the bottom of the core.
the hole. Sr-isotopic dates further support these other age constraints. Relatively few age constraints are available in the upper 224.82 m of the section, which spans from within LSU 1 to the base of LSU 4. Within this interval, datable material is sparse and sedimentation is discontinuous, with the possibility of multiple hiatuses that are several million years in duration. Some of these hiatuses are suspected to be of regional extent and thus may correlate to hiatuses that have been dated at other drill sites, particularly if the hiatuses correspond to regional seismic reflectors.

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<th>Young Age (Ma)</th>
<th>Old Age (Ma)</th>
<th>Age Used (Ma)</th>
<th>Top Depth (mbsf)</th>
<th>Bottom Depth (mbsf)</th>
<th>Depth (mbsf)</th>
<th>Sed rate (cm/k.y.)</th>
<th>Description</th>
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<td>Diatom Assemblage (FAD)</td>
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<td>11.25</td>
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<td>Diatom Assemblage (FAD)</td>
<td>N/R</td>
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</table>

Tab. 1 - Continued.
**BIOSTRATIGRAPHY**

The biostratigraphy of the AND-2A is discussed in detail in Taviani et al. (this volume). In this section, we focus on the depths of the age diagnostic fossils and biostratigraphic events.

**DIATOMS**

Most of the diatom events utilized in this initial report are derived from the average composite range model of Cody et al. (2008). Their model is based on a constrained optimization (CONOP) method, which employs a computer-assisted multidimensional correlation technique to interpolate stratigraphic events across different sections resulting in an integrated, high-resolution, quantitative, chronostratigraphic model. Diatom event ages from the average range model are used herein as was done for the AND-1B Core (Wilson et al., 2007). These ages are determined using an approach that allows for the possibility that reworking within the analyzed sections, which is likely in glacial environments, has moved some range ends beyond their original depositional levels. The average range composite model is considered to be most appropriate for preliminary analyses of new drill cores (Cooper et al., 2001; Wilson et al., 2007; Cody et al., 2008).

The composite sequence of diatom events produced by Cody et al. (2008) is based on a robust dataset integrating comprehensive diatom biostratigraphy, magnetostratigraphy, and tephrostratigraphy from 32 Neogene sections around the Southern Ocean and Antarctic continental margin as old as 18 Ma. Early Miocene ages for the First Appearance Datum (FAD) and Last Appearance Datum (LAD) of *Thalassiosira nanseni* are from Scherer et al. (2001).

Diatom datums from the AND-2A Core (Tab. 1) provide age constraints down to 772 mbsf. Up-core reworking appears to be insignificant in the diatom-bearing intervals (Taviani et al., this volume). In the upper part of the section, a diatom assemblage that includes the Last Occurrence (LO) of *Thalassiosira elliptipora* (0.64 - 2.06 Ma), LO of *Thalassiosira vulnifica* (2.15 Ma), LO of *Thalassiosira torokina* (2.20 Ma), LO and FO of *Actinocyclus maccollumii* (2.4 - 2.84 Ma), LO of *Rouxia diploneides* (2.55 Ma) (see Taviani et al., this volume) provides an age of 2.06 - 2.84 Ma for the interval 44.06 - 48.24 mbsf. Similarly, three datums — LAD *Denticulopsis lauta* sensu latu (12.46 Ma), LO of *Denticulopsis lauta* sensu stricto (15.70 Ma) to be between 15.50 and 15.70 Ma. The LAD and FAD of *Thalassiosira praefraga* (17.38 - 18.85 Ma) at 736.20 and 771.50 mbsf, respectively, and the LAD of *T. nanseni* (>17.5 Ma) provide the deepest diatom age constraints.

**FORAMINIFERA**

The first and last appearance of *Neogloboquadrina pachyderma* occurs in a sample collected from interval 83.76 - 83.80 mbsf. This indicates that the age for this interval must be younger than 11.04 Ma (younger than Chron C5r(y); we use ‘(y)’ to refer to the young end of a chron and ‘(o)’ for the old end).

**MACROFOSSILS**

The only age diagnostic macrofossil identified was *Adamussium* sp. cf. *A. alanbeui*, which occurs between 999.76 and 999.80 mbsf in LSU 13 and between 1063.71 and 1063.73 mbsf in LSU 14 (Taviani et al., this volume). *Adamussium* sp. cf. *A. alanbeui* has been reported from upper Oligocene to lower Miocene sedimentary units from Antarctica (Taviani & Beu, 2003).

**MAGNETOSTRATIGRAPHY**

Oriented samples were collected every one to two metres along the core for palaeomagnetic analysis. The paleomagnetic results are discussed in detail in Acton et al. (this volume). A characteristic remanent magnetization (ChRM) with a steep upward direction (normal polarity) or steep downward direction (reversed polarity) was well resolved in 338 of the 695 samples analyzed. These were used to define 23 magnetozones (12 reversed polarity and 11 normal polarity) (Fig. 2; Tab. 1; and Tab. 4 of Acton et al., this volume).

Resolving the ChRM direction and defining magnetozones was difficult above 224.82 mbsf (LSUs 1 through 4) owing to the coarse-grained lithologies, much of which is diamicite, and to the discontinuous sedimentary record. In this interval, only the boundary between magnetozones N1 and R1 (= N1/R1.1), which is most likely the Brunhes/Matuyama (C1n/C1r.1r) reversal (0.781 Ma), provides an age constraint. Given the other age constraints, this reversal could also be one of several other reverse-to-normal transitions less than about 2 Ma, including any of those down to about the C2n/C2r.1r reversal (1.945 Ma). Magnetozones R1.1 (31.10 - 83.56 mbsf) may span one or several reversed polarity chronozones. At least the upper part and perhaps all of it is within the reversed polarity chronozones of the Matuyama (C1r-C2r). However, below the diatom-rich unit at 48 mbsf, the magnetozone could be correlated to any reversed polarity chronzone from about C2r.2r to C5r (2.148 - 12.014 Ma). Independent age constraints are very poor down to the base of LSU 4. Thus, magnetozone R1.2 (96.80 - 115.71 mbsf) could also be correlated to any reversed polarity chronzone from about Chron C2r.2r to C5r.
From LSUs 5 through 7, the magnetozones are again identified mainly within broader zones of uncertain polarity. These magnetozones can be correlated to the geomagnetic polarity timescale (GPTS) using the independent age constraints provided by other data, but provide only weak additional age information. Sedimentation is more continuous below the LSU 4/5 boundary and the sedimentation rates are high, which aids in interpreting the magnetozones. Given these constraints, magnetozone R1.3 (265.55 - 278.48 mbsf) probably correlates to Chron C5Br (15.160 - 15.974 Ma) but could also be C5ADr (14.581 - 14.784 Ma) or C5Bn.1r (14.877 - 15.032 Ma). Magnetozones N2.1 (328.52 - 352.15 mbsf) and N2.2 (388.50 - 413.26 mbsf) probably correlate to the younger and older parts of Chron C5Cn.1n (15.974 - 16.268 Ma), respectively.

Below the LSU 7/8 contact (436.18 mbsf), the quality of paleomagnetic results improves considerably and provides a continuous polarity stratigraphy for this interval (Acton et al., this volume). The sequence of magnetozones from R2.1 through R3.3 (413.26 - 581.34 mbsf) correlates with Chrons C5Cr.1r through C5Cr (16.268 - 17.235 Ma). Below this, magnetozones N4 through N8 (643.02 mbsf to the base of the hole) can be correlated with either Chrons C5Dn through C6n (our preferred interpretation), or with Chrons C5Dn through C6An.1n (an alternate interpretation). If our preferred interpretation is correct, the ages for the magnetozone boundaries are slightly younger than...
indicated by the radioisotopic dates. Alternatively, if the magnetozones are Chrons C5Dn-C6An.1n, the ages for the magnetozone boundaries are slightly older than indicated by the radioisotopic dates. This assumes the ages given for the chrons in the Gradstein et al. (2004) GPTS are correct. The Cande and Kent (1995) GPTS gives slightly older ages for Chrons C5 through C6A, which would make our preferred correlation more compatible with the radioisotopic dates.

In both cases, the thicknesses of the reversed polarity zones relative to the normal polarity zones are somewhat less than expected from the GPTS if sedimentation rates had been relatively constant at Site AND-2A. This is particularly the case for the alternative interpretation as the very thin magnetozone R4 would correlate to C5Dr. In our preferred interpretation, magnetozone R4 is instead an excursion within Chron C5Dn. Sedimentation rates are unlikely to be constant, so neither interpretation can be eliminated based only on the relative thickness of the magnetozones.

**$^{40}$Ar/$^{39}$Ar GEOCHRONOLOGY**

A total of 23 samples were selected during on-ice activities for subsequent radioisotopic age determination (Tab. 2; Fig. 2). Twelve of the samples were collected from the upper 200 mbsf, with most of these being volcanic clasts embedded in diamictite. Given the good state of preservation of some of these clasts, their ages should be similar to that of the diamictite in which they were entrained. Selected samples were examined and ten of them were determined to contain sufficient material for $^{40}$Ar/$^{39}$Ar dating. In May 2008, additional clast samples were collected from the upper 200 m and from 358, 441 and 565 mbsf. These samples will be the focus of future studies. No datable material was collected between 200 and 358 mbsf. Eleven samples were collected below 565 mbsf, including samples from an ash layer with potassium-rich feldspar crystals at 640.16 mbsf. Most of the other samples are pumice lapilli and clasts, including a tephra sample from 1093.0 mbsf, which is near the base of the AND-2A sequence.

Radioisotopic dating was done at IGG-CNR in Pisa, Italy, using a noble gas mass spectrometer (MAP215-50) equipped with a low-volume stainless steel inlet system and using laser extraction techniques (Nd:YAG and CO$_2$ lasers). So far, 10 of the 23 samples have been dated. Uncertainties quoted are full 2σ errors that include analytical errors, uncertainties in neutron fluence, monitor age and $^{40}$K decay constants.

The youngest radioisotopic age (0.691 ± 0.049 Ma) was obtained from a volcanic clast from a volcanic breccia at 10.22 mbsf. Two lava clasts from 127 - 130 mbsf in LSU 4 give statistically indistinguishable ages, indicating that this part of LSU 4 is ~11.3 - 11.4 Ma. This supports the foraminiferal datum from 83.76 mbsf, which indicated an 11 Ma maximum age for this part of LSU 2. All three ages are further supported by a Sr-isotope date of ~11.7 Ma at 144.03 mbsf in LSU 4. An ash layer in the middle of the section (640 mbsf) gives an age of 17.30 ± 0.31 Ma. Two samples from 953 mbsf and the sample from 1093 mbsf provide

<table>
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<th>Sample Number</th>
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* indicates that insufficient material was available for dating.
age constraints that suggest the oldest sediments cored in Hole AND-1A are about 20 Ma (Tab. 1). The radioisotopic ages along with the other age constraints indicate that AND-2A contains a very thick lower Miocene record from 1138 to about 380 mbsf, a thick middle Miocene record from about 380 mbsf to near the top of LSU 4 (probably to about 140 mbsf; where the middle Miocene is 11.61 - 15.97 Ma as defined by Gradstein et al. (2004)), and an upper Miocene to Recent section above this.

**Sr-ISOTOPE DATING**

Most macrofossils recovered in the upper 125 m are decalcified, making them unsuitable for Sr isotopic dating. Five samples were collected in this interval, with three of them coming from a narrow interval (67 - 68 mbsf) (Tab. 3; Fig. 3). Macr...
Preliminary cathodoluminescence and elemental analyses on 14 of the 19 samples confirmed that diagenetic alteration, though notable in some intervals, is not a pervasive problem downcore. For this first set of samples, Sr-isotope analysis was done on all pieces despite signs of incipient alteration. Ages based on the $^{87}$Sr/$^{86}$Sr of diagenetically altered samples of all fragment types were consistently older than other age indicators (Fig. 3).

Unaltered material came from pectinid and venerid bivalves. Two samples, one from an Adamussium sp. shell fragment and the other from a costate pectinid shell fragment, provided ages coincident with other age estimates (Tab. 1; Fig. 2). Venerid pieces, which appear to be aragonitic (based on chemical makeup and XRD profiles), produced older ages than expected. The ages obtained from aragonitic fragments (as opposed to the pectinid ones) that appear to be too old are the focus of ongoing research.

The observed unaltered chemical profiles and the $^{87}$Sr/$^{86}$Sr ages obtained so far suggest that it should be possible to provide additional age constraints on at least some sections of the core with more Sr isotopic determinations. Once all preliminary analyses are completed, other samples will be selected and micro-sampled using what was learned from this initial set. Effective sample discrimination will increase chances of success while minimizing material destruction.

**ASTRONOMICAL TUNING**

The occurrence of orbitally induced variations in physical, magnetic, and chemical properties of stratigraphic sections provides another manner for dating geologic units. Currently, it is too early to say whether orbital cyclicity exists in the AND-2A record because signal analysis studies are just getting underway. Various parameters (lithology, XRF elements, physical properties, magnetic parameters) do, however, show features that are suggestive of cyclicity in some sections of the AND-2A core. For example, LSU 4 has a clear signal with a wavelength of ~20 meters. Similarly, the susceptibility has a long wavelength variation of ~100 to 200 meters from the base of the hole up to ~700 mbsf. The chronostratigraphic significance of these cycles will need to be tested once better age constraints are obtained. The ages obtained from aragonitic fragments (as opposed to the pectinid ones) that appear to be too old are the focus of ongoing research.

**REGIONAL AND GLOBAL CORRELATION**

Correlation of physical, magnetic, and chemical properties, key seismic reflectors, and lithologic variations of the AND-2A core with dated proxy records from regional or distant locations provides another viable dating method. Currently, only tentative correlations have been made using lithologic and seismic correlation to other drill sites in the Ross Sea region (Fielding et al., 2006, 2008) and are discussed in the synthesis paper (Harwood et al., this volume).

**EROSIONAL SURFACES**

Numerous erosional contacts were noted in the core (Fielding et al., this volume) and probably many others occur within some of the glacial deposits but are difficult to identify visually. Some of these undoubtedly correspond to significant hiatuses, particularly in the upper four lithostratigraphic units.

Only where dates could be obtained for the sediments above and below these contacts, could we accurately assess the amount of time missing at each contact. Unfortunately, datable material does not occur continuously throughout the sedimentary succession on a scale that allows a rigorous and precise assessment of actual time missing. Current chronostratigraphic data do allow us to recognize that time is missing in the section and that the time missing is relatively insignificant at some erosional surfaces and significant (hundreds of thousands to millions of years) at others.

Forty one glacial surfaces of erosion were included in the age model developed for the AND-1B core (Wilson et al., 2007). We follow a similar strategy for AND-2A by including the location of 71 probable contacts between sedimentary cycles. C.R. Fielding and colleagues have identified these 71 cycle boundaries in a preliminary sequence stratigraphic model that is currently being developed. Most of these sedimentary intervals represent glacial and eustatic cycles although tectonic processes have likely influenced the depositional character of some of the units. We used the cycle boundaries (plotted in Fig. 2) to guide placement of major hiatuses as we constructed the age model.

**AGE MODEL AND SEDIMENTATION RATES**

The combined, preliminary age constraints are given in table 1 and plotted in figure 2. These ages indicate that the sedimentary section is comprised of a fairly continuous and thick lower and middle Miocene section below 224.82 mbsf and a discontinuous middle/upper Miocene to Recent section above this. The upper portion of the section contains multiple hiatuses resulting from the discontinuous nature of deposition and common erosional episodes that are typical of environments at the margin of a dynamic ice sheet.

We construct an age model that fits the current age constraints and that incorporates several major hiatuses. One or more of these breaks in the record are located between 50 and 122.86 mbsf, with an accumulative loss of over 7 m.y. We cannot delineate a precise location for the hiatus or hiatuses within this interval but schematically illustrate two options.
in figure 2 with the uppermost hiatus occurring at the base of a glacial cycle at 77.66 mbsf and the lowermost hiatus occurring at the LSU 3/4 boundary (122.86 mbsf). The sediment ages within this interval can only be imprecisely dated as being between about 3 and 11 Ma. An additional hiatus that is approximately 3 m.y. in duration is placed at 224.82 mbsf (the LSU 4/5 boundary). This break in the record could actually be accommodated on multiple erosional/non-depositional surfaces that occur between 145 mbsf and the LSU 4/5 boundary (224.82 mbsf) but, at present, this is an interval without age constraints.

Ages within LSU 5 are constrained to be between about 14.2 Ma (the absence of D. simonsen i and the LAD D. maccollum i from the top of LSU 5) and 15.7 Ma (FAD D. lauta sensu latu near the top of LSU 6). The sedimentation rate is therefore at least 4.7 cm/k.y. but is more likely much higher than this and one or more hiatuses occur within LSU 5 or at the LSU 5/6 boundary.

Below the LSU 5/6 boundary (296.34 mbsf), sedimentation was relatively continuous and rapid and the age model is well constrained by 9 diatom datums, seven 40Ar/39Ar dates, one Sr-isotope date, and 19 magnetozones. Even so, short hiatuses (less than a few hundred thousand years) undoubtedly occur but are beyond the resolution of the chronostratigraphic age constraints.

Although the linear age model for the interval from 296.34 - 1138.54 (Fig. 2) is an over simplification of the true ages of the sediments, it serves to illustrate the point that sedimentation was relatively continuous over much of the early and middle Miocene at Site AND-2A. Numerous more complex age models could be derived from the age constraints but such models would not necessarily be more accurate. A more accurate representation would likely involve placing at least short hiatuses on observed erosional contacts, but the number and significance of these contacts are still under investigation.

The ‘relatively’ continuous and rapid nature of deposition is supported by diatom datums, which provide particularly good age control from LSU 6 down to 771.5 mbsf (in LSU 10), where the FO of T. praefraga (18.85 Ma) is observed. These datum ages are supported by radioisotopic dates, one Sr-isotope date, and 19 magnetozones. Even so, short hiatuses (less than a few hundred thousand years) undoubtedly occur but are beyond the resolution of the chronostratigraphic age constraints.

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