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APPENDIX

NEW INSIGHTS INTO EARTH'S HISTORY: AN INTRODUCTION TO LEG 162 POSTCRUISE RESEARCH PUBLISHED IN JOURNALS[1]

M.E. Raymo[2]

ABSTRACT

In addition to the Leg 162 scientific results presented in this volume, a number of outstanding studies by shipboard scientists have been published in journals. These include five papers published in either *Science* or *Nature*, a measure of the impact that results from this leg and these investigators have had within the scientific community. Highlights from these publications are summarized below. In conjunction with this volume, these studies comprise the initial body of scientific results from Leg 162. The list of these studies was prepared in April 1999 and will be updated on the Ocean Drilling Program Web site (http://www-odp.tamu.edu) as new papers are published.

INTRODUCTION

Results from Leg 162 are providing new insights into the role played by the high northern-latitude seas in the global climate system on time scales ranging from centuries to millions of years. The exceptionally high accumulation rates that characterize the sedimentary sequences recovered south of Iceland have permitted the study of millennial-scale variations in climate proxies as well as in the Earth's magnetic field at a level of detail not previously possible. In particular, by extending these high-resolution records back millions of years, Leg 162 investigators have been able to characterize the amplitude and frequency of millennial-scale climate variability over a time period when the average climate state has evolved toward generally colder conditions and the frequency of orbital-scale variations has changed dramatically. In addition, by examining the evolution of vertical and horizontal gradients in water mass properties on both orbital and millennial time scales, these investigations have allowed us to examine the long-term history of North Atlantic surface and deepwater circulation. Such hydrographic changes exert a fundamental control on Northern Hemisphere, and perhaps global, climate. Lastly, sediments recovered from Leg 162 sites in the Norwegian-Greenland Sea are providing new insights into the Neogene evolution of Northern Hemisphere ice sheets. Below are highlights from the Leg 162 results that have been published outside of this *Scientific Results* volume. The list of these studies was prepared in April 1999 and will be updated on the Ocean Drilling Program Web site (http://www-odp.tamu.edu) as new papers are published.

NORTH ATLANTIC CLIMATE VARIABILITY AND ICE-SHEET DYNAMICS

Millennial-Scale Climate Evolution

Of the many physical properties measurements made at sea during Leg 162, perhaps the most exciting were the records of sediment brightness in the continuous pelagic sequences recovered south of Iceland (Sites 980–984). Ortiz et al. (1999) demonstrated that the measurement of diffuse spectral reflectance provides a rapid and accurate proxy for sediment carbonate content in the North Atlantic. The reflectance-derived carbonate records from Sites 980 through 982 exhibit patterns of variability similar to the classic North Atlantic carbonate records from Sites 552, 607, and 609. However, because of the high sedimentation rates at the Leg 162 drift sites, Ortiz and colleagues were able to use the unprecedented temporal resolution (1000–2000 yr) of these several-million-year-long records to examine the high-frequency spectral evolution of the carbonate system in the North Atlantic.

After developing an age model, Ortiz et al. (1999) showed that significant sub-Milankovitch variability with periods centered near 7.6–8.4 and 4.8–6.1 ka are found not only during the period of major Northern Hemisphere glaciation after 2.5 Ma, but also before the late Pliocene intensification of Northern Hemisphere glaciation. Hence, this important study implies that the dynamics of large ice sheets cannot be the sole cause of sub-Milankovitch variability in the region. Ortiz and colleagues also point out that an analysis of a 5-m.y. rectified record of precession displays concentrations of variance at periods similar to those observed in the spectral reflectance records at Sites 980 and 981. This suggests that at least some of the millennial-scale variance at these sites may arise from a nonlinear response to precessional forcing.

In order to gain a better understanding of the specific climatic and hydrographic changes that are taking place at millennial frequencies, several Leg 162 investigators have carried out detailed examinations of the sedimentological, faunal, and geochemical characteristics of the drift site sequences at Sites 980, 981, 983, and 984. Oppo et al. (1998) generated subpolar climatic records with a 300-yr resolution for a late Pleistocene interval at Feni Drift, Site 980. Their study of marine isotope Stages (MISs) 11 and 12 and of the associated high-amplitude deglaciation, Termination V, documents climatic cycles with characteristics and pacing similar to those documented for the last glacial cycle. This study was thus one of the first to show that such millennial-scale climate variations are pervasive throughout the late Pleistocene, regardless of baseline glacial state. Oppo and colleagues further established that the highest amplitude sea-surface temperature (SST) oscillations occurred during periods of ice growth and decay and that moderate SST oscillations occurred during peak MIS 12. SST oscillations also continued with similar pacing during peak interglacial conditions (MIS 11), although their amplitude was greatly reduced (~1°C).

One of the most exciting aspects of the Oppo et al. (1998) paper is that coupled SST–deep-water oscillations were documented for all but the warmest times. In particular, the coupled oscillations ob-

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[2]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, E34-254, Cambridge, MA 02139, U.S.A. raymo@mit.edu

served during the glacial termination are shown to be consistent with findings from the last glacial cycle, suggesting that deglacial climate instabilities, such as the Younger Dryas, are part of the normal sequence of millennial climate oscillations. Oppo and colleagues also demonstrated the fidelity of the $\delta^{18}O$ of *N. pachyderma* (right coiling) in recording the full amplitude of SST variations recorded by faunal indices.

This rapidly measured isotope proxy for high-latitude SST was subsequently exploited by McManus et al. (1999). Their paper, which also focuses on the late Pleistocene record of millennial-scale climate variability at Site 980, documents the persistence of millennial-scale surface and deep variability through each of the last five climate cycles of the Quaternary. In addition, the authors show the largest range of planktic glacial–interglacial $\delta^{18}O$ values yet observed for the open ocean in the Quaternary. Such a large range brings isotopic SST estimates into agreement with previous faunal SST estimates for glacial–interglacial change in the North Atlantic.

One of the most significant discoveries of the McManus et al. (1999) study is that the amplitude of the surface hydrographic and SST response that occurs on millennial time scales is controlled by the baseline climate state (e.g., the amount of continental ice present). Indeed, it appears that a threshold in the climate-system response is reached at an ice volume/sea level equivalent of ~30 m lower than at present. In other words, when benthic $\delta^{18}O$ values exceed 3.5‰, millennial-scale SST variability increases to 4°–6°C in most glacials. At lower interglacial ice volumes, SST amplitude is only 1°–2°C. McManus and colleagues raise the possibility that ranges or “islands” of climate stability exist within the present system, beyond which enhanced climate variability reigns.

Finally, stepping back in time, Raymo et al. (1998) address the question of whether suborbital variability in surface and deep-water hydrography was present—or as pronounced—before the development of the large-amplitude 100-k.y. climate cycles of the Brunhes. These investigators show that millennial-scale climate oscillations, similar to the Dansgaard-Oeschger cycles known from the last glacial cycle, are also present in the early Pleistocene “41-k.y. world.” This study indicates that periodic variations in iceberg delivery to the subpolar North Atlantic are associated with deep-water (benthic) $\delta^{18}O$ and $\delta^{13}C$ changes in the region, implying coupled behavior between continental ice-sheet mass balance and thermohaline circulation. These events are shown to recur on time scales considerably less than 5,000 yr and probably closer to 2,000 yr. Thus, through the analysis of Leg 162 cores, we now know that millennial-scale climate cycles occur across a broader spectrum of climate boundary conditions than had been previously recognized and, indeed, that such instabilities may be a pervasive and long-term characteristic of Earth’s climate.

Pliocene–Pleistocene Climate Evolution

The continuous records of the Pliocene–Pleistocene recovered at Sites 980–985 have also provided a wealth of information on the orbital-scale and longer climate evolution of the region. In a study of the time interval from ~1.4–2.0 Ma, McIntyre et al. (in press) generated a suite of benthic isotope records from both the Feni Drift (Site 981) and the Gardar Drift (Site 983) in order to monitor the history of, and interactions between, North Atlantic Deep Water (NADW) and Glacial North Atlantic Intermediate Water (GNAIW). In contrast to the late Pleistocene, McIntyre and colleagues find no evidence for GNAIW at the depth of these sites (between ~1980 and 2200 m) during this interval. However, throughout the 1.4- to 2.0-Ma period, bottom water at Site 983 had relatively high $\delta^{18}O$ and low $\delta^{13}C$ values compared to other sites in the North Atlantic. This dense, apparently nutrient-rich water mass is most notable during the interglacial periods when it is represented by higher $\delta^{18}O$ and lower $\delta^{13}C$ than even Antarctic Bottom Water (as represented by deep equatorial Atlantic sites). Thus, the dense overflow water from the Nordic Seas that contributes to NADW had a different and unique character in this interval relative to the late Pleistocene. Overall, McIntyre et al. (in press) show that oxygen and carbon isotopic gradients in the early Pleistocene North Atlantic appear to be larger than those observed for the late Pleistocene, perhaps reflecting larger ranges of bottom-water temperature and salinity, as well as possibly a greater range of source areas for intermediate and deep water. This apparent heterogeneity in the composition of source waters over the Pleistocene implies that changes in the relative NADW flux may be difficult to quantify.

Pleistocene changes in the vertical water mass structure of the North Atlantic were also studied at Site 982, located at a water depth of 1145 m. For the interval spanning the last million years, Venz et al. (1999) were able to establish that the mid-depth northeast Atlantic was generally well ventilated during both glacial and interglacial periods but was characterized by a short interval of poor ventilation on terminations. The abrupt decreases in benthic $\delta^{13}C$ observed on the glacial–interglacial transitions suggests to these investigators that intermediate water mass production ceased at these times and did not resume until full interglacial conditions were reached. Venz et al. (1999) also demonstrated that pronounced ice-rafting events characterized the end of nearly every glacial stage in the late Pleistocene. They relate the presence of meltwater at the surface to the suppression of GNAIW as inferred from the benthic isotope data. The influence of perennial sea-ice cover in the Norwegian-Greenland Sea on North Atlantic thermohaline circulation is also explored in this paper.

Concentrating on Leg 162 cores recovered from the Norwegian-Greenland Sea, Solheim and colleagues have published a number of papers on the history of Pliocene–Pleistocene ice-sheet development in the polar regions. Solheim et al. (1996) were able to infer the glacial history of the Svalbard margin from the high-resolution seismic line network that has been developed on this continental shelf. In particular, at the time of seismic Reflector R5, dated at ~1.5 Ma at Site 986, the depositional regime in the region changed from net erosion to net deposition/shelf aggradation. Solheim and colleagues attribute this change to a transition from a glacial regime characterized by thick, eroding glaciers to one marked by fast-flowing ice streams maintained by an increased amount of interglacial and interstadial sediments. Based on sediment budget calculations, Elverhøi et al. (1998) were able to show that glaciers appear to be vastly more efficient erosional agents than rivers, when factors such as lithology, precipitation, and altitude were held constant.

In a second study (Solheim et al., 1998), these investigators compare the sedimentary facies from the East Greenland and the Svalbard–Barents Sea margins in order to outline the glacial evolution of the two regions. They were able to show that the Greenland and Barents Sea Ice Sheets evolved and behaved differently over the late Neogene. Based on the magnetic stratigraphy from Sites 986 and 987 (Channell et al., Chap. 10, this volume), glacial deposition has occurred on the East Greenland margin since the late Miocene (~7 Ma) but only since 2.5 Ma on the Svalbard–Barents Sea margin. Likewise, glacial expansion across the shelf edge also occurs earlier on the Greenland margin. This paper goes on to discuss factors responsible for the differences in ice-sheet behavior in these two regions.

History of the Earth’s Magnetic Field

Evidence is building that geomagnetic paleointensity records are largely controlled by the global-scale (axial dipole) field and can therefore be used for global correlation. Such a global correlation tool would have exciting implications for paleoclimatology, namely by providing a method with which to correlate climate records over large distances (for example, between high latitudes in the two hemispheres). The nature of the variability in geomagnetic paleointensity records is such that correlation at millennial scale is achievable. As the focus of paleoclimate studies moves to the sub-Milankovitch scale, the development of a practical means of correlating climate records at this resolution will become critical. The papers described below lay the groundwork for just such a tool.

In addition to the magnetostratigraphic papers published in this volume, Channell and colleagues have published a number of studies that present the postcruise magnetic measurements carried out on "u-channel" samples (continuous samples of core sections with a cross section that is 2 cm × 2 cm square and sealed in a plastic container). These samples allow magnetic measurements to be made at 1-cm intervals downcore and thereby yield data with unprecedented resolution, particularly at the high–deposition-rate drift sites such as Sites 983 and 984. Normalized remanence (relative geomagnetic paleointensity) records for the Brunhes and Matuyama Chrons from Sites 983 and 984 can be correlated with one another and with the few (lower resolution) records currently available from other regions. In addition, the correlation of Sites 983 and 984 paleointensity records with oxygen isotope chronologies (Channell et al., 1997) provides the basis for establishing a chronology for paleointensity records, and hence a basis for using these records as a means of (global) correlation. Channell et al. (1998) have found evidence for a 41-k.y. period in the intensity of the geomagnetic field that varies in phase with the Earth's orbital tilt. This finding, if confirmed, has implications for the effect of obliquity on precessional forces in the Earth's core and geodynamo theory. The orbital modulation of geomagnetic intensity may also serve as a new chronometer that could potentially be used to improve oxygen isotope stratigraphy.

In addition to the practical use of paleomagnetic field records for correlation of climate records, the results from Sites 983 and 984 may offer a solution to one of the outstanding puzzles in geoscience: the mechanism for the generation of polarity reversal in the geomagnetic field. At the same time as numerical (computer) simulations of the geomagnetic field are becoming more realistic, magnetic records from Leg 162 are yielding higher resolution records of geomagnetic directional secular variation and paleointensity, both within polarity chrons and across polarity reversal boundaries. The high-resolution reversal records preserved in these sites enable study of these processes at finer levels of detail than was previously possible. Although virtual geomagnetic polar (VGP) path estimates have often been derived from sediment records, the studies of Channell and Lehman (1997) and Mazaud and Channell (1999) indicate that the lack of detail in previous VGP studies can be attributed to smoothing by the remanence acquisition/measurement process on lower sedimentation rate cores. In Leg 162 sediments, the lower sedimentation rate records (~5 cm/k.y., as at Site 981) yield VGP paths (for the Brunhes/Matuyama boundary) that are longitudinally constrained over the Americas. For Sites 983 and 984, where sedimentation rates are ~10–12 cm/k.y., the VGP paths for the Brunhes/Matuyama boundary as well as the boundaries of the Jaramillo and Olduvai Subchrons are very different, featuring loops and clusters. Clusters are preferentially located in the South Atlantic and northeast Asia (broadly coinciding with centers of downward-directed flux in the modern geomagnetic field stripped of its axial dipole).

In summary, the high-fidelity magnetic records from Leg 162 sites have contributed greatly to the effort to establish a magnetic method of correlation for climate records at millennial scale. They have also provided high-resolution records of the geomagnetic field that, through comparison with computer simulations of the geodynamo, are providing new insights into the physics controlling the operation of the Earth's magnetic field.

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