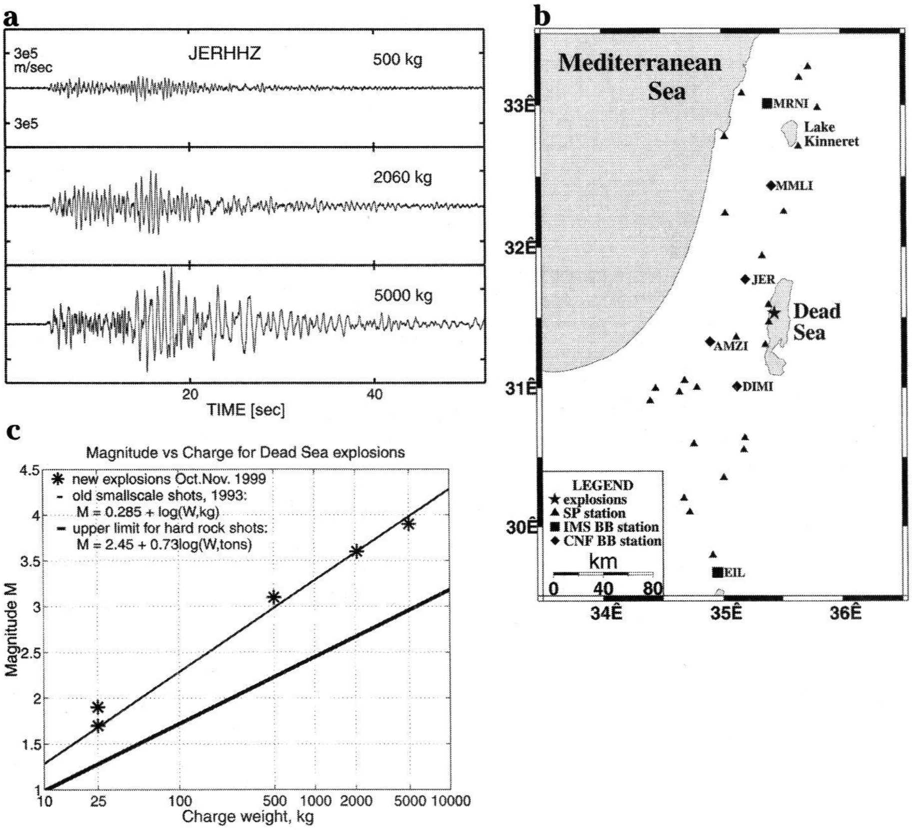

Fig. 2. (a) Seismograms at the closest JER (Jerusalem) broadband station; (b) Map shows location of the explosion site and stations of the Israel Seismic Network which made recordings of the explosions; (c) Plotted data confirm a high seismic efficiency of the Dead Sea calibration explosions and predicted magnitude values.

Israel Atomic Energy Commission and to the Arms Control Division of the Ministry of Defense, Israel, for their diplomatic efforts. The authors give special thanks to the Israel Defense Forces and the Police of Israel for their assistance in conducting the explosions. The GII management and staff provided financial and technical support throughout the experiment.

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Radiogenic Isotopes: New Tools Help Reconstruct Paleocean Circulation and Erosional Input

PAGES 66, 71

Ocean and atmosphere circulation and continental weathering regimes have undergone great changes over thousands of years as well as tens of millions of years. During the glacial stages of the Pleistocene, ocean circulation was generally more sluggish and deep water circulation in the Atlantic had a shallower flow. At the same time, weathering on the continents was enhanced by glacial erosion, particularly in high northern latitudes, which increased the input of erosional detritus into the ocean. In addition, atmospheric pressure gradients were larger, leading to higher wind speeds and increased supply of aeolian dust to the ocean. Prior to the onset of Northern Hemisphere glaciation and pronounced glacial/interglacial cyclicity at ~3 m.y.a., global climate was warmer than at present. There is also evidence for a more vigorous thermohaline circulation during the early Pliocene.

Paleogeography is another important factor that has controlled the pattern of global ocean circulation. For example, the openings of the Tasman Strait between Australia and the Antarctic ~36 m.y.a. and the Drake Passage between the Antarctic and South America ~23 m.y.a. permitted unrestricted deep water circulation around the Antarctic. This eventually led to thermal isolation and glaciation of the Antarctic and for the first time enabled the establishment of a global ocean circulation system similar to the present one.

Other pathways of deep water circulation such as the Indonesian seaway and the Panama gateway closed during the past 20 Ma, which means that the circulation system of the ocean—for example, 30 m.y.a.—was completely different from the prevailing one. These differences in ocean circulation were coupled to global climate changes. For our understanding of the factors governing present-day climate and ocean circulation, we must learn as much as possible about the way the systems worked during such different paleogeographic and climatic periods.

The tools for understanding these changes are the erosional products that originate from weathering of continental rocks, which enter the ocean either as particulates or in dissolved form mainly by riverine and aeolian transport. This material is redistributed within the global thermohaline circulation system and deposited in marine sediments. The radiogenic isotope composition of trace metals within this material—Nd, Pb, Hf, Sr, and Os—varies as a function of age and composition of the source rocks and the weathering processes involved. Consequently, different water masses in the ocean have different isotopic compositions of their dissolved trace metals, and also carry fine-grained detrital material with highly variable isotopic composition as a function of the source areas of the inputs.

Thus, variations in the isotopic composition of detrital sediments potentially provide information on changes in inputs or changes in the circulation pattern of the ocean. In dissolved form, some of these trace metals—Nd, Pb, and Hf—have oceanic residence times of 10^2 to 10^3 years, which is on the order of or shorter than the global mixing time of the oceans. Dissolved trace metals are deposited in ferromanganese crusts, which act as recorders of ancient sea water composition and past ocean circulation. These trace metal isotopes contribute valuable information to what we know from paleoceanographic reconstructions based on classical tracers such as stable carbon isotopes and Cd/Ca ratios of benthic foraminifera.

Since October 1996, the European Union has funded a Training and Mobility Through Research (TMR) Network for collaborative research titled "The Marine Record of

Continental Tectonics and Erosion." Its objective is to contribute to the understanding of links between major climatic, tectonic, and erosional processes and their reflection in the marine sedimentary record on time scales ranging from 10^3 to 10^7 years.

The principal goals of the E.U.TMR Network program are to train postdoctoral researchers under 35 to produce and interpret geochemical and isotopic proxy records from the marine environment and encourage their mobility within Europe in pursuit of these research interests. Participants in the network are the universities of Oxford, Aix-Marseille, Paris, and Amsterdam, and the Max Planck Institute for Chemistry, Mainz. So far, 11 postdocs have been supported by the network for periods from 1 to 3 years.

Here we report results and highlights from participating groups in Oxford, Mainz, and Amsterdam, concentrating on two specific topics of investigation within this network: isotopic studies of ferromanganese crusts and nodules and the record preserved by clay minerals in deep sea sediments.

Ferromanganese Crusts

Hydrogenetic ferromanganese crusts incorporate trace metals from ambient sea water during growth and record their isotopic composition. These crusts grow on hard substrates in the deep sea at extremely low rates on the order of 1–10 mm/Ma at locations that are kept free of sediments by bottom currents. Trace metal isotope time series obtained from ferromanganese crusts allow reconstruction of the isotopic signature of water masses back to at least 30 m.y.a.

Much effort has been devoted to dating ferromanganese crusts using radioactive isotopes. It has been demonstrated that dating based on the decay of ^{230}Th (half-life = 75,000 years) yields a reliable stratigraphy for the past 400,000 years, in contrast to ^{234}U-based methods, which appear to be biased by post-depositional mobility of U within the crusts [*Claude-Ivanaj et al.*, 1998]. This conclusion concurs with results recently obtained by other groups. On longer time scales it was shown that dating using the cosmogenic radioisotope ^{10}Be (half-life = 1.5 Ma) provides reliable results back to about 10 m.y.a.

For crust sections older than 10 Ma, a dating method based on the constant flux of Co is used to reconstruct growth rates (see *Frank et al.* [1999a] for a summary). On the basis of chronologies for the crusts derived this way, time series of Nd and Pb isotopes from various locations have been produced that provide new insight into past ocean circulation and tectonic processes. In addition to dating the crusts, advances in measurement precision of the Pb isotope composition have been made by applying new techniques involving Pb triple-spiking for thermal ionization mass spectrometery (TIMS) in Mainz and Tl-spiking for multi-collector inductively coupled plasma mass spectrometry (MC-ICPMS) in Oxford.

An example of this work is presented in Figure 1. A relatively shallow-water ferromanganese crust of 800 m, collected within Gulf Stream waters on the Blake Plateau off the coast of Florida (BM1963.897; 31°N, 78°W), shows pronounced Nd and Pb isotope variations over the past 3–4 Ma that are comparable to records of the isotopic signature of North Atlantic Deep Water (NADW) in the western North Atlantic. It has been suggested that the reason for these variations is increased erosion rates of the old continental land masses of the Canadian Shield and Greenland related to the onset of Northern Hemisphere glaciation. Even more noteworthy is a shift in Pb and Nd isotope composition between 8 m.y.a. and 5 m.y.a. in this same shallow-water crust, which is not observed in the deeper-water crusts from the western north Atlantic (Figure 1) [*Reynolds et al.*, 1999]. We interpret this pattern as a consequence of a decrease in the admixture of deep and intermediate Pacific water masses with high ε_{Nd} and low ^{206}Pb/^{204}Pb caused by the progressive closure of the Panama gateway, which was essentially complete by ~5 m.y.a.

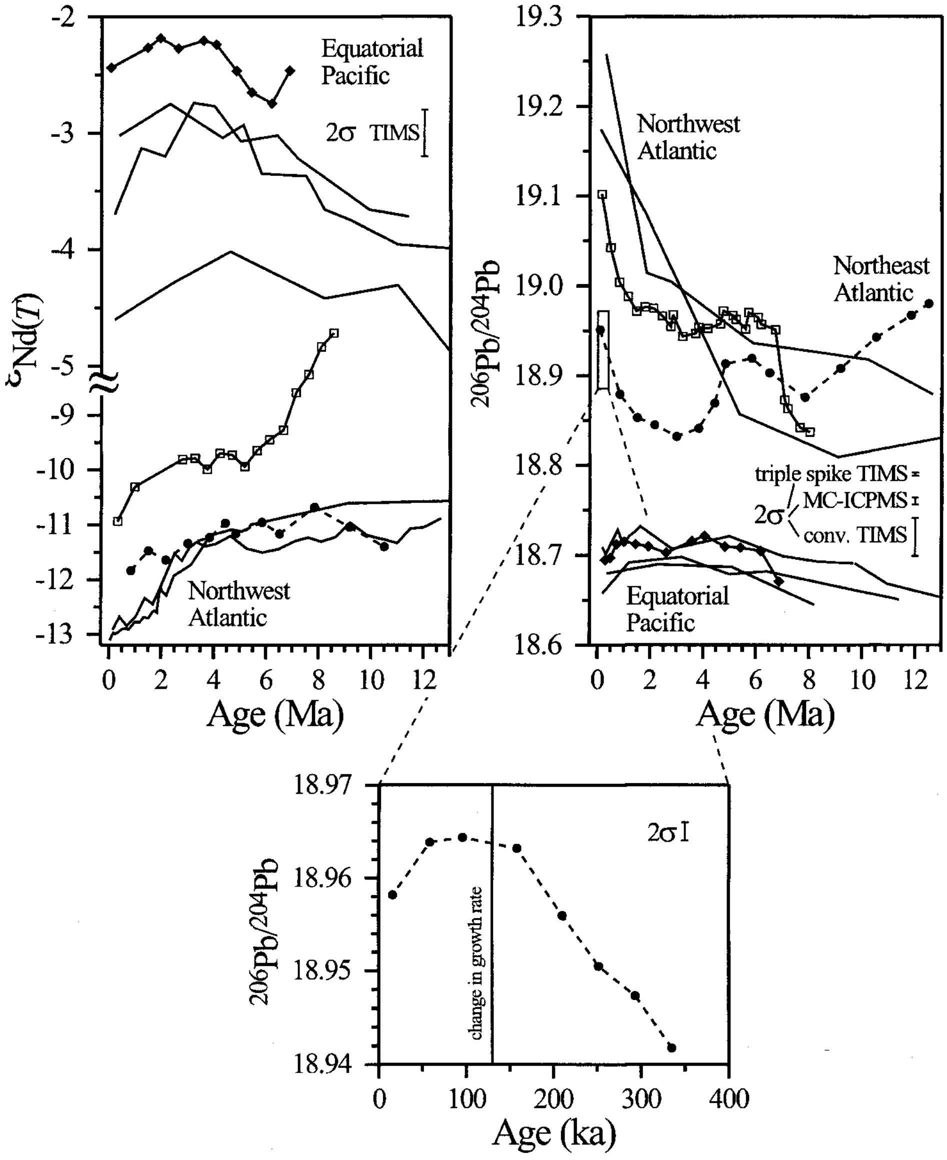

Fig. 1. Variations of the Nd isotope ratios (given as age-corrected $\varepsilon_{Nd}(T)$ values; ε_{Nd} stands for the measured ^{143}Nd/^{144}Nd, normalized to the chondritic uniform reservoir CHUR (0.512638), multiplied by 10,000) and ^{206}Pb/^{204}Pb in ferromanganese crusts from the Northwest Atlantic (low ε_{Nd}/high ^{206}Pb/^{204}Pb) and the eastern Equatorial Pacific (high ε_{Nd}/low ^{206}Pb/^{204}Pb) over the last 13 Ma (solid lines) [Frank et al., 1999b; see references therein for sources of all data]. A shallow Blake Plateau crust (BM1963.897) is marked by open squares and a deep equatorial Pacific crust (GMAT 14D) located west of the former Panama gateway is marked by solid diamonds. In addition, Pb isotope results of a crust from the Northeast Atlantic (121DK) are shown as dashed line and solid circles [Abouchami et al., 1999]. The higher resolution Pb isotope record for the past 400 kyr of crust 121DK is shown in the inset [Claude-Ivanaj et al., 2000]. 2σ external reproducibilities of the measurement techniques are indicated.

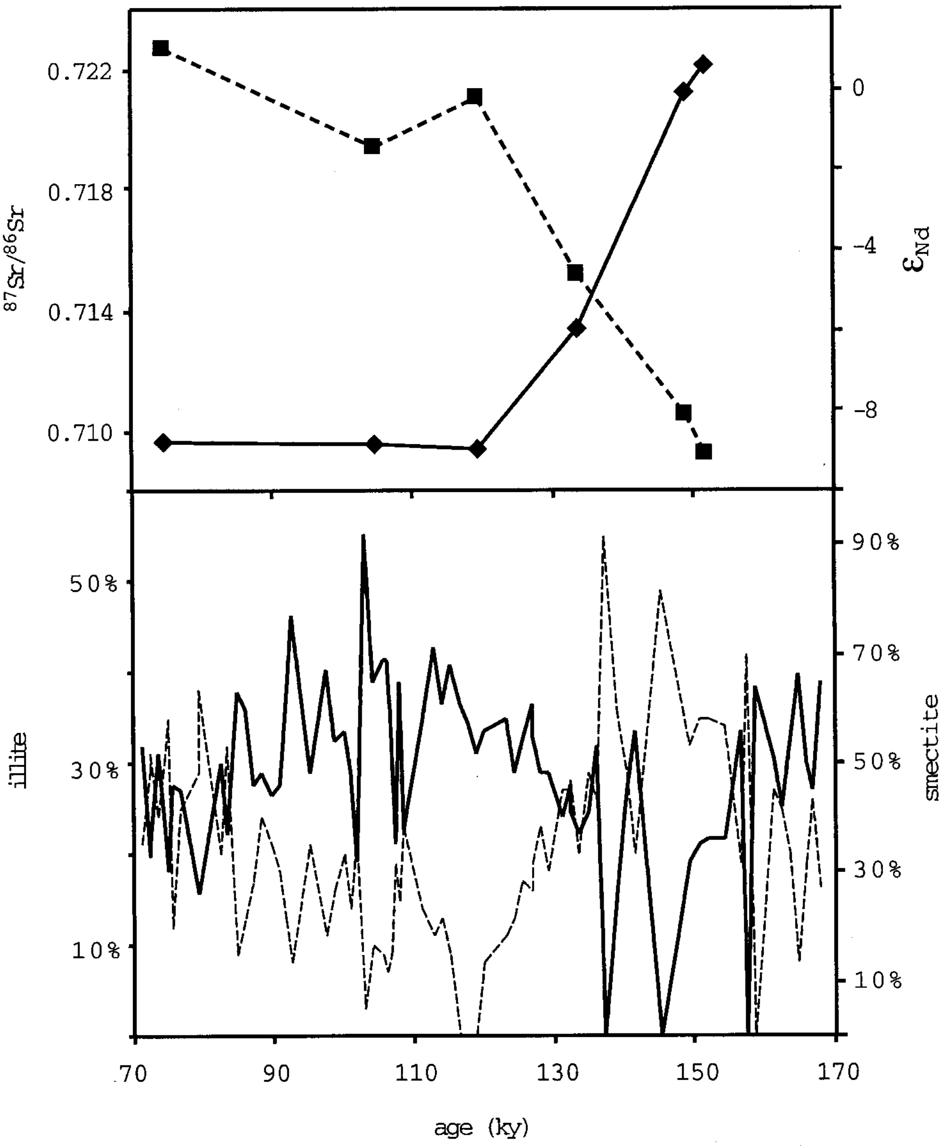

Fig. 2. (a) ^{87}Sr/^{86}Sr (solid line) and ε_{Nd} (dashed line) versus age for core 984, ODP leg 162. (b) Variations of the smectite (solid line) and illite (dashed line) abundances versus age in the same core [Bout-Roumazeilles et al., 1998].

Between 5 m.y.a. and the final closure of the Panama gateway by a land bridge at ~3.5 m.y.a., the seaway was apparently already too shallow for significant exchange of Pacific-derived water masses. A trace metal isotope record obtained from a crust on the deep eastern equatorial Pacific side of the Panama gateway (GMAT 14D; 14°N, 96°W) shows no significant changes in Pb and Nd isotopes over the past 7 Myr (Figure 1). This supports the view that water-mass exchange was predominantly directed from the Pacific into the Atlantic prior to closure of the Panama gateway [*Frank et al.*, 1999b]. The timing of the observed changes in the Blake Plateau crust suggests that the closure of the Panama gateway may have been a necessary precondition for the onset of Northern Hemisphere glaciation even though it was not a direct cause.

The recent development of high-precision lead isotope ratio measurements allows very small differences in isotopic composition to be resolved independently in three isotope ratios: ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, and ^{208}Pb/^{204}Pb. Given the new levels of measurement precision, a single chemical element, lead, now yields three truly independent source parameters, which is opening completely new ways of using this tracer.

In one such study, conducted on a crust from Tropic Seamount (121DK) located off the coast of Africa, Abouchami et al. [1999] showed that rather abrupt changes in provenance occurred 8 m.y.a. and 4 m.y.a. A further remarkable result was that between 13 and 8 m.y.a., 8 and 4 m.y.a., and 4 and 0 m.y.a., two and only two lead components were progressively mixed, but the end members of these binary mixtures were different for each of these periods. At the time of that study, no high-precision data were available from other locations. Thus, the data were consistent with the interpretation that one of the major components present in the deep water at the location of this crust during 0–4 m.y.a. was NADW derived from the western Atlantic basin (WNADW).

More recently, Reynolds et al. [1999] re-analyzed several crusts from the western North Atlantic also using high-precision methods. These results and interlaboratory calibrations between the Oxford and Mainz laboratories [*Claude-Ivanaj et al.*, 2000] have shown that the interpretation of Abouchami et al. [1999] must be revised, because lead from the western North Atlantic is too low in ^{207}Pb/^{204}Pb to serve as a viable end member of lead found in the eastern Atlantic. Evidently, the Pb isotopes in WNADW are modified before they mix with water masses coming from the South Atlantic and travel eastward toward the coast of Africa. One likely cause of such a modification is lead derived from the suspended loads of the Amazon and Orinoco Rivers [*Claude-Ivanaj et al.*, 2000]. Overall, the new analytical precision shows a level of fine structure in the data that was not previously perceived. This complexity poses new problems for interpretation, but it also offers new promise in understanding and tracing multiple sources of input into the ocean, which would simply not be possible using other tracers.

Clay Minerals in Deep Sea Sediments

The isotope studies on ferromanganese crusts presented above reflect oceanographic reorganization and variability of erosional input into the ocean on timescales of 10^5-10^6 years, but to resolve changes on a glacial-interglacial timescale in detail requires a different archive. Therefore, we have tried to use the Pb-, Nd-, and Sr-isotopic composition of the terrigenous fraction in Late Quaternary sediments, for which a high-resolution stratigraphy is available, as proxies for changes in the provenance of detrital sources to the North Atlantic. The approach focuses on the clay-size fraction (< 2 μm), which represents a large part of the bulk sediment in the North Atlantic. This fine-grained fraction is predominantly delivered from the surrounding continents to the deep-sea by deep-ocean circulation, in contrast to silt- or sand-size particles, which are mainly transported via the atmosphere and the surface circulation of the ocean.

This particular aspect of the network project was initiated in the North Atlantic because formation of NADW is one of the fundamental processes that controls the thermohaline circulation of the ocean and consequently Earth's climate. Paleoceanographic studies using nutrient proxies have suggested overall changes in oceanographic conditions in the North Atlantic on glacial to interglacial time scales, but reconstructing provenance changes of water masses supplying NADW is difficult using those methods. It has been shown that the mineralogical composition of the clay-size fraction has recorded pronounced glacial-interglacial alternations. Over the last climatic cycle, the most prominent changes in clay mineralogical and marine proxy signatures

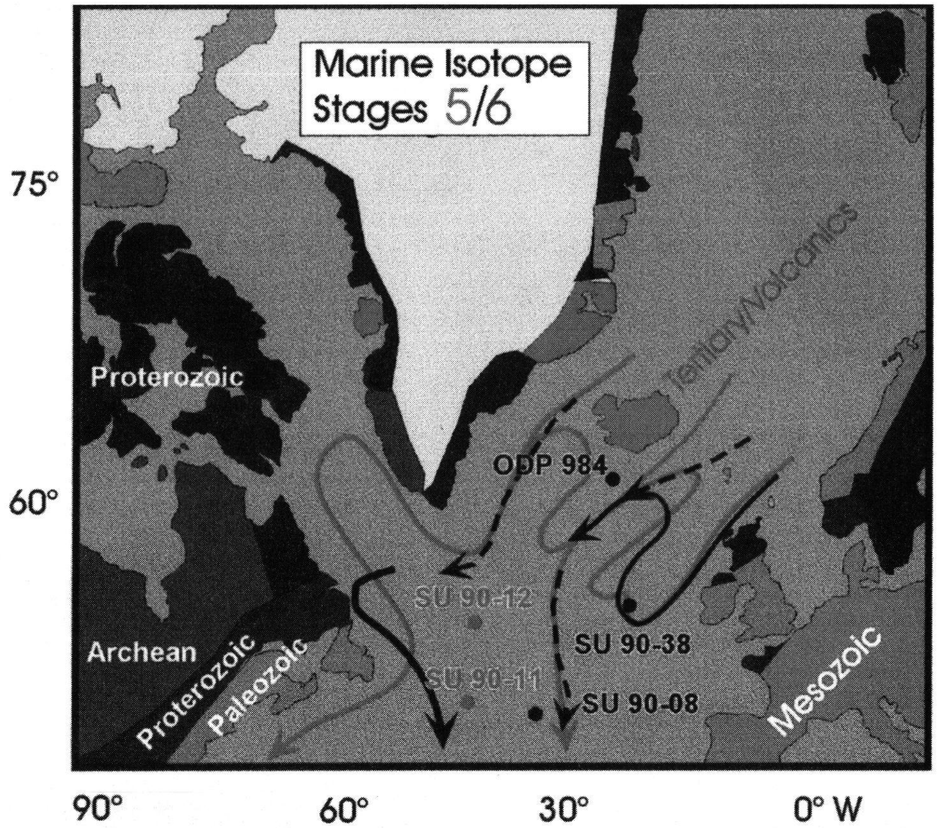

Fig. 3. Schematic map of the North Atlantic showing the reconstructed variation of the pattern of deep water flow between interglacial stage 5 (red line) and glacial stage 6 (blue line). The schematic age distribution of exposed rocks on the adjoining continents is indicated on the map. Also given are five of the sampling points used to infer the changes in circulation. Original color image appears at the back of this volume.

are associated with the transition from glacial stage 6 to interglacial stage 5 (~130 ka). The beginning of interglacial stage 5, the Eemian, is a close climatic analogue of the Holocene. Sampling, therefore, concentrated on this period.

Mineralogical and Sr-Nd isotope variations of the clay-size fraction at ODP site 984, 60°N, 22°W, 400 km south of Iceland are presented as an example in Figure 2 [*Bout-Roumazeilles et al.*, 1998]. The abundances of the clay minerals smectite and illite clearly follow the climate change, with high illite/smectite ratios characterizing glacial stage 6. This variation is accompanied by marked isotopic changes of the clay minerals. Radiogenic Nd and unradiogenic Sr and Pb isotope ratios (radiogenic = high contributions from the decay of the parent isotopes in the source rocks due to high parent isotope abundances) indicate that the smectite-rich last interglacial detritus was, as today, mainly derived from weathering of Iceland.

In contrast, during the glacial period, most of the clays apparently originated from the European continent. Previous studies have suggested that the observed changes in clay mineralogy relate to different physical and chemical weathering conditions during glacial and interglacial times. We argue that the coupled changes in clay mineralogy and radiogenic isotope composition of the clay-size fraction reflect changes in source provenances and deep-ocean currents rather than simply weathering conditions. These data therefore establish a major reconfiguration in deep ocean currents at the transition from glacial stage 6 to interglacial stage 5. Changes in clay provenance over time at various sites in the North Atlantic are now being determined by the Amsterdam group to map past NADW variability. A provisional circulation map (Figure 3) implies that the sites of NADW formation moved further south during glacial times. Once refined, such reconstructions of circulation will provide important information for climate modeling.

Further general information on the TMR network program and its successor (IHP networks) in the new framework 5 can be obtained via http://www.cordis.lu/tmr.

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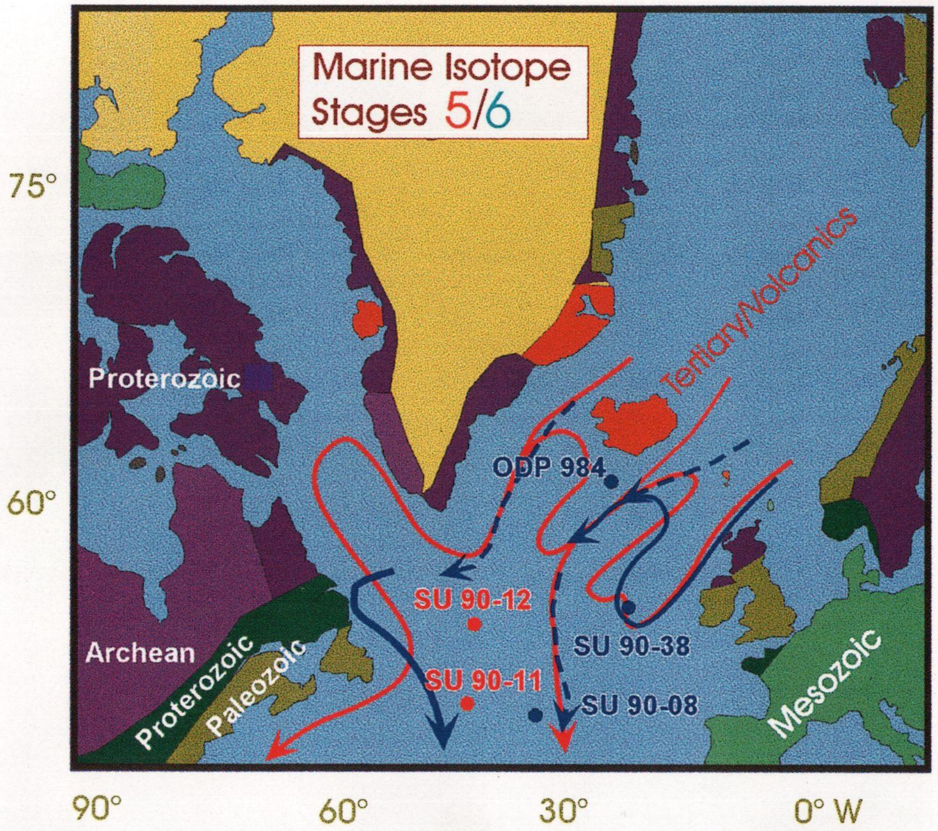

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Fig. 3. Schematic map of the North Atlantic showing the reconstructed variation of the pattern of deep water flow between interglacial stage 5 (red line) and glacial stage 6 (blue line). The schematic age distribution of exposed rocks on the adjoining continents is indicated on the map. Also given are five of the sampling points used to infer the changes in circulation.

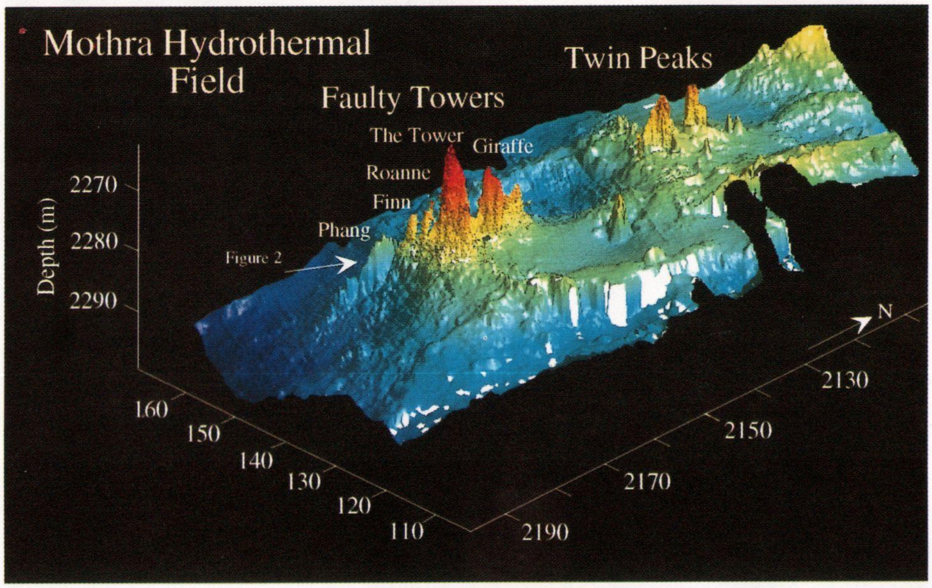

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Fig. 1. Three-dimensional image of the sulfide clusters Faulty Towers and Twin Peaks in the Mothra Hydrothermal Field generated using over 400,000 sonar data transmissions from the Jason ROV system gridded with spatial smoothing of 0.2–0.05 m. The Mothra Hydrothermal Field is the southern-most of four fields on the Endeavour Segment of the Juan de Fuca Ridge, which is located 290 km off the Oregon-Washington coast.