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DEEP-WATER CIRCULATION IN THE WESTERN EQUATORIAL ATLANTIC: INFERENCES FROM CARBONATE PRESERVATION STUDIES AND SILT GRAIN-SIZE ANALYSIS
Deep-water circulation in the western equatorial Atlantic: inferences from carbonate preservation studies and silt grain-size analysis

Dissertation
zur Erlangung des Doktorgrades
der Naturwissenschaften

am Fachbereich Geowissenschaften
der Universität Bremen

vorgelegt von
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Bremen, 2002
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Abstract

The period of Pliocene-Pleistocene climate may be considered the most interesting one of the entire Earth’s history. To explain the cyclic changes between climatic extremes requires studying both, the heat exchange between low and high latitudes and the concentration of greenhouse gases (e.g., CO₂) in the atmosphere. Both of these topics are intimately tied to the world oceans by the global thermohaline circulation which controls the distribution of heat, salt and chemical components. In this thesis, Ocean Drilling Program (ODP) sites from the western equatorial Atlantic and the Caribbean were selected to reconstruct changes in the deep-water layers, e.g., Lower North Atlantic Deep Water (LNADW, ODP Site 927), Antarctic Bottom Water (AABW, ODP Site 929), and at intermediate levels, e.g., Antarctic Intermediate Water (AAIW) and Upper North Atlantic Deep Water (UNADW, Site 999). For this purpose, deep water physical and chemical properties were reconstructed using a multi-parameter approach in order to monitor the history of Atlantic deep-water circulation throughout the Pliocene-Pleistocene.

Geochemical proxies, such as the paleo-nutrient content (benthic foraminifer δ¹³C) and carbonate corrosiveness were used to estimate past changes in the vertical depth distribution of deep-water. Changes in the geostrophic flow of deep water were interpreted through estimates of varying bottom-current intensity. Records of mean-grain size in the terrigenous silt fraction (mean sortable silt = mean_{ss}) were produced using a Micromeritics SediGraph 5100 to estimate paleo-bottom-current intensity. Changes in deep water mass carbonate corrosiveness were estimated from planktonic foraminiferal shell preservation and from grain-size analysis of the calcareous silt fraction.

Inferred from the mean_{ss} record of site 927, three end-member modes of LNADW circulation were proposed for the Pleistocene: (1) The interglacial mode of strong circulation with coarse mean_{ss} values, indicating strong bottom currents and, hence, vigorous LNADW, (2) A slowdown of circulation within the LNADW cell, indicated by overall finer mean_{ss} values at site 927, operating preferentially during glacial periods, (3) A scenario of episodic shutdown of circulation at the glacial to interglacial transitions, indicated by extremely fine mean_{ss} minima (~12 μm), which suggest an absence of significant bottom-current vigor.

During mode (2) the deep water was more poorly ventilated compared to the interglacial mode (1), as indicated by its lower glacial benthic δ¹³C values. In addition, a higher carbonate corrosiveness of deep water is indicated by an overall worsening of planktonic foraminiferal preservation in mode (2) intervals, and grain-size analysis reveals an enrichment of the 2-10 μm fraction in the calcareous silt component. This is interpreted to reflect higher contents of finer-grained coccoliths, which are more resistant to dissolution than the larger foraminiferal fragments (~10-63 μm). By contrast, the interglacial mode (1) is characterized by higher benthic foraminiferal δ¹³C values and by generally good carbonate preservation.

During the Pleistocene, the most pronounced change occurs during the mid-Pleistocene climate transition between 1.1 and 0.9 Ma. It is characterized by a considerable decrease in bottom-
Iniferal preservation during glacial periods is recognized in the LNADW flux to the Atlantic Ocean. These fundamental changes are due to the glacial ice-shield build-up in the Northern Hemisphere, the shutdown of circulation scenarios (~1.0-0.3 Ma).

LNADW circulation is recognized between planktonic foraminifers and relatively high 818O values. A fundamental change is registered in the glacial ice sheets around N.-America, with an increase in the mean(SO4)2--minima and a reduction in bottom-current intensity and carbonate productivity, introducing the Pleistocene seawater during glacial periods.

For the Pleistocene, a stepwise decrease in the average carbonate preservation at the Ceara Rise. This indicates a reduction in its contribution to the sediment.

Foraminifers at ODP site 999, where a trend toward the Pleistocene is seen. This indicates waters through the Caribbean sill front and LNADW relative to AAIW to the Atlantic Ocean.

The Pleistocene is characterized by a significant change in the oceanic circulation, with phases of more intense and less intense circulation. The changes in carbonate preservation are linked to changes in oceanic circulation and carbonate productivity. The Pleistocene phase is marked by a decrease in bottom-current intensity and carbonate productivity, introducing the Pleistocene seawater during glacial periods.

The decrease in carbonate preservation is linked to changes in oceanic circulation, with phases of more intense and less intense circulation. The changes in carbonate preservation are linked to changes in oceanic circulation and carbonate productivity. The Pleistocene phase is marked by a decrease in bottom-current intensity and carbonate productivity, introducing the Pleistocene seawater during glacial periods.

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arktisches Bodenwasser (AABW) und Zwischenwässer (e.g. Antarktisches Zwischenwasser (AAIW) und Oberes Nordatlantisches Tiefenwasser (UNADW)) untersucht. Als indirektes Maß für die Strömungseffizienz der Wassermassen liefern Korngrößenuntersuchungen der terrigenen Grobsiltfraktion Hinweise für die Intensität von Bodenströmungen. Anhand des Erhaltungszustandes planktonischer Foraminifersenchalen wurde die Carbonatkorrosivität der Wassermassen abgeschätzt, welche in hohem Maße von ihrer CO₂-Konzentration abhängig ist.

Die Studien wurden an ODP-Bohrungen der Ceará-Schwellen (Leg 154, Site 927 und Site 929), welche auf halbem Wege zwischen den Quellgebieten beider Tiefen- und Zwischenwassermassen positioniert ist, und in der Karibik an ODP Bohrung 999 in ausgewählten Zeitintervallen der vergangenen ~3,5 Ma durchgeführt.

Für das Pleistozän wurden drei unterschiedliche Stadien der Zirkulation identifiziert:


Langzeitvergleiche zwischen den Bohrungen aus dem westlichen aquatorialen Atlantik und der Karibik dokumentieren die gegensätzlichen Trends in der Carbonaterhaltung zwischen dem Tiefenwasser- und dem Zwischenwasserstockwerk seit dem späten Pliozän. Allgemein gute Karbonaterhaltung im Zeitabschnitt zwischen 3,4-2,6 Ma kennzeichnet den relativ großen Einfluß von unterem NADW im westlichen aquatorialen Atlantik (Ceará-Schwelle, Site 927). Ein deutli-
cher Wechsel zu generell schlechterer Karbonaterhaltung in Glazialen deutet hier auf den Beginn des sich allmählich verringernden Einflusses von unterem NADW ab etwa 2,75 Ma mit eingehender Verflachung der Lysokline in den Glazialen hin. Demgegenüber offenbart die Bohrung 999 in der Karibik einen generellen Trend zu bessereer Karbonaterhaltung seit dem späten Pliozan und deutet damit auf einen stärker werdenden Einstrom von UNADW über die Passagen der karibischen Schwellenfront und damit auf eine höhere Aktivität der Zwischenwasserschleife.
Part I: Introduction

1.1 The influence of deep- and surface-water circulation on global climate

Heat transport via oceanic currents compensates for about one half of the differences in the energy budget between low- and high- latitude regions that are caused by the pole- to- equator gradient of incoming solar radiation. Broecker et al. (1985) and Gordon (1986) introduced the concept of a "global thermohaline conveyor belt" connecting the oceans and enabling the inter-oceanic and meridional exchange of heat and salt. The conveyor is driven by the sinking of saline surface waters in the northern North Atlantic, producing the North Atlantic Deep Water (NADW) between 60 and 80 °N. Today, a volume of about 15 Sv of NADW (Ganachaud and Wunsch, 2000, 1 sverdrup=10^{15} m^3 s^{-1}) enters the Atlantic Ocean, mainly through the Greenland-Iceland-Scotland Ridge at 65 °N. The main body of NADW flows via the Deep Western Boundary Current (DWBC) southward across the equator, and finally joins the Antarctic Circumpolar Current (ACC, e.g., Gordon, 1996). Via the ACC, NADW is contributed to the Indian and Pacific Oceans where it flows northward again to the equator. Upwelling of these cold deep waters in the equatorial region of the Indian Ocean at around 50 °N in the North Pacific leads to a renewal there of intermediate and surface waters.

In the Indian Ocean the intermediate waters rise to a depth of several hundreded meters, and flow in part southwestward around the Cape of Africa where they enter the South Atlantic again. The remaining portion merges with the ACC and returns to the South Atlantic through the Drake Passage. In the Pacific upwelling region, intermediate waters rise to the uppermost layers. Through the Indonesian Seas and the Indian Ocean these waters are again introduced into the South Atlantic gyre, which subsequently feeds the Gulf Stream. Via the Gulf Stream, the North Atlantic Drift, and the Norwegian Current warm and saline surface waters are transported to the north where their marginal vortices are deflected westward and are injected into the formation area of NADW (Fig. 1). Together, these waters account for about 95 % of the ~15 Sv that leave the Atlantic Ocean via the NADW. A small additional amount (~0.8 Sv) is derived from the Arctic Seas through the Bering Strait (Ganachaud et al., 2000).

The Atlantic Ocean plays a key role in the maintenance and efficiency of Global Thermohaline Circulation (GTC) because it is only here that the production of deep waters occurs. The production is the result of the density difference between the water in the Atlantic and the other oceans due to the high salt concentration of the Atlantic, which exceeds that of the Pacific and Indian Oceans by an average of about 1 %. For example, the 2-3 %, lower salinity of the North Pacific (as compared to the North Atlantic) would be too low for the formation of deep water even if the surface water were cooled to the freezing point (~ -1.8 °C). Accordingly, the salinity difference between the Atlantic Ocean and the Pacific and Indian Oceans is a crucial factor for the maintenance of GTC.

The Atlantic-Pacific salinity difference results from the atmospheric net export of fresh water from the Atlantic-Caribbean basins to the Pacific Ocean, which is driven by major wind systems
Fig. 1: Flow paths of major deep-water currents in the modern Atlantic (modified after Reid, 1996; Sarnthein et al., 1994; Faugère et al., 1993, Peterson and Strammer, 1991): AABB, Antarctic Bottom Water; AAIW, Antarctic Intermediate Water; ACC, Antarctic Circumpolar Current; NADW, North Atlantic Deep Water; UNADW, Upper North Atlantic Deep Water. Surface currents (hatched arrows) important for the global thermohaline circulation: AC, Angola Current; BC, Brazil Current; BOC, Benguela Oceanic Current; GS, Gulf Stream; NAD, North Atlantic Drift; NBC, North Brazil Current; NC, Norwegian Current; SAC, South Atlantic Current; SEC, South Equatorial Current.
Part I: Introduction

and the continental orography (e.g., Broecker and Denton, 1989). The greatest loss of fresh water is accomplished by the tropical trade wind system, which carries about 0.2 Sv of water-vapor across the narrow and low-lying land bridge of Panama (Broecker and Denton, 1989, Weyl, 1968). By contrast, there is no similar transport from the Indian Ocean across the African continent. In addition, the import of water-vapor via the Northern Hemisphere west wind drift is blocked by the barrier of the Rocky Mountains, while comparatively more water-vapor is delivered across the Eurasian continent to the Pacific. The resulting net loss of fresh water of about 0.4 Sv (Broecker and Denton, 1989) would lead to a salinity increase in the Atlantic Ocean of about 1.4 ‰ within a thousand years if not compensated for by the export of highly saline NADW.

One very important aspect of the conveyor is the considerable amount of heat it absorbs, carries, and releases to the atmosphere. Today, the Northern Hemisphere benefits considerably from the oceanic heat transport as it receives enormous amounts of heat. Based on hydrographic data from the World Ocean Circulation Experiment (WOCE), Ganachaud and Wunsch (2000) estimate an oceanic heat release of about 1.7 PW (1 petawatt=10^{15} W) to atmosphere north of 25°N.

As a result of the sinking of surface waters in the northern North Atlantic (maintaining a strong undertow there), salty and heat-bearing surface currents from equatorial regions are enabled to push forward far to the north. As a consequence, the main part of the global oceanic meridional heat transport, occurs through the Atlantic. For example, Ganachaud and Wunsch (2000) estimated a northward heat transport in the North Atlantic of 0.6 PW (zonally integrated at 40 °N). Model simulations have suggested that changes in the rate of oceanic heat transport can have a large impact on atmospheric temperature and pressure gradients, and thus, on climate (e.g., Manabe and Stouffer, 1988, Marotzke and Stone 1995).

1.2. Atlantic deep-water oceanography

1.2.1. Production, distribution and flow paths of Atlantic deep-water masses

Atlantic deep-water production is concentrated near the northern and southern polar regions (Fig. 1). The major NADW production sites are located in the Norwegian-Greenland Sea (NGS) where Lower NADW (LNADW) is produced, and in the Labrador Sea where the less dense Upper NADW (UNADW) is produced before it moves into the intermediate Atlantic. Large amounts of surface water must compensate for the deep-water export in the Atlantic, thus enforcing the strong meridional northward-flowing surface currents, including the Gulf Stream, the North Atlantic Drift and the Norwegian Current. Therefore, NADW production can be considered as the main driver for the GTC and meridional heat transfer.

The deepest regions of the Atlantic are occupied by Antarctic Bottom Water (AABW), which flows northward across the equator and partly mixes with LNADW. AABW is a mixture of Weddell Sea Deep Water and very old waters originating from the Circumpolar Deep Water (Reid, 1996, Siedler et al., 1996). Hence, since no significant amounts of surface water are involved in the AABW formation, no similar meridional surface-current system heating the Southern Hemisphere analogous to the Gulf Stream can develop. Therefore, the AABW is of only minor importance for the global oceanic heat transfer (Broecker and Denton, 1989).
On their journeys across the equator AABW and LNADW fill the major Atlantic Ocean basins (Fig. 1). Influenced by the Coriolis Force, the main streams flow as DWBC near the continental slope in the western Atlantic. However, small amounts of northern- and southern-source deep waters can enter the eastern Atlantic through the Romanche Fracture Zone (Fig. 1). Today, total NADW production rates amount to ~15 Sv in the North Atlantic. However, the NADW stream increases as a result of mixing with southern-source deep waters to 23 Sv (Ganachaud and Wunsch, 2000) before it leaves the South Atlantic at 30°S and merges with the ACC.

The ACC is the largest current system on earth, transporting water at a rate of 100-140 Sv around the Southern Ocean (Ganachaud and Wunsch, 2000, Orsi et al. 1995). It is of great importance for the GTC, as it provides the linkage among the world oceans and thus acts as a main controller for the distribution of heat and salt around the globe (e.g., Nowlin and Klinck, 1986).

AABW formation has been estimated as about 21 Sv, produced mostly in the Weddell Sea and in the Ross Sea (Ganachaud and Wunsch, 2000). Bottom-water inflow to the South Atlantic at 30°S has been estimated at ~6 Sv (Ganachaud and Wunsch, 2000).

At intermediate water depths (>2000 m) the Atlantic is occupied by UNADW and southern-sourced waters (Antarctic Intermediate Water=AAIW). Today a mixture of these water masses penetrates through the Caribbean sill front (1600-1800 m) and occupies the deep Caribbean basins (e.g., Haddad and Droxler, 1996, de Menocal, 1992).

1.2.2. Deep-water physical and chemical properties and their potential for tracing past ocean circulation

Due to the different initial composition of contributing source waters, northern- and southern-source deep- and intermediate water masses can be clearly distinguished by their chemical properties. Because of the significant quantities of surface waters in the source region, NADW is relatively warm and saline. It is nutrient-depleted, O₂-rich, and in low CO₂ content. Accordingly, NADW has high CO₃²⁻ concentrations (Fig. 2a) and (due to its low nutrient content) the isotopic composition of the dissolved CO₂ (ΣCO₂) is marked by high ¹³C concentrations (Kroopnick, 1980).

As an older water mass, AABW is O₂-depleted, nutrient-rich, and has high CO₂ concentrations. Accordingly, it has low δ¹³C values of ΣCO₂ and due to its high CO₂ concentration, it is for the most part undersaturated with CO₃²⁻ (Fig. 2b). In the Atlantic Ocean, the relatively warm NADW overrides the denser AABW. The transition zone between the two water masses is marked by decreases in temperature, salinity, ¹³C concentration of ΣCO₂ and CO₃²⁻ concentrations (Fig 2a).

The difference in the chemistry of Atlantic deep-water masses has encouraged many investigators to apply geochemical proxies for the study of past ocean circulation. Table 1 sketches some deep-water properties that are important for tracing past ocean circulation. Changes in carbonate preservation and in epibenthonic foraminiferal δ¹³C (recording the ¹³C composition of bottom-water CO₂) have been most often used for the detection of past variations in the vertical depth distribution of NADW and AABW in the Atlantic Ocean (e.g., Bickert et al., 1997a,b, Curry and Cullen, 1997, Cullen and Curry, 1997, Henrich et al., in press, Tiedemann and Franz, 1997,
Fig. 2: a) Vertical distribution of deep- and intermediate-water masses in the western Atlantic using \( \text{CO}_3^2^- \) concentration (umol/l) calculated from GEOSecs data after Bainbridge (1981). b) Calcite corrosiveness of deep water estimated from Delta \( \text{CO}_3^2^- \) concentration (umol/l) calculated from GEOSecs data (Geosecs, 1999). Today the hydrographical calcite lysodine is linked to boundary between LNADW and AABW (e.g. Bickert et al., 1997, Tiedemann and Franz, 1997). AABW, Antarctic Bottom Water; AAIW, Antarctic Intermediate Water; NADW, North Atlantic Deep Water.
Part I: Introduction

Curry, 1996, Sarnthein et al, 1994). However, the stable carbon isotope ratio ($^{13}$C/$^{12}$C) determined in living benthonic foraminiferal species are also affected by temperature, availability of nutrients, respiration of organic carbon, and carbonate concentration (e.g., Broecker and Peng, 1982, Spero et al., 1997, Mackensen et al., 1993). Bottom-water carbonate-ion concentration may be influenced by respiration-driven carbonate dissolution (e.g., Emerson and Bender, 1981). Additionally, the Cd/Ca and Ba/Ca elemental ratios are subject to thermodynamic effects (Boyle, 1988). More recently, neodymium and lead isotope ratios measured in ferromanganese crusts grown on foraminifer shells were successfully applied to monitor changes in Atlantic deep-water circulation (e.g., Rutberg et al., 2000, Abouchami et al., 1999). Their isotopic compositions are related to the radioactive decay within the continental crust surrounding the source regions of deepwaters and is not subject to modifications by uptake, dissolution, respiration etc. (von Blankenburg, 1999).

### Table 1: Deep-water properties preserved in benthonic foraminifer shells.

<table>
<thead>
<tr>
<th>Proxy</th>
<th>NADW</th>
<th>AABW</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{13}$C of $\Sigma$CO$_2$</td>
<td>~1.1 %o*</td>
<td>~0.3 %o*</td>
<td>Curry et al., 1988, Mackensen and Bickert, 1999</td>
</tr>
<tr>
<td>[CO$_2^{\text{aq}}$]</td>
<td>high</td>
<td>low</td>
<td>Boyle, 1988, Martin and Lea, 1998</td>
</tr>
<tr>
<td>Ba/Ca</td>
<td>low</td>
<td>high</td>
<td>O’Nions et al., 1998, v. Blankenburg, 1999</td>
</tr>
<tr>
<td>$^{144}$Nd/$^{144}$Nd</td>
<td>e=-13.5**</td>
<td>e=-9.0**</td>
<td></td>
</tr>
<tr>
<td>$^{207}$Pb/$^{206}$Pb</td>
<td>0.815**</td>
<td>0.830**</td>
<td></td>
</tr>
</tbody>
</table>

Initial composition of deep water. Values measured in ferromanganese crusts grown on benthic foraminiferal shells. Citations refer to studies providing a broader discussion of the applicability of the respective proxies.

However, physical oceanographers, using hydrographical data (e.g., temperature, salinity, and density) and anthropogenic tracers, such as chloro-fluoro-carbons (CFC), and tritium, were able to distinguish six different water layers in the tropical western Atlantic (e.g., Rhein et al., 1998, Rhein et al., 1996, Rhein et al., 1995). The uppermost layer (1200-1900 m) consists of the shallow upper NADW (SUNADW), which presumably originates from the southern Labrador and Irminger Seas. This water mass can be clearly distinguished from the classical Labrador Sea water (1900-2400 m) by its high CFC concentrations. In the deep-water layer, an older water mass (LNADW-old, 2400-3450 m) with low CFC concentrations can be distinguished from a layer with high CFC contents (Overflow-LNADW, 3450-3900 m) produced presumably in the NGS (Rhein et al., 1996). The deepest layer is the AABW, which is characterized by lower salinity, temperature and CFC (Rhein et al., 1996). The higher CFC concentrations of SUNADW and OLNADW reflect a more recent renewal of these waters (Rhein et al., 1996), and thus pointing to a more efficient production and circulation at present.

For paleoceanographers these results show that deep-water circulation during the past may have been subject to a much wider range of interactions than previously believed. Furthermore, this
imply that past variations in deep-water circulation cannot be adequately described with models using flat-terms like NADW and AABW.

1.3. The variability of Atlantic deep- and intermediate-water circulation

Since the intensification of Northern Hemisphere glaciation 2.75 m.y. ago (e.g., Thiede et al., 1998, Jansen and Sjøholm, 1991, Shackleton et al., 1984, Raymo et al., 1992) the production of northern-source deep waters and hence, Atlantic deep-water circulation is strongly linked to the glacial-interglacial climatic cycles (e.g., Henrich et al., in press, Haug and Tiedemann, 1998, Tiedemann and Franz, 1997, Raymo et al. 1990).

A diminished contribution of LNADW to the Atlantic Ocean basins during glacial periods has been suggested by a rapidly growing number of $\delta^{13}$C and carbonate preservation studies. Most of these studies consistently indicated a shallowing of the carbonate lysocline and the steep $\delta^{13}$C gradients that mark the transition zone between LNADW and AABW today (e.g., Bickert et al., 1997a,b, Curry and Cullen, 1997, Cullen and Curry, 1997, Henrich et al., in press, Tiedemann and Franz, 1997, Curry, 1996 Sarthein et al., 1994, Oppo et al., 1995, Raymo et al., 1997, Raymo et al. 1990). These changes are commonly explained by vertical redistributions of NADW and AABW controlled by varying production rates of NADW (e.g. Bickert et al., 1997a,b, Curry and Cullen, 1997, Cullen and Curry, 1997, Henrich et al., in press, Tiedemann and Franz, 1997, Curry, 1996 Sarthein et al., 1994, Oppo et al., 1995, Raymo et al., 1997, Raymo et al., 1990).

A crucial drawback of all geochemical studies is, however, that they in fact principally monitor past variations of the relative deep-water mass proportions of northern and southern deep waters in the water column. Therefore, they are impracticable for the estimation of the efficiency (e.g., the mean geostrophic flow velocity) with that these water masses circulate. For example, long-term current meter mooring measurements and geostrophic calculations reveal the highest mean geostrophic velocities in the DWBC to be between 10 and 20 cm s$^{-1}$ (Schott et al., 1993, Molinari et al., 1992) in the equatorial Atlantic. It is clear, that changes in the mean velocity may have a large impact on the mean transport rates of the GTC and thus are a crucial point concerning the meridional heat exchange (e.g. Rhein, 1994). Therefore, estimating the efficiency of geostrophic flow during the past would considerably improve our knowledge about the linkage between deep-ocean circulation and climate (e.g. Berger and Wefer, 1996).

In this thesis both the chemical and physical properties of deep-water are considered to estimate past changes in deep- and intermediate-water circulation. Variations in the flux of northern- and southern-source deep- and intermediate-water masses to the Atlantic Ocean are hereby inferred from carbonate preservation investigations in the tropical Atlantic and in the deep Caribbean. Past changes in the mean geostrophic flow within the core layers of AABW and LNADW are investigated by studying the history of bottom-currents intensity inferred from grain-size analysis of the terrigenous sortable silt fraction (McCave et al., 1995).
Part I: Introduction

1.4. Study area and core locations

1.4.1. Western equatorial Atlantic
For the study of deep-water circulation, Ocean Drilling Program (ODP) Sites from the Ceará Rise depth transect (Leg 154) in the Guyana Basin were selected (Fig. 3). The western equatorial Atlantic is the main passage for the Atlantic deep-waters, bundling them into narrow basins bordered by the Mid Ocean Ridge (MOR) and the South American Continental Margin (SCM). Therefore, the western tropical Atlantic is a key area for studying both the present-day and past deep-water mass distributions and the geostrophic flow along the DWBC (e.g. Bianchi et al., 2001, Bickert et al., 1997a,b, Curry and Cullen, 1997, Hall et al., 1997, Tiedemann and Franz, 1997, Curry, 1996. Oppo et al., 1995, Raymo et al., 1997, Rhein et al., 1996, Schott et al., 1993). Located at a central position about half the distance between the MOR and the SCM, the Ceará Rise truncates the deep-water masses below depths of ~3000 m. West of the Rise the sloping topography between the Amazon cone and the southwest flank of the Ceará Rise serves as a barrier for waters below 4250 m (Whitehead and Worthington, 1982). Because of this and the strong flow of LNADW, AABW flow is restricted to the west of the Rise (Rhein et al., 1998, Whitehead and Worthington, 1982). In contrast, the strong flow of LNADW has been traced by CFC on both sides of the Ceara Rise (Rhein et al., 1996).

However, lateral and vertical fluctuations in the paleo-position of the axis of the fast-flowing DWBC may have considerably influenced the local bottom-current velocity, and could have disturbed or overprinted the physical deep-water signal relating to real variations in the GTC (Bianchi et al., 2001). Since the Ceará Rise is located at a position far removed from the axis of the DWBC, it is ideally situated for the reconstruction of paleophysical deep-water properties caused by variations in GTC.

Today, the vertical transition zone from the net southeastward flow (LNADW) to the net northwestward flow (AABW) is located in the depth interval between 3900 and 4100 m (Rhein et al., 1998, Hall et al., 1997). Remarkably, this is close to the AABW/LNADW boundary inferred from geochemical data. The hydrographical cacite lysocline lies at around 4100 m (Fig. 2b), which is in good agreement with the foraminiferal lysocline in the tropical Atlantic (4100 m) reported by Cullen and Curry, 1997. Furthermore, GEOSECS data (Kroopnick, 1980) reveal strongest gradients δ¹³C of ΣCO₂ at around 4000 m. All these facts considered, it is reasonable to consider the AABW/LNADW boundary at around 4000 m in the study area.

Drilled in ~3300 m of water in the Guyana Basin, ODP Site 927 is positioned well within the core of southeastward flowing LNADW (e.g. Rhein et al., 1996, Schott et al., 1993, Molinari, 1992). Site 929, the deepest site recovered during Leg 154, was drilled at a water depth ~4300 m, which lies well within the northwestward-flowing AABW layer (e.g., Hall et al., 1997, Rhein et al., 1998, Rhein et al., 1996).

Geostrophic calculations revealed a total of ~13 Sv of LNADW (3100-4100 m or 1.8°-2.4°C) arriving northwest of the Ceará Rise (Molinari et al., 1992, Speer and McCartney, 1991). While small volumes recirculate it was estimated that the main share of these waters (7 Sv) passes the

¹ level where a maximum rate of change in their foraminiferal preservation index (=fragmentation of planktonic foraminifers) occurs
Fig. 3: Map showing the Guyana basin and the location of investigated ODP sites on the northeastern flank of the Ceará Rise. Deep water hydrography refers to Rhein et al., 1998, Rhein et al., 1996, and Hall et al., 1997. Due to the sloping topography between the Amazon cone and the Ceará Rise most of LNADW passes northeast of the Ceará Rise through the Guyana Basin; the deeper AABW is restricted on the northwestern side.
Ceará Rise at its northeastern flank (Fig. 3, Rhein et al., 1996, Schott et al., 1993). These estimations indicate that considerable amounts of LNADW are also deflected eastward by the narrowing topography between the Amazon cone and the Ceará Rise. Current-meter mooring profiles deployed at 44°W on the continental margin west of the Amazon Fan revealed maximal mean southeasterly flow velocities in the UNADW and LNADW cores of 30 and 15 cm s\(^{-1}\) respectively (Schott et al., 1993).

For the AABW layer an inflow of about 2.0-2.6 Sv through the southern equatorial channel into the Guyana Basin was estimated from a moored array near the equator and also deduced from mass balance considerations (Hall et al., 1997, Rhein et al., 1998, Rhein et al., 1996, Rhein et al., 1995). Combined hydrographic tracer data, and directly measured velocity profiles revealed a total of 1.9-2.2 Sv AABW passing through the Guyana Basin northeast of the Ceará Rise while the rest recirculates (Rhein et al., 1998).

The Ceará Rise sediments consist mainly of calcareous planktonic foraminifera and their fragments, nannofossil ooze and various amounts of terrigenous material. Biogenic opal content is low and does not exceed 1% (Curry et al., 1995). Most of the fine terrigenous sediment deposited on the Ceará Rise originates from the nearby Amazon River. Its transport is controlled by interactions between the Amazon freshwater plume and the equatorial surface-current system (Rühlemann et al., 2001). Therefore, during the past 380 k.y. the terrigenous sediment supply varied with a strong 23 k.y. precessional periodicity, and was dependent on both the distance of the Amazon River mouth to the shelf edge and the flow direction of the Amazon freshwater plume (Rühlemann et al., 2001, Tiedemann et al., 1997). Rühlemann et al. (2001) proposed that during colder climatic stages the North Brazil Current retroreflection was strengthened, resulting in a more vigorous eastward flow of surface waters.

1.4.2. Caribbean

In this thesis, changes in the intermediate water layer are interpreted based on carbonate preservation investigations. Figure 2a illustrates that both AAIW and AABW have relatively low carbonate-ion contents. Because AAIW is at much shallower depths in the Atlantic Ocean, however, undersaturation with respect to calcite is attained only in the AABW layer (Fig. 2b). This is because at the first order the solubility of calcite increases with increasing water pressure, and so, the AAIW dissolves only aragonite. Accordingly, past changes in the carbonate-ion concentration in the intermediate Atlantic can be well characterized by investigating the preservation of aragonitic pteropod shells (e.g., Gerhard and Henrich, 2001).

However, since the abyssal plains of the Caribbean basins are occupied by Atlantic intermediate water masses (up to 5000 m waterdepth), this is an is an ideal region for studying changes in Atlantic intermediate water circulation employing the preservation of calcitic shells (e.g., planktonic foraminifera, see manuscript 2 in Part II, Volbers and Henrich, in press, Haug et al., 1998, Haddad and Droxl er, 1996, Droxl er et al., 1991).

In this thesis, we focus on past changes in the relative proportions of AAIW and UNADW entering the deep Caribbean. For this purpose, sediment cores from ODP Site 999 (Leg 165), located at ~2800 m waterdepth in the Colombian Basin (12°45'N, 78°44'W) were examined (manuscript 3).
Hole 999A recovered a continuous turbidite-free Pliocene-Pleistocene section, recording the deep-water chemical and physical history of the western Caribbean (Sigurdsson et al., 1996). Site 999 cores consist predominantly of nannofossil clayey mixed sediments with foraminifers and low dispersed ash content (Sigurdsson et al., 1996). Biogenic opal is negligible. The terrigenous material originates mainly from the Andes supplied by the Magdalena River sediment discharge and (Peters et al., 2000).

2. Methodical approach and laboratory analyses

The methods and laboratory procedures employed in this study are described in detail in the respective manuscripts. An analytical flow chart for all the methods used in this thesis is presented in Fig. 4. In general, changes in deep-water chemistry (here used to infer variations in the contribution of northern- and southern-source water masses to the Atlantic Ocean) are reflected by carbonate chemistry and \(^{13}C\) concentration in benthonic foraminifera. Variations in the physical flow characteristics of deep waters are inferred from silt texture characteristics which are sensitive to variations in the strength of bottom-current flow (see below, McCave et al., 1995).

2.1. Deep-water carbonate chemistry

Changes in deep-water carbonate chemistry were estimated by bulk sediment parameters (e.g., % CaCO\(_3\), % >63 μm fraction), and by examining the fragmentation of planktonic foraminiferal shells. The use of the latter parameter is based on the weakening and breakage of foraminiferal shells with progressive dissolution, which leads to an enrichment of foraminiferal fragments in the >63μm fraction and hence to a mass transfer from coarser to finer fractions (Berger et al., 1982). However, the use of bulk carbonate and sand content has to be considered with caution, because both of these parameters are strongly influenced by variations in the ratio between nannofossils (e.g., coccolithophores) and other microfossils (e.g., foraminifera), and by the amount of dilution by non-CaCO\(_3\) material. In manuscript 3 a new proxy, generated from the grain-size distribution of the calcareous silt component is introduced that is more independent of these disturbing influences. A detailed overview of well-established carbonate preservation proxies is given in Volbers and Henrich (in press) and Dittert et al. (1999).

Bulk sediment carbonate contents was determined with a Leco CS 300 infrared elemental analyser. The procedure includes the determination of TC (=Total Carbon) and TOC (Total Organic Carbon) contents in a homogenized subsample. Calcium carbonate content was then calculated by

\[
\text{CaCO}_3 \text{ wt.-%} = (\text{TC wt.-%}-\text{TOC wt.-%}) \times 8.33
\]

The bulk sand content was determined by washing about 20 cm\(^3\) of bulk sediment over a 63 μm sieve and is given in wt.-% of bulk sediment. Further description of analytical and laboratory procedures is provided in all three manuscripts in Part 2.
Part I: Introduction

Fig. 4: Flow-chart of lab methods.
2.2. Stable carbon and oxygen-isotope chemistry and stratigraphy

All benthonic (C. wuellerstorfi) $\delta^{13}$C and $\delta^{18}$O proxy records and depth-age models for ODP Sites 927 and 929 are taken from Bickert et al. (1997b). Stratigraphical framework for ODP Site 999 has been provided by Haug and Tiedemann (1998) and Sigurdsso n et al. (1996).

2.3. Inference of paleo-bottom-current intensity from silt-grain size analysis

Figure 5 illustrates the effect of bottom-current induced sediment sorting on the size distribution of sediment deposited on the Nova Scotian Rise (McCave, 1985).

Significant sorting effects become apparent under moderate and strong bottom-current conditions. With increasing current velocity sediment sorting becomes better, and progressively better defined modal values are displaced toward the coarser end of the spectrum. Because sediment particles become more cohesive with decreasing diameter, those finer than $\sim 10 \mu m$ may be transported as aggregates in the viscous sublayer (McCave et al., 1995). The implications are that (1) the critical bed shear stress for particle erosion increases progressively below $10 \mu m$, and (2) bottom currents do not sort sediment finer than $10 \mu m$. Thus, only the $>10 \mu m$ fraction is considered for the inference of bottom current induced sediment sorting (McCave et al., 1995).

To evaluate the limitations of grain-size based interpretations of bottom-current intensity the dynamical origin of geostrophic currents must be enquired. Sorting occurs primarily by repeated resuspension and deposition of sediment (McCave et al., 1995). The shear velocity that works within the turbulent bottom boundary layer is related to the geostrophic velocity above it by:

$$V_{geostr.} = 30u_{shear} \text{ to } 22u_{shear} \text{ depending on a drag coefficient (McCave et al., 1995) that relates mainly to bottom roughness and the coriolis parameter (Weatherly, 1972).}$$

It is not possible, however, to actually define a relationship between mean silt-size parameters and paleobottom-current velocity. The reason lies in the dynamic origin of geostrophic currents.
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Figure 6. Time series of deep ocean currents measured near bed from the Hatton Drift and the Nova Scotian Rise (modified after McCave et al. 1995). Data from the Nova Scotian Rise refer to High Energy Benthic Boundary Layer experiment (HEBBLE site, Gross et al., 1991). $u_{crit}$ indicates flow speed where the critical erosion shear stress in the turbulent boundary layer is being attained for particles of a given diameter.

Figure 6 shows that deep-ocean currents may be subject to daily to weekly high-amplitude fluctuations in flow speed. Accordingly, sediment sorting is the result of a time integrated function of current velocity (McCave et al., 1995). Actually, it is not possible to determine whether a change in the mean particle size is the product of variations in mean speed or of variations in the frequency and/or amplitude of current velocity (McCave et al., 1995). Presently, this limits interpretations of grain-size related bottom flow parameters to comparisons of trends in relative bottom-current intensity rather than permitting absolute estimates of current speed.

Despite the ambiguous nature of silt-size based current-speed parameters, however, a new study has developed a reliable empirical calibration at distinct transects in eastern and western Atlantic Ocean basins (Frenz and Henrich, in prep.).

2.3.1. Grain-size measurements

In this thesis both the lithogenic (carbonate-free) and biogenic silt components have been investigated following the standard technique of McCave et al. (1995). After separating the sand fraction (>63 μm) by wet sieving the clay fractions (<2 μm) was removed according to Stokes' law using Atterberg settling tubes (Fig. 4). A detailed grain-size analysis of the extracted bulk silt was performed with a Micromeritics SediGraph 5100. The SediGraph determines the particle-size distribution from a dispersed suspension in an analysis cell, assuming Stoke’s settling. A detailed description of the measurement principle is given by Stein (1985). The particle size is expressed in diameters of equivalent settling velocity and is calculated as:

$$d = \left[ \frac{18 \eta \nu}{(D_1-D_2)g} \right]^{0.5},$$

where

- $\eta$ = viscosity of the settling liquid (0.7073 cp for water at 36.3°C)
- $\nu$ = settling velocity
- $D_1$ = particle density (set at 2.65 for quartz)
- $D_2$ = liquid density (0.9936 g/cc for water at 36.3°C)
- $g$ = acceleration by gravity (982 cm/s²)
After the first run measuring the bulk silt the sample was treated with ~12% HCl to remove the carbonate. In a second run the grain-size distribution of the terrigenous (lithogenic, since biogenic opal is absent) silt was determined. The grain-size distribution of the calcareous silt \( f(d)_{\text{carbonate}} \) is given by the difference of the size distribution of the bulk silt \( f(d)_{\text{bulk silt}} \) minus \( (1-C) \) times the size distribution of the lithogenic residue \( f(d)_{\text{lithogenic silt}} \) the formula:

\[
 f(d)_{\text{carbonate}} = f(d)_{\text{bulk silt}} - (1-C) f(d)_{\text{lithogenic silt}}
\]

(McCave et al. 1995),

where \( C \) is the percentage of carbonate in the bulk silt.

Further description of the analytical and laboratory procedures is provided in all three manuscripts in Part II. The standard methods employed for these sedimentological determinations and their analytical errors are discussed in detail by McCave et al. (1995) and Bianchi et al. (1999).

Previous studies employing silt analysis for paleoceanographic interpretations have focused mostly on the terrigenous silt component, providing a sensitive tool for the inference of distinct environmental and oceanographic depositional-regimes (for example, sediment transport by ice or wind, bottom-current induced sediment sorting, turbidity currents, etc.). The calcareous silt component was excluded in most considerations because of the known uncertainties relating to the ecological and biological aspects of calcifying organisms. However, in manuscript 1, in Part II of this thesis, grain-size distributions generated from the calcareous fraction were successfully applied for distinguishing between the smaller nanofossil placoliths and larger juvenile foraminifers and foraminiferal fragments. At the Ceará Rise, variations in the ratio of these two components are caused mainly by selective dissolution (see manuscript 1 for a detailed discussion). These results show that detailed grain-size analyses of the calcareous silt fraction may have a great potential for rapid investigations of size-differentiated specimens (for example coccolithophores) in deep-sea sediments.

3. References
Bickert, T., Cordes, R. and Wefer, G. 1997a. Late Pliocene to mid-Pleistocene (2.6-0 Ma) carbonate dissolution in the western equatorial Atlantic: result of Leg 154, Ceará Rise. Proc. ODP. Sci. Results. 154, 229-237.
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Bickert, T., Curry, W.B., and Wefer, G. 1997b. Late Pliocene to Holocene (2.6-0 Ma) western equatorial Atlantic deep-water circulation: inferences from benthic stable isotopes. Proc. ODP. Sci. Results, 154, 239-254.


GEOSECS (1999): GEOSECS: Geochemical Ocean Sections Study, a global survey of the three-dimensional distribution of chemical, isotopic, and radiocarbon tracers in the ocean. The expeditions were in the Atlantic from July 1972 to May 1973.


Gerhard, S., and Henrich, R., subm. Intermediate water circulation during the last glacial maximum in the South Atlantic ocean inferred from changes in the shell preservation of Limacina inflata (Pteropoda). Subm. to Deep-Sea Res.I.


Part II of this thesis consists of three research papers that contribute to international activities in research, addressing the Pliocene-Pleistocene history of deep- and intermediate-water circulation. The first paper investigates the history of current strength and carbonate preservation at glacial-interglacial time-scales in the western equatorial Atlantic at ODP Site 927. The second paper focuses on long-term changes during the Pliocene-Pleistocene history of LNADW and UNADW circulation. The third manuscript provides a depth transect study, comparing the evolution of bottom-current strength and chemistry at deep- and intermediate water levels on the Ceará Rise depth transect. All papers are submitted to international journals. Their content are briefly described below.


In the first paper, glacial-interglacial changes in deep-water circulation were investigated at the Ceará Rise for the early- to mid-Brunhes epoch (0.8-0.3 Ma). For this purpose proxies for deep-water chemistry (benthic foraminiferal δ13C, carbonate preservation) and bottom-current intensity (mean grain-size of the 10-63 μm fraction) were employed. Silt grain-size analysis has been applied successfully in previous studies, but almost exclusively on sedimentary drifts in the northern North Atlantic. There, the bottom-current strength is primarily controlled by the strength of vertical deep convection, which is driven by the density contrast between the overlying water masses.

In this paper, for the first time, direct sedimentological evidence for considerable variations in LNADW circulation is presented at a location approximately 15,000 km downcurrent from the production area. Excellent covariation between geochemical and sedimentological proxies was found. During glacial periods, low benthic δ13C values and poor preservation of planktonic foraminiferal shells indicate a reduced LNADW flux to the tropical western Atlantic. Finer grain sizes indicate weaker bottom current-intensity in the LNADW, thus pointing to considerably reduced transfer rates of heat and salt in the glacial GTC.

A second aspect focuses on the effect that intense carbonate dissolution has on the particle-size distribution of the calcareous silt (2-63 μm). Previous studies comparing coccoliths and foraminiferal fragments (the main contributors to the calcareous silt) have indicated large differences in their resistance to dissolution. The two components can be easily distinguished in grain-size distributions, allowing the introduction of the wt.-% of 10-63 μm particles in the overall calcareous silt (2-63 μm) as a proxy for estimating carbonate dissolution. This proxy is independent of dilution by non-CaCO3 particles because only the calcareous silt is considered. Since particles finer than 63 μm offer a larger surface area for corrosive waters than larger and more massive particles, the new proxy is more sensitive to dissolution than other conventional proxies (e.g., wt.-% of sand, foraminiferal fragmentation indices).
Part II: Publications

(2) Variability of silt grain size and planktonic foraminiferal preservation in Plio/ Pleistocene sediments from the western equatorial Atlantic (ODP site 927) and Caribbean (ODP Site 999): Implications for the history of Atlantic Deep and Intermediate Water circulation. Gröger, M., Henrich, R., and Bickert, T. (Subm. to Palaeogeogr., Palaeoclimat., Palaeoecol.).

An important feature of Quaternary climate evolution is that the Earth's climate system has often jumped from one mode of operation to an other, thereby substantially influencing substantially ocean circulation. Addressing these large impacts, the second manuscript considers the Pliocene-Pleistocene evolution of deep- and intermediate-water circulation in the Atlantic Ocean and Caribbean Sea. In particular, two periods of fundamental climatic change are addressed: the initiation of large-scale northern hemisphere glaciation at ~2.75 Ma, and the mid-Pleistocene climatic transition (MPT) centered around 1 Ma. Most shifts observed in the tropical western Atlantic are probably linked to climatic and oceanographic changes in the source regions of Nordic deep and intermediate water, e.g., the northern North Atlantic and the Norwegian-Greenland-Sea. The most substantial change is registered contemporaneously with the introduction of large-scale continental ice shields in the Northern Hemisphere at 2.75 Ma. At site 927 a drastic decrease in carbonate preservation and a considerable reduction of bottom-current intensity during glacial periods is observed. A similar decrease in carbonate preservation and bottom-current intensity occurs with the transition from the more modest ice shields before the MPT to the large-scale ice shields thereafter. These observations portray a stepwise weakening of LNADW circulation from the mid-Pliocene to the Pleistocene. In contrast, an increasing contribution of UNADW to the Atlantic Ocean basins from the Pliocene to the Pleistocene intervals can be inferred from carbonate preservation studies at ODP site 999 in the Caribbean. The observed asymmetry in carbonate preservation between the deep Atlantic and deep Caribbean supports the idea of a flip-flop mechanism switching the Nordic deep-water production between modes of stronger intermediate-water (UNADW) and denser deep-water production (LNADW).

(3) Deep-water circulation during the Pleistocene (0.8-0.25 Ma): inferences from near bottom-current flow variability and deep water chemistry in the western equatorial Atlantic. Gröger, M., and Henrich, R., (Subm. to Paleoceanography).

The third manuscript involves a high-resolution multiparameter comparative study investigating the LNADW flow at site 927 (~3300 m) and the AABW flow at site 929 (~4400 m). The two sites exhibit a similar history of deep-water chemistry ($\delta^{13}$C, carbonate preservation) in terms of the frequency and trend of observed changes. By contrast, large inter-site differences in bottom-current intensity are inferred from silt grain-size analysis. Spectral analysis reveals that deep-water chemistry at both sites and bottom-current intensity at the LNADW site varied with a strong 100 k.y. periodicity, whereas bottom-current intensity at the AABW site varied with a 41 k.y. periodicity. This indicates, that variations in the quantity and quality of LNADW production may influence not only the deep-water chemistry within the LNADW layer, but synchronously that of
the AABW. It is proposed that changes in the contribution of LNADW to the Antarctic Circumpolar Current will influence the chemical properties of the source water for AABW (e.g., the Circumpolar Deep Water and the Weddell Sea Deep Water). However, cross-spectral analysis reveals that changes in bottom-current intensity at the LNADW site 927 lag those in ice volume and deep-water chemistry by about ~8 k.y. at the Earth’s eccentricity frequency band. The different phasing between deep-water chemistry and bottom-current dynamics with respect to ice volume may reflect a lag time between water mass reconfigurations of LNADW and AABW in the water column, and subsequent changes in the flow velocity of LNADW in response to changes in NADW production.
Glacial-Interglacial variability and long-term changes in the lower circulation loop of North Atlantic Deep Water: Inference from silt grain-size analysis and carbonate preservation studies at Ceará Rise, western equatorial Atlantic

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Abstract
In this study, grain-size records of the terrigenous and biogenic silt fraction and the preservation of planktonic foraminifers have been produced and investigated at ODP Site 927 on Ceará Rise (5°27.7'N, 44°28.8'W) comprising the time interval from 0.8 to 0.3 Ma. In a multiparameter approach, supplemented by benthic foraminiferal stable-isotope data ($\delta^{13}$C, $\delta^{18}$O of C. wuellerstorfi) from Bickert et al. (1997b), we monitor variations in the history of bottom-current strength, ventilation, and carbonate corrosiveness of deep waters, all of which are induced by the glacial/interglacial climate variability.

Our results provide evidence for stronger circulation in the lower NADW circulation loop during interglacials and a well-ventilated deep water-mass, indicating the predominance of lower North Atlantic Deep Water (LNADW) in the western equatorial Atlantic. In contrast to this interglacial situation, the glacial periods exhibit a considerably weakened circulation in the lower NADW loop and the presence of an older, less ventilated and more corrosive deep water mass with respect to carbonate. The observed pattern is related to changes in the relative flux of upper versus lower NADW to the total export of northern deep waters to the Southern Ocean.

Most of the striking changes in bottom current speed, inferred from the mean grain size of the sortable silt (10-63µm), occur during glacial to interglacial transitions. Lowest velocities are observed near the end of glacials (terminations), and these were followed by a shift to very high current speeds during the deglaciation phase. A contemporaneous shift to very high $\delta^{13}$C values indicates a considerable refreshment of deep waters.

A long-term trend toward generally poorer carbonate preservation and higher variability after the onset of glacial stage 12, coincides with a global decrease in carbonate preservation, as documented by studies from other regions. In the western equatorial Atlantic, this phenomenon is recognized during isotope stages 12 and 10 and might be interpreted as a consequence of climatic changes in the source region of the NADW.

Keywords: Mid-Brunhes dissolution cycle, paleo-bottom current speed, western equatorial Atlantic, carbonate preservation.

1. Introduction

Variations in the relative contributions of Upper North Atlantic Deep Water (UNADW) versus Lower North Atlantic Deep Water (LNADW) to the total flux of North Atlantic Deep and Intermediate
waters to the Southern Ocean have been identified as a driving force in the meridional heat and salt transfer between the Northern and Southern Hemispheres. Such variations are also an important feature of the glacial-interglacial deep-water circulation variability of the late Pliocene/Pleistocene Atlantic (e.g., Oppo et al., 1995, Raymo, et al., 1990). Studies of δ¹³C and Cd/Ca values have shown that the production of LNADW was drastically suppressed during glacial, whereas the production of UNADW was enhanced (Oppo et al., 1995, Raymo, et al., 1990, Curry et al., 1988, Duplessy et al., 1988, Boyle and Keigwin, 1987). As a consequence, southern source deep water (Antarctic Bottom Water (AABW)) expanded to shallower depths, compensating for the LNADW in the western and eastern Atlantic basins (e.g., Bickert et al., 1997a,b, Curry and Cullen, 1997, Cullen and Curry, 1997, Tiedemann and Franz, 1997, Bickert and Wefer, 1996, Curry, 1996, Sarnthein et al. 1994).

1.1 Study area

Previous investigations have documented a highly variable carbonate preservation and benthic δ¹³C history at ODP Site 827 interpreted to result from substantial changes in deep-water circulation (Bickert et al. 1997a,b, Curry and Cullen, 1997, Cullen and Curry, 1997, Tiedemann and Franz, 1997). Accordingly, we chose this Site for our own investigations.

Fig 1: Configuration of deep- and intermediate-water masses in the western equatorial Atlantic as indicated by the calculated δ CO₃^2⁻ ion concentration (mmol/kg). The thick line indicates the calcite saturation state (δ [CO₃^2⁻]=0) which deepens northward due to the greater influence of NADW. AAIW=Antarctic Intermediate Water, NADW=North Atlantic Deep Water, AABW=Antarctic Bottom Water. Carbonate ion distribution from GEOSECS stations 34, 36, 37, 39, 40, 48, 49, 53, 54, 55, 57, 58, 59, 60, 61, 64, 66, 67, 76 and 78. (GEOSECS, Bainbridge, 1981).
ODP Leg 154 (Sites 925-929) sediments are ideal for the study of past changes in the depth distribution of deep-water properties, located centrally at a position about halfway between the source regions for northern and southern deep-water masses. In the modern western equatorial Atlantic, NADW overlies the denser AABW at depths shallower than ~4000 m (Fig. 1, Tiedemann and Franz, 1997). Today ODP Site 927 (3315 m) is bathed by NADW.

Figure 2 shows the topography of the study area and the general flow path of the main deep-water masses in the Guyana basin. Site 927 is located on the northeastern flank of the Ceará Rise. The nearby Amazon deep-sea fan extends to depths greater than 4700 m, where it merges with the Demerara and Ceará Abyssal Plains (Damuth et al., 1988, Manley and Flood, 1988). Today, wide areas of the Amazon Fan are exposed to the flow regime of NADW just in front of the northwestern wedge of the Ceará Rise (Fig. 2). Hence, Amazon Fan sediments are an important source of terrigenous sediment supply to the Ceará Rise.

Fig. 2: Study area. ODP Site 927 (3315 m) is located on the northeast slope of the Ceara-Rise. The flow paths of NADW and AABW within the Guyana basin are generalized after Rhein et al. (1998) and Rhein et al. (1996).

1.2 Results from previous investigations.

Previous studies at the Ceará Rise have documented cyclic changes in ventilation and carbonate preservation on orbital time scales (e.g., Bickert et al., 1997a,b, Curry and Cullen, 1997, Cullen and Curry, 1997, Tiedemann and Franz, 1997, Bickert and Wefer, 1996, Curry, 1996). These variations were commonly attributed to the cyclic deepening and shoaling of the mixing zone between NADW and AABW.
These results suggest a considerably weakening circulation in the lower NADW loop during glacials as compared to interglacials. In this study we reconstruct the weakening/strengthening history of the lower NADW circulation loop by investigating late Quaternary mean sortable silt records. This is an important matter, because a significantly weaker circulation would increase the residence time of LNADW in the deep ocean, thereby lowering its $\delta^{13}C$ signal and the $[\text{CO}_3^{2-}]$. Therefore, modern gradients in $[\text{CO}_2^+]$ and $\delta^{13}C$ between NADW and AABW might have been less well defined during periods of weaker LNADW circulation. Furthermore, a slowdown of LNADW circulation would account for a considerable reduction in the meridional oceanic heat transfer which would have amplified Pleistocene glaciations.

Of special interest are the glacial to interglacial transitions, when drastic changes in the flux of lower versus upper NADW occurred, triggering shifts in the Atlantic deep-water circulation from one mode to another. An enhanced global thermocline overturn during glacial to interglacial transitions has been postulated by the four-stage model of global thermohaline circulation introduced by Imbrie et al. (1992). This is corroborated by the results of Duplessy et al. (1991). They found a significant small lag time in transferring the oxygen isotopic meltwater signal of surface and deep waters from the North Atlantic to the major oceanic basins during the last glacial to interglacial transition. This was attributed to an enhanced thermohaline circulation (Duplessy et al., 1991). Accordingly, the greatest changes in bottom-current speeds are expected to occur during the glacial to interglacial transitions.

Another remaining question is how far the Plio/Pleistocene carbonate dissolution patterns at Ceará Rise, as documented by Bickert et al., 1997a, Curry and Cullen, 1997, Cullen and Curry, 1997, and Tiedemann and Franz, 1997 are linked to changes in deep-water circulation. Today ODP Site 927 (3315 m) is located well above the modern calcite lysocline (Fig. 1). Bickert and Wefer (1996) and Curry and Lohmann (1990) found that the sedimentary lysocline never rose above 3800-3700 m in the tropical Atlantic Ocean. On the other hand, high rates of carbonate loss due to dissolution are inferred from porewater profiles at the Ceará Rise (Martin and Sayles, 1996, Hayles and Emerson, 1997). Bickert et al. (1997a) proposed that the metabolic CO$_2$ production from respiration of additional terrigenous organic matter supplied from the nearby Amazon Fan (Rühlemann, 1996) might be responsible for the observed dissolution patterns. $\delta^{13}C$ studies on the total organic carbon (TOC) at the southwestern flank and at the top of Ceará Rise revealed that 25 to 40% of the TOC is of terrigenous origin. The proposal of Bickert et al. (1997a), however, remains speculative since there is nothing known about the reactivity of the terrigenous organic material.

1.3 Long-term trends

A major characteristic of late Quaternary carbonate preservation records is a global signal of intensified dissolution centered around the mid-Brunhes (~400 ka). Such dissolution spikes have been well documented in the North Atlantic (Henrich et al., subm., Crowley, 1985), in the Indian Ocean (e.g. Bassinot et al., 1994, Peterson and Prell, 1985), in the Pacific (e.g. Farrell and Prell, 1991), and the southeast Atlantic (Diester-Haas and Rothe, 1987). The origin of these long-term trends is poorly understood. Because of the global character of the mid Brunhes dissolution cycle, long term-changes in the transfers between global carbon-carbonate reservoirs or in
Part II: Glacial-Interglacial variability and long-term changes...

The main object of this study is to improve our understanding of changes in the lower circulation loop of NADW, and their relations to geochemical and physical properties of deep waters in the western equatorial Atlantic, focusing on the following questions:

1) Is there evidence for variable paleo bottom-current speeds at the Ceará Rise, and how do changes relate to the glacial-interglacial cyclicity?

2) Is there evidence for weaker circulation in the lower loop of NADW during glacials?

3) Is there evidence for stronger alteration (with respect to carbonate corrosiveness and $\delta^{13}C$) of glacial LNADW compared to interglacials.

4) Is there evidence for greater changes in paleo bottom current-speeds at glacial to interglacial transitions?

5) Is there evidence for a linkage between carbonate preservation at 3315 m water depth (ODP Site 927) and changes in deep-water circulation?

6) Can the mid Brunhes dissolution cycles be recognized in the western equatorial Atlantic, and how do carbonate preservation patterns change during this period?

We consider these questions in a multiparameter approach. Carbonate preservation proxies and $\delta^{13}C$ records from Bickert et al. (1997) are used to estimate ventilation and the $[CO_3^{–}]$ saturation state of deep water. Further, a record of the mean sortable silt gives information about bottom currents speeds (McCave, 1995), which allows us to estimate changes in the relative strength of circulation within lower NADW loop. Finally, we use the $\delta^{18}O$ record of Bickert et al. (1997) to determine relationships between changes observed in the deep-water mass proxies and changes in ice volume.

A minor objective of this study is to investigate, whether carbonate dissolution can be estimated from silt grain-size analysis. The response of the calcareous silt texture to strong dissolution is therefore examined.

2. Material and methods

ODP-Site 927A was sampled at 20-cm intervals from 13.43 to 35.15 meters composite depth (mcd), which corresponds to the time interval from $\approx$ 270 ka to 800 ka, and yields a resolution of about 5 ky.

Coarse and fine fractions were separated by wet-sieving of $\sim$20 cm$^3$ of bulk sediment through a 63 μm-mesh sieve. The coarse fraction was then subdivided by dry-sieving at intervals of 63, 125, 250, 500 and 1000 μm. The 125-500 μm size fraction was split in half, and aliquots of this...
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material containing a minimum of 300 particles were used to record particle counts of whole-test planktonic foraminifers and planktonic foraminiferal fragments. A planktonic foraminiferal preservation index is given as percent whole foraminifers (=100 X number of whole foraminifer tests/(number of whole tests + number of fragments)).

Grain size distribution of the various silt components (bulk, calcareous silt and non-CaCO₃ silt) was measured with a Micromeritics SediGraph 5100, and was carried out for every second sample in order to reduce the labor effort, yielding a resolution of about 10 ky. The high accuracy of this system, which provides particle-size measurements in a size spectrum from 300 down to 0.1 μm, has been demonstrated in several studies (Coakley and Syvitsky, 1991, Stein, 1985). Stein (1985) noted, however, that montmorillonite-rich samples were difficult to analyze, because of their thixotropic properties, which increase the viscosity of the liquid and therefore hinder particle in settling.

XRD studies by Debrabant et al. (1997) indicate, that smectite was the dominant clay mineral in sediments of the nearby Amazon Fan (30% to 50% of the clay minerals) from the middle Pleistocene to the Holocene. We therefore reduced the clay content in our samples to 3-10 wt.% using the Atterberg method.

Each silt extract was measured twice in order to obtain the grain-size distribution of the distinct silt components (Robinson and McCave, 1994). After the first run, in which the frequency distribution of the total silt was determined, the carbonate was removed with 12% HCl. In a second run the lithogenic residue was measured to obtain the frequency distribution of the terrigenous component (since biogenic opal is negligible). According to Robinson and McCave (1994), the particle-size distribution of the calcareous silt component was obtained by subtracting the distribution of the lithogenic silt from that of the bulk silt.

We analyzed the silt within a given size spectrum ranging from 100,0 to 0,1 μm. From the raw data we calculated the grain size distributions of the 10-63 μm fraction and the total silt (2-63 μm) separately, with each spectrum rescaled to 100%. This procedure was applied to the bulk, lithogenic, and calcareous components. Standard deviation (SRD), mean grain diameter, and % (10-63 μm) silt were then calculated to characterize the textural features of each spectrum. In this study, the size classes greater than 10 μm are referred to as sortable silt, those with particles smaller than this, as fine silt.

Age models for the ODP Leg 154 Sites were developed by Bickert et al. (1997b). Dating is based on tuning variations of the magnetic susceptibility to orbital parameters (for details see Bickert et al., 1997b).

3. Results

3.1 Carbonate preservation

As demonstrated by Curry and Cullen (1997) at the Ceará Rise and the adjacent tropical Atlantic, carbonate preservation is best reflected by the record of percentage of whole foraminiferal tests. This is due to the weakening and breakage of foraminifer shells with progressive dissolution (e.g. Berger et al., 1982). The extend of carbonate dissolution is further estimated by grain-size
analysis of the calcareous silt component. We found the % (10-63 μm) silt in the calcareous silt component to be a useful parameter (Fig. 3).

The excellent covariation between this record and the % whole-test foraminifera qualifies this proxy as a reliable tool for estimating carbonate dissolution (Fig. 3). Accordingly, during phases of enhanced dissolution, as indicated by a stronger fragmentation of foraminiferal shells, we observe a considerable reduction in the % (10-63 μm) silt.

![Graph of carbonate preservation proxies](image)

**Fig. 3**: Carbonate preservation proxies (% whole-test foraminifera (bottom) and % (10-63 μm) silt in the calcareous silt component (middle)) vs. δ¹⁸O C. wuellerstorfi (Bickert et al. 1997b). Numbers at the top indicate oxygen isotope stages. The % whole-test foraminifera was calculated from particle counts in the 125-500 μm fraction.

The dissolution proxies exhibit the "Atlantic type" of preservation pattern with better preservation during interglacials compared to glacialis (Bickert et al., 1997b, Curry and Cullen, 1997, Tiedemann and Franz 1997). Comparison with the δ¹⁸O record from Bickert et al. (1997, Fig. 3) reveals that maxima in carbonate preservation occur at glacial-interglacial transitions, supporting the former results of Cullen and Curry (1997).

Minima in carbonate preservation of planktonic foraminifera occur predominantly around the interglacial to glacial transitions. This is most obvious at the transitions 19/18, 15/14, 13/12 and 11/10, where the strongest fragmentation of foraminiferal shells is observed (Fig. 3).

The most striking impact on planktonic foraminiferal preservation, however, is seen around the onset of glacial stage 12 (~480 ka, Fig. 3, bottom), where a distinct shift to generally poorer pre-
observation and much higher variability is recognized during both glacials and interglacials. During glacial stages 12 and 10, the preservation of planktonic foraminifera is the poorest of the entire record, indicating the mid-Brunhes dissolution cycle. This shift is less well recorded in the % (10-63 μm) silt of the calcareous silt component because of its lower resolution (~10 kys) (Fig. 3, middle).

3.2 Changes of the calcareous silt texture in response to dissolution

To test the response of the silt texture to strong dissolution, we compare the grain-size distribution of a well-preserved interglacial sample with that of a glacial sample that underwent considerable dissolution (Fig. 4). Modal values do not differ significantly and are centered around 3 μm, indicating the predominance of fine-grained coccoliths in both samples. The glacial sample, however, exhibits a significant reduction of particles in the size classes between 7 and 63 μm.

The calcareous fine fraction consists of three different components, in the order of their relative abundance: (1) nannofossil placoliths, consisting mainly of coccoliths, which are present exclusively in the fine silt with a maximum around 3 μm and in the clay fraction, (2) fragments of foraminifera, preferentially present in the silt, and (3) juvenile foraminifera and larvae with a relatively negligible abundance, preferentially present in the (10-63 μm) silt. Hence, we propose the preferential dissolution of foraminiferal fragments and larvae, relative to the nannofossil placoliths, as a possible explanation for the observed pattern.

Fig. 4: Comparison between the grain-size distribution of a well-preserved interglacial sample (dashed line) and a glacial sample that underwent considerable dissolution. Both distributions are generated from the calcareous silt component. While modal values are nearly identical, the glacial sample is considerably reduced in (10-63 μm) silt.

To verify that the pattern of % (10-63 μm) silt does not result from winnowing, we compare the % (10-63 μm) silt in the calcareous silt component with the record of % (10-63 μm) silt in the terri-
genous silt component (Fig. 5). If both records were, in fact, controlled by winnowing, they
should exhibit the same pattern. The patterns are, however, complete different \( (r=0.08, \text{Fig. 5}) \),
implying that the calcareous \((10-63 \mu m)\) silt record is controlled primarily by differential dissolution
of coccoliths/foraminiferal fragments. Greater resistance by coccoliths to dissolution compared
to foraminiferal tests has been reported by Hay (1970), who found coccoliths to be more
abundant close to the CCD. Their greater resistance is most likely related to protective organic
membranes (McIntyre and McIntyre, 1971) obtained during transport by fecal pellets, which is
the most important process in transferring phytoplankton skeletons to the deep sea floor (Honjo,
1976).

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Fig. 5: Comparison between the percentage \((10-63 \mu m)\) silt in the calcareous silt (bottom) and the
percentage of \((10-63 \mu m)\) silt in the terrigenous silt (top).

3.1 Terrigenous silt fraction.
The sortable silt exhibits cyclic variations in the mean grain diameter record and sorting. Both
parameters show a negative relationship \( (r=-0.5) \), which we interpret as documenting the deposit-
ion from suspension load. Generally, sorting becomes poorer with higher current velocity, as
increasingly coarser grain classes are added into the suspension load.
The downcore records of the mean grain diameters in the sortable silt \( (\text{mean}_{ss}) \) reflect a size
range from \( \sim 11 \mu m \) to \( \sim 18 \mu m \). Figure 6 compares the \( \text{mean}_{ss} \) record to the benthic \( \delta^{18}O \) record
of Bickert et al. (1997). In general, the \( \text{mean}_{ss} \) record exhibits an assymetry similar to that of
the \( \delta^{18}O \) record, with coarser \( \text{mean}_{ss} \) observed in interglacials and a fining of \( \text{mean}_{ss} \) values in
 glacials.
Minima in the \( \text{mean}_{ss} \) record occur at the glacial to interglacial transitions, where \( \text{mean}_{ss} \) values are finer than \( 13 \mu m \), which is near the boundary of the grain-size window. Comparison
with \( \delta^{18}O \) values show that these minima were followed by abrupt shifts to very coarse values
(Fig. 6). At terminations 18/17 and 14/13, the shift to coarser \( \text{mean}_{ss} \) values occurs well within
the deglaciation phase as indicated by the oxygen-isotope record (which shows a less steep
trend to lighter \( \delta^{18}O \) values compared to the other transitions). This pattern is less obvious, but
still recognizable during the deglaciation at 10/9. At transitions 16/15 and 12/11, the shift to
coarser mean\textsubscript{(SS)} values seems to be in phase with the $\delta^18O$ record. This could be, However, an effect of the lower resolution (10ky) of the mean\textsubscript{(SS)} record, since these deglaciation phases are characterized by rapid transitions to interglacial conditions.

Fig. 6: Comparison between the mean grain diameter of the terrigenous "sortable silt" (10-63 µm) and benthic $\delta^18$O (Cibicidodes wuellerstorfi). Note the inverse scale of the oxygen isotope record. Stable isotope data from Bickert et al. (1997b). Numbers at the top indicate oxygen isotope stages.

The coarsest mean\textsubscript{(SS)} value throughout the whole record is observed at about 480 ka corresponding to the onset of glacial stage 12. This coincides with a distinct shift to poorer carbonate preservation, which we will discuss below.

Figure 7 compares the mean\textsubscript{(SS)} record with the benthic $\delta^{13}$C record from Bickert et al. (1997). In general, we observe a positive relationship between the parameters, with finer mean\textsubscript{(SS)} values accompanied by lighter $\delta^{13}$C values during glacials. At the glacial-interglacial transitions, a similar pattern as described for the $\delta^{18}$O curve is recognizable. At terminations 18/17 and 14/13 (and less well defined at the transition 10/9), the deglacial shift to coarser mean\textsubscript{(SS)} values lies well within a moderate trend to heavier $\delta^{13}$C values, while during transitions 16/15 and 12/11 it seems to occur contemporaneously with a rapid increase to heavier $\delta^{13}$C values. This may be, as mentioned above, an effect of the poorer resolution of the mean\textsubscript{(SS)} record.

In summary, interglacials are characterized by generally coarser mean\textsubscript{(SS)} values, while glacialis exhibit a trend to finer values. The most significant changes occur during glacial-interglacial transitions where absolute minima in mean\textsubscript{(SS)} are followed by a rapid shift to very coarse me-
an$_{(SS)}$ during deglaciations. The shifts coincide with contemporaneous shifts to heavier benthic foraminiferal $\delta^{13}$C values from C.wuellerstorfi.

4. Discussion

4.1 Glacial-interglacial variability

4.1.1 Inference of current speed from grain size distributions at Ceará Rise.

Previous studies (e.g. McCave, 1985, McCave et al., 1995, Robinson, 1994) have established that the >10 μm silt fraction is most sensitive to sorting processes. The theoretical and empirical basis has been documented in detail by McCave et al. (1995). Accordingly, a greater mean grain size of the sortable silt is considered to be evidence for stronger bottom currents. The hydrographic and depositional background at the Ceará Rise, however, is more complex because of the various flow and transport regimes of deep water masses and surface currents.

1) Changes in mean$_{(SS)}$ could reflect different sources of sediment supply associated with the distinct flow regimes of AABW and NADW. (2) Climatically induced changes in the Amazon sediment discharge may disturb or overprint the normal marine bottom-current signal. (3) Additional variability of sediment supply may be encountered via the eastward flowing North Equatorial Counter Current (NECC). At relatively longer time scales, the NECC is linked to the latitudinal paleoposition of the Intertropical Convergence Zone (Tiedemann and Franz, 1997).

Robinson and McCave (1994) argued that only the physical processes of sedimentation and post-formation effects (e.g. bottom currents) can influence the particle sorting of both the bioge-
nic and lithogenic components of the sediment. To test whether the mean\(_{(SS)}\) proxy is a reliable indicator for bottom-current strength, we compare in Figure 8 the mean\(_{(SS)}\) record of the terrigenous silt to that generated from the calcareous component. The two records covary well, providing strong evidence that changes in the terrigenous sortable silt mainly reflect changes in paleo bottom-current strength. Minor differences between the calcareous and the terrigenous sortable silt records, may be related to dissolution effects and/or variations in the mean thickness of shell walls.

![Graph](image)

**Fig. 8:** Comparison between the mean grain diameter of the terrigenous "sortable silt" (10-63 \(\mu\)m) with the mean grain diameter of the calcareous "sortable silt" (10-63 \(\mu\)m). Covariation between the two records indicates the presence of bottom currents (Robinson and McCave, 1994)

Furthermore, the calcareous mean\(_{(SS)}\) values are much coarser than those of the terrigenous mean\(_{(SS)}\) values. Assuming a similar hydrographic behavior by both components, this would imply that the bottom-current speeds had to be much stronger than inferred from the terrigenous mean\(_{(SS)}\) record. This might also reflect the distal position of Site 927 on the northeastern slope of the Ceará Rise.

Interpreting the terrigenous mean\(_{(SS)}\) record to result mainly as a function of variable bottom-current speeds, glacial-interglacial differences in the terrigenous mean\(_{(SS)}\) provide evidence for higher current speeds during interglacials compared to glacialms, (Fig. 6). Furthermore, the distinct shifts during the glacial-interglacial transitions indicate initiation of the highest current speeds during deglaciations (Fig. 6), just after a "shutdown" in current velocity around the end of glaciations. This assumption is in agreement with the four stage model of Imbrie et al. (1992), which postulates a maximum overturn of global thermohaline circulation during deglaciations.

A model to explain the observed pattern at Site 927 could be as follows:

Due to the reduced LNADW formation during glacials, flow in the lower NADW circulation loop was considerably weakened, resulting in a general suppression of bottom-current speeds. This situation culminates in a "shutdown" scenario at the end of the glacial periods, where periods of weakest bottom-current speeds and lowest ventilation were indicated at the Ceará Rise.
From a hydrodynamical point of view there may be two ways to balance variations in LNADW production. For example the interglacial excess of LNADW can be balanced by a volumetric expansion of the LNADW layer in the Atlantic Ocean. This would require a lower density gradient toward the underlying AABW for enabling the LNADW to entrain into greater waterdepths. In this model, a diminished flux of LNADW during glacials leads to a smaller LNADW layer in the Atlantic ocean.

In a second scenario the LNADW excess may be balanced by a stronger and thus more efficient circulation of LNADW. This would require a faster streaming LNADW in order to transfer larger volumes of LNADW from the Atlantic to the other oceans. This model is in well agreement with our assumption of a stronger circulation in the LNADW loop during interglacials.

The two mechanisms may not be exclusive but can be considered to operate side by side. Anyway, the large glacial-interglacial differences in inferred bottom-current strength suggest that there are two modes of LNADW circulation: a fast conveyor during interglacials, and a "slow conveyor" during glacials. It appears plausible that the "slow conveyor" must have been associated with a considerably reduced meridional heat transfer and, thus amplified the Pleistocene glaciations.

In order to explain the "shutdown" scenario at the glacial to interglacial transitions we hypothesize that the development of the largest (most expansive) ice sheets at the ends of glacials may have triggered an almost complete suppression of LNADW formation, leading to the most prominent weakening of the lower NADW circulation loop. These ice sheets may have forced a seasonal enhanced meltwater discharge into the area of LNADW formation. Simultaneous with, or just after the beginning of the deglaciation phase, the system is restabilizes. The lower NADW circulation is rapidly reestablished, causing a shift to the very high current speeds observed at the Ceará Rise. This is in accord with the results of Venz et al. (1999), who deduced an increase in LNADW production during terminations from benthic δ¹³C records at ODP-Sites 607 and 982 in the North Atlantic.

The strong positive relationship between the mean₅₅ record and the carbon-isotope record of Bickert et al. (1997, Fig. 7), gives further evidence for such a scenario. Accordingly, heavier δ¹³C values indicate an increased ventilation during interglacial periods of higher bottom-current speed, whereas lighter δ¹³C values result from decreased ventilation associated with periods of weaker bottom currents during glacials.

At glacial-interglacial transitions (16/15, 14/13, 12/11, and 10/9) the distinct shift to coarser mean₅₅ is paralleled by a shift from very light to very heavy δ¹³C values (Fig. 7), indicating a rapid reinitiation of the lower NADW loop.

However, this model has to be verified in a high-resolution study along a depth transect to focus more precisely on the distinct phase relations between the δ¹³C, δ¹⁸O and mean₅₅ records. Another implication of the reduced current speeds during glacial periods is that, due to the weaker circulation of the LNADW, this water mass appears much "older" compared to interglacials. This is also evidenced by the strong negative relationship between the mean₅₅ and δ¹³C records (Fig. 7). In consequence, δ¹³C and [CO₂] gradients between LNADW and southern-source deep waters might have been less steep during glacials compared to interglacials.
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Hence, a key question remains as to the extent the observed changes in the $\delta^{13}C$ and $\text{mean}_{\text{ss}}$ records can be explained solely through varying ventilation effects (related to a strengthening/weakening of the circulation within lower NADW loop), or whether there is evidence for the variable influence of low $\delta^{13}C$ AABW?

4.1.2 Preservation, ventilation, circulation

The records of preservation proxies show a strong positive relationship to the $\delta^{13}C$ record (Fig. 9). Hence, during glacials, the poorer preservation of foraminifera and diminished coarse silt content are associated with lighter $\delta^{13}C$ values. This could reflect, at least partly, an older LNADW mass during glacial periods, with weaker circulation and more organic carbon remineralized in the water column, and thus a lower $[\text{CO}_2]$.

Explaining the preservation and $\delta^{13}C$ pattern with a stronger alteration of the LNADW during glacial periods of weaker circulation, however, would suggest that this LNADW mass is much more corrosive compared than in the interglacials.

**Fig. 9:** Comparison of carbonate preservation proxies with the $\delta^{13}C$ (C. wuellerstorfi) record from Bickert et al. (1997b). A positive relationship evidences the linkage between changes in deep-water circulation and carbonate preservation at ODP Site 927.

Explaining this pattern by variable influences of AABW would imply that the expanded mixing zone between the water masses and the calcite lysocline were shallower than is suggested by previous studies (e.g. Bickert et al., 1997, Bickert and Wefer, 1996). Such a scenario seems to be rather plausible during isotope stages 12 and 10, where we found the distinct shifts to generally
poorer carbonate preservation. Further evidence for an important role of AABW is provided from carbonate preservation studies on two gravity cores from the southwestern flank and from the top of the Ceará Rise by Rühlemann (1996). He reported a considerable increase in carbonate dissolution at depths above 3300m during isotope stages 4, 8, 9 and 10. This observation was attributed to a decreased production of NADW associated with a vertical expansion of Southern-Source Deep Water. This assumption, however of an expanded mixing zone between NADW and AABW has to be further verified in a depth transect at the Ceará Rise.

On the other hand, explaining the strong negative relationship between the δ13C record and the dissolution proxies solely by the respiration of organic matter at Site 927, we would expect a strong "Mackensen effect" (Mackensen, 1993), which decreases the δ13C of ΣCO₂ in the water column. On the other hand, our results reveal that TOC content does not exceed 0.4% (≈0.25%) of the bulk sediment. Based on these very low TOC contents, a "Mackensen effect" is rather unlikely. Accordingly, the good covariation between the carbonate preservation proxies and the δ13C record (Fig. 9) evidences the linkage between changes in the deep-water circulation and carbonate preservation.

4.2 Long term trends

The most striking shift in the carbonate preservation curve (Fig. 9) occurs rather abruptly at the onset of isotope stage 12 (~480 ka). Thereafter, the preservation of foraminifers is generally lower than before, and the variability is much greater during both the glacials and the interglacials. This indicates that changes in carbonate preservation in this interval now occur not only in response to glacial-interglacial climatic change, rather the variation is stronger at sub-orbital time scales. This indicates:

(1) a generally decreased influence of well-ventilated LNADW, which may have been (at least partly) compensated by an increasing influence of southern-component water, and (2) a less stable LNADW production in the Nordic Seas. If we assume that the large ice sheets developed during this period might have decreased the stability of LNADW production, the observed pattern might be viewed as a direct consequence of drastic climatic changes in the source region of NADW. This is supported by IRD studies of Henrich et al. (1989) and more recently by Thiede et al. (1998), which suggest that the largest ice sheets in the Northern Hemisphere were developed during the mid-Brunhes event.

Furthermore, our results show that the observed impact on carbonate preservation coincides with the highest bottom current speeds as indicated by the coarsest means(SS) values along the whole record. This argues for a widespread rebalancing in deep water circulation around the onset of glacial stage 12.

Additional evidence for an important role of the UNADW/LNADW flux during the mid-Brunhes dissolution cycle, at least for the Atlantic, comes from carbonate preservation studies in the Caribbean. Ferraro et al. (1996) reported the most intense dissolution around interglacial stage 11 at ODP Site 999 (Colombian basin) and 1000 (Nicaraguan Rise), whereas our results reveal strong dissolution during glacial stages 12 and 10 for the western equatorial Atlantic. This as-
symmetry could be controlled by variations in the relative flux of LNADW/UNADW. During glacials 12 and 10 the LNADW production is considerably reduced, with a corresponding enhancement of UNADW production. This initiates an increased export of UNADW through the passages across the Caribbean sill front into the Caribbean basins. During interglacial stage 11 LNADW production is higher, resulting in better carbonate preservation in the western equatorial Atlantic, while UNADW production is depleted. This diminishes the export of UNADW to the Caribbean basins, and this is then compensated by more corrosive Antarctic Intermediate Water. Hence, the asymmetry between the Caribbean and western Atlantic carbonate preservation pattern during the mid-Brunhes interval argues for an essential role of the relative LNADW/UNADW flux in controlling the mid-Brunhes dissolution cycle, at least for a coupled Atlantic-Caribbean system.

Conclusions

Late Quaternary records of terrigenous mean "sortable silt" indicate a history of highly variable bottom current speeds at the Ceará Rise, western equatorial Atlantic.

Comparison of mean "sortable silt" with carbonate preservation proxies and benthic foraminiferal stable-isotope records ($\delta^{13}C$, $\delta^{18}O$) from Bickert et al., (1997b) evidence a considerably weakened circulation of lower NADW and a less well-ventilated deep-water mass during glacials. In contrast, during interglacials the lower NADW circulation loop strengthened and the water mass was better ventilated.

The lower inferred bottom-currents speeds suggest a considerable "slowdown" of LNADW circulation which points to a considerably reduced meridional heat transfer amplifying the Pleistocene glaciations.

Due to the weakening circulation during glacials, the LNADW might have been considerably "older" compared to interglacials periods. This is corroborated by a strong negative relationship between the mean sortable silt and $\delta^{13}C$ records. Thus, gradients in $\delta^{13}C$ and [CO$_3^{2-}$] between LNADW and southern-source deep waters might have been less extreme during glacials compared to interglacials.

The most striking changes in paleocurrent speeds, inferred from records of mean sortable silt, occur during glacial-to-interglacial transitions, showing a shift from the lowest to very high bottom-currents speeds during the transitions 18/17, 14/13 and 10/9. This indicates a rapid reinstatement of the lower NADW circulation relatively soon after a considerable stage of "shutdown". As a consequence, this pattern evidences a widespread rebalancing of western Atlantic deep-water circulation during the Late Quaternary glacial to interglacial transitions.

A strong negative relationship between carbonate preservation proxies and the $\delta^{13}C$ record (Bickert et al., 1997) support a linkage between changes in the deep-water circulation and carbonate preservation at ODP-Site 927 (3315 m).

An abrupt shift to generally poorer preservation of planktonic foraminifera together with the highest current speeds, inferred from the mean sortable silt record, is recognized at the onset of
glacial stage 12. This marks the beginning of the mid-Brunhes dissolution cycle in the western equatorial Atlantic. In this region this phenomenon might be interpreted as a consequence of climatic changes in the source region of the NADW.

After the onset of glacial stage 12 (~480 ka), a much higher variability is recorded in the foraminiferal preservation during both glacial and interglacial periods. This indicates that changes in carbonate preservation at the Ceará Rise from then on not only occur in response to glacial-interglacial climatic change, but also to sub-orbital time scales.

Grain-size analysis of the calcareous silt component from sediments on the Ceará Rise indicate that the coarser foraminiferal fragments are less resistant to carbonate dissolution compared to coccoliths. This qualifies the % (10-63 μm) silt in the calcareous silt fractions as a reliable tool for estimating carbonate dissolution.

Acknowledgements
We thank W. Hale, T. Wagner, and A. Volbers for comments and criticism. This work was supported by the Deutsche Forschungsgemeinschaft (DFG).

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**Remark**

Recent advances were made concerning the controlling factors of Amazon sediment supply to the southern region of the Ceará Rise (Rühlemann, C., Diekmann, B., Mulitza, S., and Frank, M. 2001. Late Quaternary changes of western equatorial Atlantic surface circulation and Amazon lowland climate recorded in Ceará Rise deep-sea sediments. Paleoceanography, 16 (3):293-305.). These results results generally confirm my assumption of bottom current induced sediment sorting at site 927. Unfortunately, the results were published after this manuscript was submitted. However, the results of Rühlemann et al., are considered in the following two manuscripts. In manuscript 3 a broader discussion about the depositional setting at the Ceará Rise is provided.
Variability of silt grain size and planktonic foraminiferal preservation in Plio/ Pleistocene sediments from the western equatorial Atlantic (ODP Site 927) and Caribbean (ODP Site 999): Implications for the history of Atlantic Deep- and Intermediate-Water circulation

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Abstract

Records of mean sortable silt and planktonic foraminiferal preservation from the Ceará Rise (western equatorial Atlantic) and from the Caribbean are presented to analyze the Pliocene (3.5-2.2 Ma) - Pleistocene (1.6-0.3 Ma) evolution of near-bottom current strength and the carbonate corrosiveness of deep water. According to our results at the Ceará Rise, glacial periods in the Pleistocene are characterized by weaker bottom-current strengths and a higher carbonate corrosiveness of deep water than interglacials during. This is interpreted to reflect a reduced circulation in the Lower North Atlantic Deep Water (LNADW) cell and a diminished flux of calcite-saturated LNADW to the western equatorial Atlantic. During the mid-Pleistocene climate transition (~1 Ma) a drastic decrease in glacial bottom-current strength and an increase in carbonate corrosiveness is registered, demonstrating a substantial decrease in the glacial contribution of LNADW to the Atlantic Ocean. This is consistent with results of carbonate preservation studies in the northern North Atlantic that indicate a drastic reduction in deep-water formation during this period (Henrich et al., in press).

We found evidence for the strongest and most stable circulation within the LNADW cell during the northern hemisphere cooling period between ~3.2 and 2.75 Ma. This is in agreement with the "superconveyor model" of Raymo (1992) which postulates the highest NADW production prior to ~2.7 Ma. A considerable decrease in bottom-current strength and planktonic foraminiferal preservation are observed synchronous with the first occurrences of large-scale continental ice sheets on the northern hemisphere. This documents the final termination of the "superconveyor" at around 2.75 Ma. However, our data do not support a "superconveyor" in the interval between 3.5 and 3.2 Ma where high-amplitude fluctuations in bottom-current flow and preservation in planktonic foraminifera are observed. Because of the great sensitivity of the NADW production to changes in surface water salinity, we assume that high-amplitude fluctuations of LNADW circulation prior to ~3.2 Ma are linked to changes in the Atlantic salinity budget. After 2.75 Ma they are primarily controlled by ice-sheet forcing.

In contrast to the stepwise deterioration of planktonic foraminiferal preservation in the western deep Atlantic, a trend toward better preservation from the Pliocene to Pleistocene is observed in the deep Caribbean. We assume that this relates to a stepwise increase in the contribution of Upper North Atlantic Deep Water to the Atlantic Ocean.
1. Introduction

Major changes in Plio/Pleistocene climate history have been presumed to be coupled with re-organisations in the global thermohaline circulation (e.g. Broecker, 2000, Broecker and Henderson, 1998, Oppo et al., 1995). In particular, it was suggested that variations of production rate and flux of North Atlantic Deep Water (NADW) to the Southern Ocean were related to a reduction in the meridional heat transfer, thus amplifying the Pliocene/Pleistocene glaciations (e.g Raymo et al., 1996, Oppo et al., 1995, Charles and Fairbanks, 1992).

At present, the deep Atlantic is occupied by two principal water masses:

(1) Lower NADW (LNADW) that is produced by supercooling and deep convection of saline surface waters in the Norwegian Greenland Sea (NGS) and Upper NADW (UNADW) that is mainly formed in the Labrador Sea (e.g. Marshall and Schott, 1999, Duplessy et al., 1996, Labeyrie, 1992).

(2) The northward expanding Antarctic Bottom Water (AABW) is a mixture of very cold outflow waters from the Weddell Sea and very old waters, originating from the Circumpolar Current (e.g. Reid, 1989). As an older water mass it is nutrient and CO$_2$ rich, and is characterized by lower $\delta^{13}$C values of the $\Sigma$CO$_2$.

Most studies agree that during the Plio/Pleistocene glacials the production of LNADW was suppressed by ice-sheet forcing (e.g., "the blocking off" of saline surface waters from the northern North Atlantic regions, Henrich et al., in press). Accordingly, its contribution to the Atlantic Ocean was decreased (Oppo et al., 1995, Raymo, et al., 1990, Curry et al., 1988, Duplessy et al., 1988).

In this study we focus on long-term changes in the history of North Atlantic Deep Water circulation. In particular, two periods of fundamental global climate change are considered: The transition to large-scale Northern Hemisphere Glaciation (NHG) at ~3.2 Ma, and the mid-Pleistocene climate transition (MPT ~1 Ma). For our investigations we selected Ocean Drilling Program (ODP) sites from the western equatorial Atlantic (ODP Site 927, 5°27’N, 44°29’W) to monitor changes in northern source deep-water circulation (LNADW), and from the Caribbean (ODP Site 999, 12°45’N, 78°44’W) to monitor changes in intermediate-water circulation (UNADW).

1.1 Regional depositional and hydrological setting

Today, the western tropical Atlantic constitutes the main passage for the meridional transfer of northern- and southern-source deep and intermediate waters. The Ceará Rise is an ideal site for the reconstruction of past changes in deep-water circulation because it intersects these deep water masses at a central position about halfway between their source regions.

In the western equatorial Atlantic NADW is underlain by the denser and nutrient-rich AABW. The transition from NADW to AABW is marked by decreases in temperature, salinity, the $\delta^{13}$C of $\Sigma$CO$_2$, and [CO$_2$] (Fig. 1, Kroopnick, 1985). ODP Site 927 is located at the northeastern flank of the Ceará Rise (Fig. 2) at approximately 3300 m water depth. Today, ODP Site 927 is exposed to the flow regime of NADW. Because of the sloping topography between the broadly extending
Part II: Variability of silt grain size and planktonic foraminifera preservation.

Fig. 1: Configuration of deep- and intermediate-water masses in the western equatorial Atlantic as indicated by the calculated $\delta^{18}$O ion concentration (mmol/kg, modified after Gröger et al., subm., and Haddad and Droxler, 1996). The thick line indicates the pressure normalized calcite saturation state ($\delta [\text{CO}_3^{2-}]=0$) which deepens northward due to the greater influence of NADW. AAIW=Antarctic Intermediate Water, NADW=North Atlantic Deep Water, AABW=Antarctic Bottom Water. Carbonate ion distribution from GEOSECS stations 34, 36, 37, 39, 40, 48, 49, 53, 54, 55, 57, 58, 59, 60, 61, 64, 66, 67, 76 and 78. (GEOSECS, Bainbridge, 1981).

Amazon fan and the Ceará Rise (Fig. 2) the carbonate-corrosive AABW is presently restricted to the eastern slope of the Ceará Rise (Rhein et al., 1998). By contrast, NADW has been identified at both slopes of the Ceará Rise (Rhein et al., 1996). At the Ceará Rise the foraminiferal lysocline lies at around 4200 m, which is within the depth interval of the modern mixing zone between the two water masses (Fig. 1a, e.g. Bickert et al., 1997a, Cullen and Curry, 1997, Tiedemann and Franz, 1997).

Terrigenous material at the Ceará Rise originates mainly from Amazon river sediment discharge being transported eastward, mainly via the North Equatorial Counter Current (NECC, Fig. 2, Rühlemann et al., 2001, Tiedemann and Franz, 1997). The position and intensity of the NECC is driven by retroreflection of the North Brazil Current, which, in turn, is controlled by the Intertropical Convergence Zone (ITCZ). At present, the NECC is strongest during the second half of the year, when the southern trade winds are strongest and push the ITCZ to its northernmost position (Rühlemann, 2001). Therefore, during the past, the Amazon sediment supply to the Ceará Rise has been related to the equatorial surface-current system, which was controlled by the paleo-position of the ITCZ and trade-wind intensity (Rühlemann et al., 2001, Tiedemann and Franz, 1997). However, another important effect on the sediment deposition at this site has re-
Part II: Variability of silt grain size and planktonic foraminifera preservation.

Fig. 3: Topographic map of the Caribbean showing the position of ODP site 999 in the Colombian Basin. Arrows indicate the modern flow path of Atlantic intermediate waters through the main passages of the Caribbean sill front (adapted from Roth et al., 2000, and Haddad and Droxlé, 1996).

1.2 Results from previous studies

Previous studies on Ceará Rise sediments have revealed a highly variable history of past changes in carbonate dissolution and benthic foraminiferal $\delta^{13}C$ (e.g., Groger et al., subm., Bickert et al., 1997a,b, Curry and Cullen, 1997, Cullen and Curry, 1997, Tiedemann and Franz, 1997, Curry, 1996). These changes were commonly explained by cyclic variations in the depth distribution of NADW and AABW (e.g., Bickert et al., 1997a,b, Curry and Cullen, 1997, Cullen and Curry, 1997, Tiedemann and Franz, 1997). Most studies agree that during glacial periods NADW was reduced and compensated for by vertical expansion of AABW (e.g. Bickert et al., 1997a,b, Curry and Cullen, 1997, Cullen and Curry, 1997, Tiedemann and Franz, 1997, Bickert and Wefer, 1996).

This model, however, is based primarily on geochemical proxy records which indicate a shoaling of the carbonate lysocline and the steep vertical gradients of benthic foraminiferal $\delta^{13}C$ during glacial periods (e.g. Bickert et al., 1997a,b, Curry and Cullen, 1997, Cullen and Curry, 1997, Tiedemann and Franz, 1997). However, the geochemical proxies are impracticable for the study of the physical flow characteristics of deep waters. Focusing on this target, recent studies by Gröger et al. (subm.) and Gröger and Henrich (subm.) provide evidence that the decreased influence of glacial NADW in the tropical western Atlantic was accompanied by a weakening of the bottom-current flow regime at ODP Site 927. This finding is in good agreement with the commonly accepted model indicating a weaker circulation in the LNADW cell during glacial (Gröger et al. subm., Gröger and Henrich, subm.).
In contrast to the reduced flux of LNADW to the Atlantic Ocean basins, various evidence exists that the glacial UNADW production was enhanced throughout the Pliocene/Pleistocene glacial periods (e.g., Gerhardt and Henrich, subm., Oppo et al., 1995, Raymo, et al., 1990, Curry et al., 1988, Duplessy et al., 1988). In agreement with this, an increased glacial influence of uppermost NADW in the deep Caribbean has been indicated by benthic foraminiferal $\delta^{13}C$ and carbonate preservation studies for the Late Quaternary (e.g. Haddad and Droxler, 1996, Charles and Fairbanks, 1992, Oppo and Fairbanks, 1990).

1.3 Background and objectives

In this study Late Pliocene (3.4-2.2 Ma) and Pleistocene (1.5-0.9 and 0.8-0.3 Ma) records of planktonic foraminiferal shell preservation and silt grain-size variability are presented to monitor long-term changes in deep-water chemistry and near-bottom current vigor at the Ceará Rise.

Ice-sheet dynamics have been postulated as a significant influencing factor on NADW production and Atlantic deep-water circulation. Hence, special interest is focused on the MPT, including the shift from smaller ice caps in the 41 k.y. world to the more expanded ones in the modern 100 k.y. world at around 1.0 Ma (e.g. Raymo et al., 1997, Imbrie et al., 1993). The influence of ice-sheet dynamics on NADW production during the last 3 m.y. has been recently investigated by Henrich et al. (in press). Fresh-water export from the ice sheets, the spreading of low-salinity layers of polar waters and the "blocking off" of saline surface waters derived from the equatorial regions may strongly impede deep-water formation (Henrich et al., in press).

During the Late Pliocene the change from the mid-Pliocene warmth (e.g. Raymo, et al., 1996, Henrich and Baumann, 1994, Henrich et al., in press) to the increasing NHG occurred. This was ultimately triggered by an increase in the Earth’s obliquity amplitude fluctuations (Haug and Tiedemann, 1998) and culminated with the growth of large-scale continental ice sheets in the northern hemisphere at ~2.75 Ma (Raymo et al., 1996, Raymo, 1992). This was accompanied by a change in the North Atlantic Deep Water circulation. The Late Pliocene mode, with predominance of NADW in the Atlantic Ocean (e.g. the "superconveyor" scenario of Raymo et al. (1996)), changed stepwise, diminishing NADW contribution to the Atlantic as indicated by benthic foraminiferal $\delta^{13}C$ evidence (e.g. de Menocal, 1992, Raymo et al., 1996, Raymo, 1992). Recently obtained carbonate preservation records from various sites in the northern North Atlantic indicate drastic changes in deep-water ventilation and deep-water formation during the MPT as well as in the main Phase of NHG (Henrich et al., in press). In the first part of this study, we address the question of whether analogous changes in carbonate preservation and/or bottom-current vigor can be recognized in the deep western equatorial Atlantic at a core location that is sensitive to changes in the LNADW circulation (Site 927).

The second aspect of this study focusses on the Plio/Pleistocene evolution of Atlantic intermediate-water circulation, which is addressed through a comparative examination of planktonic foraminiferal shell preservation records from the deep Caribbean at ODP Site 999 and the deep western Atlantic at ODP Site 927.
Part II: Variability of silt grain size and planktonic foraminifera preservation.

2. Material and methods

2.1 Sampling strategy

ODP Site 927 Hole A was sampled at ~20-cm intervals from 38.66 to 62.38 and from 84.63 to 125.80 meters composite depth (mcd). This corresponds to the time intervals from ~0.8 to 1.55 Ma and ~2.2-3.4 Ma and yields an average resolution of ~5 k.y. In addition, we include data for the mid Pleistocene (0.8-0.3 Ma) produced by Gröger et al. (subm.). Bickert et al. (1997b) and Tiedemann and Franz (1997) provide age models for ODP Leg 154 sites. Dating is based on tuning variations of the magnetic susceptibility to orbital parameters (for details see Bickert et al., 1997b and Tiedemann and Franz, 1997).

ODP Site 999 Hole A was sampled from 9.11 to 49.92 and from 74.18 to 110.07 meters below sea floor (mbsf). Each of the selected time sections was sub-sampled at ~20 cm intervals, which is equivalent to approximately one sample per 6 k.y.

The Pleistocene section includes two major biostratigraphic events: the first appearance datum of *Emiliania huxleyi* (CN 15, 250 ka) at ~8.71 mbsf (Kameo and Bralower, 2000) and the first appearance datum of *Gephyrocapsa* spp. (large) (CN 14a, 1.45 Ma) at ~51.21 mbsf (Kameo and Bralower, 2000).

The Pleistocene record of % whole-test foraminifers (% WTF) is applied to the age model of Sigurdsson et al. (1997). This age model is based on linear interpolation between major planktonic foraminifera and calcareous nannofossil datums (Sigurdsson et al., 1997). The depth uncertainty for these datum is about 1.5 m (Sigurdsson et al., 1997). Accordingly, the uncertainty associated with dating of individual samples may theoretically exceed 40 k.y (=one obliquity cycle), and thus prevent interpretations on shorter time scales.

The Pliocene records of planktonic foraminifer preservation from Site 999 are applied to the high-resolution age model developed by Haug and Tiedemann (1998). This age model is based on the adjustment of benthic δ^{18}O fluctuations to the astronomically calibrated benthic δ^{18}O records of Sites 846 (Shackleton et al., 1995) and 659 (Tiedemann et al., 1994).

2.2 Planktonic foraminiferal preservation

The weakening and breakage of foraminiferal shells with progressive carbonate dissolution leads to an enrichment of foraminiferal fragments in the >63 μm fraction, and thus to a mass transfer from coarser to finer fractions (e.g. Berger et al., 1982). Hence, preservation of planktonic foraminifers was examined for shell fragmentation to estimate the corrosiveness of deep-water masses.

The >63 μm fraction was separated by wet sieving of ~20 cc of bulk sediment. The 125-500 μm fraction was obtained by dry sieving, and splits of this material containing a minimum 300 particles were used to produce particle counts of whole-test planktonic foraminifers and planktonic foraminiferal shell fragments. A foraminiferal fragmentation index is calculated as % WTF (=100 X number of whole foraminifer tests/(number of whole tests + number of fragments)).
2.3 Particle size data

McCave et al. (1995) found the 10-63 μm mean size to be the most useful parameter for the inference of bottom current strength. The theoretical and empirical basis for the use of the mean sortable silt (mean$_{ss}$) parameter as an indicator for paleo-current strength was established by McCave et al. (1995). Simply put, stronger bottom currents produce coarser mean$_{ss}$ because the >10 μm fraction behaves non-cohesively and thus is mainly transported as individual particles in the viscous sub-layer (McCave et al., 1995). On the other hand, deep ocean currents are rarely strong enough to transport sand-sized particles (McCave et al., 1995). Sorting effects due to strong bottom currents are therefore recorded almost exclusively by the sortable silt fraction (10-63 μm).

In order to reduce the laboratory effort, grain-size analyses were only carried out for every second sample on the carbonate-free material, yielding a resolution of ~10 ky. Particle-size determinations of the <63 μm fraction were made using a Micromeritics SediGraph 5100 over the 0.1-63 μm range. The SediGraph determines particle-size distribution from a dispersed suspension in a settling tube, applying Stoke's law for the settling of particles. Standard methods for the analytical procedure are described in detail by McCave et al. (1995).

Stein (1985) found that samples containing high concentrations of montmorillonite minerals were difficult to analyze, because of their thixotropic character, which increases the viscosity of the settling liquid and therefore hinders particles in settling. XRD studies by Debraban et al. (1997) detected high smectite abundance in sediments from the nearby Amazon fan (e.g. 30% to 50% of the clay minerals). Therefore, before running the SediGraph measurements, clay was separated using the Atterberg method yielding a clay residual between 3 and 10% in the analyzed samples.

3. Results

3.1 Particle-size data at site 927

The SediGraph measurements yielded an average sortable silt abundance of 9.3 wt.% (±2.5%). Mean$_{ss}$ sizes vary within a size window between 11 and 19 μm. This is comparable with results obtained from sedimentary drifts, e.g., the Blake-Bahama Outer Ridge (Bianchi et al., 2001) and from the North Atlantic (Gardar Drift, Bianchi and McCave, 1999). To account for the uncertainty associated with individual mean$_{ss}$ measurements we calculated error estimates on mean$_{ss}$ after the method of Bianchi et al. (1999). Generally, the analytical precision using a SediGraph 5100 in the determination of the mean$_{ss}$ decreases with lower % sortable silt (Bianchi et al. 2001, Bianchi et al., 1999). The error estimates are expressed as error bars for individual samples. The results are shown in Figure 4.

The Pliocene-Pleistocene evolution is characterized by a long-term decrease in average mean$_{ss}$ values, which is paralleled by a drastic increase in amplitudes toward the middle-Pleistocene. This pattern results mainly from an extreme decrease in the recorded minima. By contrast, maxima remain near the same level through the entire record.
Fig. 4: Pliocene to Pleistocene record of calculated mean grain diameters from the sortable silt (10-63 \( \mu m \)) fractions at Site 927, western equatorial Atlantic. The trend lines indicate major steps in the Pliocene and Pleistocene history of Atlantic deep-water circulation.
We subdivide the Pliocene interval into three phases, as distinguished by different amplitude characteristics (Fig. 4). Phase Plio-1 (3.5-3.2 Ma) is characterized by large amplitudes that become gradually smaller during the transition to Phase Plio-2 due to larger values in the recorded mean$_{ss}$ minima. Phase Plio-2 (3.2-2.75 Ma) exhibits the smallest amplitude fluctuations throughout the entire record. A pronounced shift to high amplitude fluctuations is observed at 2.75 Ma, marking the beginning of Phase Plio-3 (2.75-2.2 Ma), which also displays a minor shift to coarser minima at ~2.5 Ma (Fig. 4).

A three-phased division is also recognised in the Pleistocene (Fig. 4). Higher amplitudes are observed during Phase Pleist-1 (1.6-1.3 Ma). Lower amplitude fluctuations and coarser minimum extremes are registered during Phase Pleist-2 (1.3-0.95 Ma). Phase Pleist-3 (0.95-0.3 Ma) displays the highest amplitude fluctuations throughout the record. Phase Pleist-3 is separated from Phase Pleist-2 by a pronounced shift at around 0.95 Ma.

Unique to Phase Pleist-3 is the occurrence of extraordinarily fine mean$_{ss}$ minima, generally less than ~12 μm (arrows in Fig. 5b). Comparison with the benthic foraminiferal δ$^{18}$O record of Bickert et al. (1997b, Fig. 5c) verifies that these events occur at the glacial to interglacial transitions (see also Gröger et al., subm.).

Consistent with previous results from Gröger et al. (subm.), the Pleistocene changes in mean$_{ss}$ are related to glacial-interglacial cycles of deep-water circulation as indicated by the good covariance with the benthic δ$^{18}$O and δ$^{13}$C records from Bickert et al. (1997; Fig. 5b and c).

![Fig. 5: Comparison of (a) benthic foraminiferal δ$^{13}$C (Cibicides wuellerstorfi, Bickert et al., 1997), (b) mean$_{ss}$ and (c) benthic foraminifer δ$^{18}$O (Cibicides wuellerstorfi, Bickert et al., 1997) for the early and mid-Pleistocene intervals at site 927. Note: Because of the negative relationship to ice volume, the scale of the mean$_{ss}$ and δ$^{13}$C plots are inverted to illustrate the relationship with (a). Black arrows mark extraordinarily fine mean$_{ss}$ extremes at the glacial to interglacial transitions.](image-url)
3.2 Planktonic foraminiferal preservation at ODP Site 927 (western equatorial Atlantic)
The record of % WTF exhibits remarkable similarities to the mean$_{SS}$ curve. Figure 6a displays a stepwise decrease in planktonic foraminiferal preservation, a pattern that is paralleled by an increase in amplitudes from the late Pliocene toward the Pleistocene intervals.

Figure 6: a) Pliocene to Pleistocene record of % whole-test foraminifers derived from particle counts of the 125-500 μm fraction for (a) ODP site 927 (western equatorial Atlantic) and (b) for ODP site 999 (Caribbean). The trend lines indicate major steps in the Pliocene and Pleistocene history of planktonic foraminiferal preservation.
During the Pliocene three phases with different patterns are recognised in the % WTF record (Fig. 6a) similar to those described in the mean$_{SS}$ curve (Fig. 3). The best preservation and lowest amplitudes are registered during Phase Plio-2 (from ~3.1 to ~2.7 Ma) with values all above 70 % WTF (Fig. 6a). Phase Plio-1 (3.5-3.1 Ma) shows slightly worse preservation compared to Phase Plio-2. The poorest preservation and highest amplitudes are observed in Phase Plio-3, starting at ~2.7 Ma, where a drastic decrease of the recorded minima is registered. A dissolution maximum is indicated around 2.3 Ma (Fig. 6a) with only 20 % WTF.

Confirming earlier results of Gröger et al. (subm.) the Pleistocene high-amplitude fluctuations in planktonic foraminiferal preservation are related to glacial-interglacial changes in deep-water circulation. This is indicated by the good covariance with the benthic foraminiferal $\delta^{18}$O and $\delta^{13}$C records from Bickert et al. (1997 Fig. 7). Preservation is generally better during interglacials. Maximum foraminiferal preservation occurs at the glacial to interglacial transitions (see also Gröger et al., subm.).

The glacial minima in carbonate preservation are much more pronounced in the younger sections, while interglacial preservation maxima are similar to those recorded during the Pliocene (Fig. 6a). However, a short period with better preservation is observed during Phase Pleist-2 (1.3-1.1 Ma), where only one value falls below 60 % WTF (Fig. 6a). Highest amplitude fluctuations are found during Phase Pleist-3 (1.1-0.3 Ma, Fig. 6a). Glacial periods younger than 480 ka show a drastic increase in frequency together with a shift to generally worse preservation. This event is associated with a global sequence of carbonate dissolution events related to the mid-Brunhes dissolution cycle around oxygen isotope stages (OIS) 12 and 11, and is discussed in detail by Gröger et al. (subm.).

### 3.3 Planktonic foraminifera preservation at ODP site 999 (Caribbean)

Relatively high amplitude fluctuations of planktonic foraminiferal preservation are observed throughout the entire record (Fig. 6b). Preservation is generally worse during the Pliocene interval. In general both the maxima and minima exhibit higher fragmentation levels in the Pliocene compared to those recorded during the Pleistocene. A shift toward considerably better preservation occurs at ~3.3 Ma. The best preservation during the Pliocene is observed at around 2.5 Ma with values exceeding 80 % WTF (Fig. 6b).

The Pleistocene history at this site can be subdivided into three steps (Fig. 6b). The poorest preservation is registered from 1.5-1.0 Ma. Here, distinct dissolution spikes occur at 1.3 and Ma 1.0 Ma with values falling below 40 % WTF. Between 1.0-0.7 Ma a short interval with the lowest indices follows, where values never fall below 80 % WTF. In the youngest section, a return to higher amplitude fluctuations with prominent dissolution events around 450, 600, and 700 Ma is recorded.

### 4. Discussion

#### 4.1. The depositional control of mean$_{SS}$ at ODP site 927

Sediment supply to the Ceará Rise may be controlled by the regional equatorial surface-water hydrology (Rühlemann, 2001). However, Gröger and Henrich (subm.) have demonstrated that the
Part II: Variability of silt grain size and planktonic foraminifera preservation.

Fig. 7: Comparison of (a) % whole-test foraminifers and (b) benthic foraminiferal $\delta^{13}$C (Cibicides wuellerstorfi, Bickert et al., 1997) with (c) benthic foraminiferal $\delta^{18}$O (Cibicides wuellerstorfi, Bickert et al., 1997) for the early and mid-Pleistocene intervals at site 927.

mean$_{ss}$ at site 927 is controlled by the weakening and strengthening of bottom-current intensity. The main argument for this assumption is the good correlation between the mean$_{ss}$ records generated from the terrigenous (lithogenic) and the biogenic (calcareous) silt components (Gröger et al., subm.), pointing to post-depositional processes of sediment sorting (Robinson and McCave, 1994). Additional corroboration has been recently obtained from mean$_{ss}$ records from ODP Site 929, which is located farther to the east and deeper on the Ceará Rise at ~4370 m water depth. Throughout the Brunhes epoch (0.8-0.3 Ma), the site 929 record displays mean$_{ss}$ values up to 8 µm higher than those from the shallower site 927 (Gröger and Henrich, subm.). Because of the proximity of the two sites, it is very unlikely that differences in surface-water hy-
drography could explain these large vertical differences in $\text{mean}_{(SS)}$. In addition, spectral analysis of the $\text{mean}_{(SS)}$ records from site 927 and 929 reveals that most of the spectral power is concentrated at the eccentricity and obliquity frequency bands, with only weak and statistically insignificant power at the precession frequency band (Gröger and Henrich, subm.). On the other hand, Rühlemann et al. (2001) demonstrated that the terrigenous sediment supply to the Ceará Rise varied with a strong precessional 23 k.y. periodicity, due to its linkage to the equatorial trade wind system. Thus, the lack of significant power in the precession frequency band for the $\text{mean}_{(SS)}$ records from site 927 and 929 clearly argues against a control by the equatorial surface-current system (Gröger and Henrich, subm.). In conclusion, we consider the $\text{mean}_{(SS)}$ variability to be mainly controlled by variations in bottom-current vigor. A detailed discussion of $\text{mean}_{(SS)}$ control at the NE flank of the Ceará Rise is provided by Gröger and Henrich (subm.).

The question whether bottom-current strength at the Ceará Rise is related to the strength of circulation within the LNADW cell is of basic relevance for the interpretation of the $\text{mean}_{(SS)}$ proxy. In Figure 4 we compare the Pleistocene record of $\text{mean}_{(SS)}$ with the benthic $\delta^{13}$C values. The benthic $\delta^{13}$C proxy broadly reflects the nutrient content of the water mass while the $\text{mean}_{(SS)}$ proxy is directly related to the physical flow regime which transports these waters (Bianchi et al., 2000). Nevertheless, despite the different nature of the two proxies, they appear to correlate very well throughout the Pleistocene (Fig. 4, a and b). This argues for a coupling between the bottom-current velocities at the Ceará Rise and the effective circulation strength within the LNADW cell, because only the geostrophic currents should be capable of influencing both the physical flow and the geochemical properties of deep waters.

4.2. Pliocene-Pleistocene trends in the history of bottom current strength and planktonic foraminifer preservation in the western equatorial Atlantic (site 927)

Results from benthic foraminiferal $\delta^{13}$C studies at ODP site 607 document the transition in the mid-Pliocene from a strong flux of LNADW (e.g. superconveyor model) to a progressively decreasing LNADW influence in the Atlantic Ocean (Raymo, 1992, Raymo et al., 1989, Ruddiman et al., 1989). This evolution is clearly displayed by the $\text{mean}_{(SS)}$ curve, which indicates a considerable decrease in average bottom-current strength at the Ceará Rise during the Pliocene to Pleistocene glacialis (Fig. 3), and thus, a glacial weakening of circulation within the LNADW cell from the mid-Pliocene toward the Pleistocene. Additionally, the progressive worsening of planktonic foraminiferal preservation in younger glacialis (Fig. 5a) reflects a progressive decrease in the volume of NADW in the western equatorial Atlantic.

The two parameters clearly exhibit a three-phase evolution during both the Pliocene and Pleistocene intervals (Fig. 3, 5a). Differences between the two proxies in the timing of phase transitions are likely to be related to different response times to climatically induced changes in LNADW production between the physics of deep water flow and the more complex interactions in the carbonate system (Gröger and Henrich, subm.). In each phase distinct modes of deep-water circulation in the western equatorial Atlantic are recorded. In order to find the trigger for the transitions it is reasonable to focus on synchronous changes in the North Atlantic Deep Water production, which controls the NADW flux to the Southern Ocean.
4.3 Early Pleistocene to mid-Pleistocene stepwise changes in deep-water circulation in the western equatorial Atlantic

Short-term fluctuations of the mean\(_{ss}\) curve show a positive relationship to the benthic \(\delta^{13}\)C record, and a negative relationship to ice volume as recorded by the \(\delta^{18}\)O record (Fig. 4). This indicates that the deep-water mass was less well ventilated during glacial periods of reduced current strength. The % WTF fluctuations are positively related to the benthic \(\delta^{13}\)C record and negatively related to the benthic \(\delta^{18}\)O record (Fig. 6). This indicates a lower glacial carbonate ion content of the deep water mass during glacials and thus evidences a diminished influence of NADW. Altogether, this points to a considerably weaker circulation in the LNADW cell during the Pleistocene glacials compared to the interglacials (see also Gröger et al., subm.).

Superimposed on these short-term orbitally induced changes, the Pleistocene history of bottom-current strength and deep-water chemistry at the Ceará Rise is marked by long-term changes as illustrated by prominent shifts in the mean\(_{ss}\) and % WTF record.

The transition from the early Pleistocene Phase Pleist-1 (1.6-1.3) to Phase Pleist-2 (1.3-0.95) is marked by decreasing amplitudes in the mean\(_{ss}\) (Fig. 3b) and the % WTF records (Fig. 3, 5a). Higher amplitudes are characteristic of Phase Pleist-1, indicating that the glacial-interglacial differences in deep-water chemistry and bottom-current strength are more extreme than in Phase Pleist-2.

In the NGS (e.g., the main area of LNADW formation in the modern Atlantic (Dickson and Brown, 1994, Duplessy et al., 1996)) this time interval is characterized by extreme changes in carbonate preservation (Henrich et al., in press.). This is interpreted to reflect stepwise changes in deep-water production, which were mainly driven by the northward expansion of the entrainment of saline surface waters into this area via the Proto-Atlantic Current (Henrich et al., in press.).

This gives rise to the possibility that during the periods of enhanced entrainment of saline waters into the NGS (e.g., interglacials), the deep-water produced there was dense enough to contribute to the LNADW. This, in turn, would have reinforced the circulation in the LNADW cell, resulting in stronger bottom currents recorded at site 927. In contrast, during glacial periods, when the entrainment of saline waters into the NGS was suppressed by larger ice sheets, deep-water contribution was mainly limited to the UNADW. This would have weakened the LNADW circulation and led to weaker bottom currents at site 927. This might explain the stronger glacial-interglacial contrasts in bottom-current strength during Phase 1.

After 1.3 Ma, however, the situation changed. The records display a decrease in amplitudes and glacial mean\(_{ss}\) minima are significantly coarser compared to Phase Pleist-1 (Fig. 3). This suggests that Phase Pleist-2 (1.3-0.95 Ma) was a period of rather stable bottom currents at site 927 and, thus, points to a persistent strong circulation within the LNADW cell. Moreover, better preservation of planktonic foraminifers is registered during Phase Pleist-2 with only one value falling below 50 % WTF at ~1.25 Ma (Fig. 5a). This points to an increased influence of LNADW in the western equatorial Atlantic.

The shift from Phase Pleist-2 to Phase Pleist-3 displays very fundamental changes contemporaneous with the MPT between 1.1 and 0.7 Ma. At the Ceará Rise this period includes the most
extreme decreases in glacial bottom-current strength and a shift toward a higher glacial nutrient content of the deep-water mass at site 927 (see the very pronounced benthic $\delta^{13}C$ minima in Fig. 4a). We conclude that, contemporaneously with the establishment of the modern mega-scale glaciations during the MPT (e.g., Imbrie et al., 1993), a pronounced weakening of circulation within the LNADW cell during glacials occurred. In agreement with this we observe a considerable decrease in glacial planktonic foraminiferal preservation (Fig. 5a) during Phase Pleist-3, portraying the diminished LNADW influence in the equatorial Atlantic.

By contrast, the interglacial maxima of mean$_{65}$ and foraminiferal preservation remained nearly at the same level throughout the Pleistocene indicating a persistent strong circulation in the LNADW cell during interglacials.

Widespread changes associated with the MPT are also recognized in carbonate preservation records from the NGS, Labrador Sea, and North Atlantic (Henrich et al., in press.). This indicates that the northern deep-water production areas shifted into another mode of operation. A sequence of gradual shifts toward better carbonate preservation occurs between 1.1 and 0.7 Ma, and expands successively farther into northern and western regions of the NGS. It appears plausible that with the increased recruiting from northernmost areas in the NGS for the overall southern deep-water export, the production of LNADW changed to a modus which became most vulnerable to glacial-interglacial induced-changes in sea-ice expansion in this region. Consequently, the density of deep waters produced in the NGS was sufficient to guarantee a contribution into the LNADW layer preferentially during interglacial periods (Henrich et al., in press). Accordingly, during interglacials only, when the NGS was for the most part ice-free, a strong circulation could be maintained within the LNADW cell. Under these conditions, the transition from the smaller ice sheets of the 41 k.y. world to the development of larger ice caps during the 100 k.y. world must have triggered the significant weakening of circulation in the LNADW cell during glacial periods.

In summary, the recorded shifts in deep-water proxy records from the western equatorial Atlantic associated with the MPT can be understood as a direct response to the climatically induced changes in both deep-water and sea-ice formation in the NGS.

Another fundamental difference between the Phases Pleist-3 and Pleist-2 is the character of the glacial to interglacial transitions. During and after the MPT, the transitions are characterized by rapid shifts from very low to high mean$_{65}$ values (see arrows in Fig. 4b). Gröger et al. (subm.) proposed a "shutdown" scenario of LNADW production caused by meltwater discharge events in the North Atlantic that lower the salinity of the surface water in the LNADW formation area. Figure 4b illustrates that such events are only observed during Phase Pleist-3. The absence of such events prior to the MPT may be explained by the less extensive sea-ice covering (Jansen and Sjoholm, 1991, Henrich and Baumann, 1994, Raymo, 1992) and/or may be attributed to a more southerly positioned center of LNADW formation in the NGS. The occurrence of these events, however, further illustrates the increased vulnerability of LNADW formation after the MPT.
4.3 The Late Pliocene

The Pliocene interval shows a three-phase evolution in bottom-current strength and planktonic foraminiferal preservation (Fig. 3, 5a).

During Phase Plio-1 (3.5-3.2 Ma) the rather unstable circulation in the lower NADW cell is evidenced by higher amplitude fluctuations exhibited in the mean$_{(ss)}$ record (Fig. 3). The shift to Phase Plio-2 (3.2-2.75 Ma) resulted in a stronger and more stable circulation during the intensification of NHG, which endured until ~2.75 Ma (evidenced by a drastic decrease in amplitudes and an increase in average mean$_{(ss)}$ values, Fig. 3). In addition, the excellent preservation of foraminifera during Phase Pleist-2 is indicative of the predominance of well ventilated NADW in the western equatorial Atlantic.

Both the NADW predominance and the strong circulation indicated for Phase Plio-2 support the "superconveyor belt" model of Raymo (1992) and Raymo et al. (1996), which is based on benthic $\delta^{13}$C evidence. It postulates higher NADW production before the initiation of major NHG.

This situation, however, changes drastically with the beginning of Phase Plio-3 where considerable decreases in the recorded mean$_{(ss)}$ minima (Fig. 3) and %WTF minima (Fig. 5a) are observed. The timing of this shift coincides well with the first occurrence of large-scale continental ice shields at about 2.75 Ma. This is indicated by the massive appearance of ice-rafted debris in northern high latitude oceans (Thiede et al., 1998, Jansen and Sjöholm, 1991, Shackleton et al., 1984) and oxygen-isotope evidence (e.g. Raymo et al., 1992).

Interestingly, a contemporaneous shift has been detected in carbonate preservation records from the NGS. The overall good carbonate preservation before ~2.8 Ma is replaced by generally poor carbonate preservation in the southeastern NGS from 2.8 to 1.9 Ma (Henrich et al., in press.). This indicates the beginning of a drastic decrease in deep-water production in this area (Henrich et al. in press.). We conclude that, with the appearance of large-scale continental ice sheets in the Northern Hemisphere, circulation in the LNADW cell became considerably suppressed in a manner similar to the modern modus of ice sheet-forcing (e.g. Henrich et al., in press.). This drastic change resulted in the termination of the superconveyor. Higher amplitude fluctuations, however, observed during Phase Plio-1 in the records of mean$_{(ss)}$ (Fig. 3) and %WTF (Fig. 5a) indicate that the LNADW circulation remained strong at least during warmer periods when the large ice sheets retreated.

On the other hand, higher amplitude fluctuations in mean$_{(ss)}$ and %WTF indicate a rather unstable LNADW circulation during Phase Plio-1 (Fig. 3, 5a). This argues against the presence of a superconveyor prior to ~3.2 Ma. Since there is no evidence of large ice accumulations in the Northern Hemisphere at this time, the moderately fluctuating LNADW circulation can not be plausibly explained by ice-sheet forcing. Notably, the transition from a somewhat fluctuating mode to the more stable circulation at around 3.2 Ma coincides well with the inception of strong cooling on the Northern Hemisphere (Haug and Tiedemann, 1998, Thiede et al., 1998, Raymo et al., 1996, Raymo, 1992, Loubere, 1988, Keigwin, 1987). In order to understand the extraordinarily stable LNADW circulation between ~3.2 and 2.75 Ma (and the weaker circulation...
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prior to 3.2 Ma), we discuss below three possible mechanisms, each of them assuming the northern high-latitude cooling starting at 3.2 Ma as a necessary precursor.

1) One explanation may be that the density of deep waters produced in the NGS before the inception of strong cooling at 3.2 Ma was not sufficient to support a continuous deep-water entrainment into the lower NADW cell. Such conditions could be attained by a lower salinity of Atlantic surface waters entering the NGS. In the modern world the salinity of the Atlantic Ocean is linked to the net atmospheric export of water vapor through the Central American pathway to the Pacific Ocean, which is driven primarily by the trade winds (e.g., Stocker and Wright, 1991, Zaucker et al., 1994). The salinity of the Atlantic Ocean is a crucial factor for NADW production and the maintenance of global thermohaline circulation (Broecker et al., 1990). We speculate that the strong cooling at northern high latitudes after ~3.2 Ma might have intensified the pole-to-equator gradients in temperature and air pressure. In this case the NE trade winds would have been strengthened, triggering a higher net export of water vapor from the Atlantic to the Pacific Ocean. This would have resulted in a salinity increase in the Atlantic Ocean favoring the production of denser deep waters at high northern latitudes. So far, however, no proxy data exist that would suggest such a strengthening of trade winds during the required time frame.

Another mechanism that could increase the density of deep waters is a lowering of the temperature of surface waters entering the NGS. Today, these waters are cooled to a temperature of 2-4 °C by the cold dry winds streaming off Canada and Greenland. Intensification of these winds during the period of Northern Hemisphere cooling (between ~3.2 and 2.75 Ma) might have acted as a further positive feedback for the production of denser deep waters. Model simulations have suggested an intensification of these winds resulting from the enhancement of pressure gradients between the Icelandic low and Azores high-pressure systems during the middle Pleistocene (Haywood et al., 2000). Moreover, Haywood et al. (2000) noted that the associated increase of wind stress applied to the surface of the North Atlantic would have strengthened the surface circulation, including the Gulf Stream. This, in turn, would have a positive effect on deep-water production by strengthening the transport of saline surface waters to the northern North Atlantic.

2) As evidenced by numerous model simulations (e.g. Cubash et al., 1992), higher air temperatures may influence the precipitation/vaporization ratio positively. Accordingly, an increase in mid- to high-latitude precipitation would lower the salinity of surface waters, suppressing deep-convection in the subpolar North Atlantic (e.g. Crowley, 1996, Cubash et al., 1992). Hence, the strong cooling in the Northern Hemisphere may have been responsible for the inverse effect, resulting in a lower precipitation/vaporization ratio, thus strengthening the thermohaline overflow in the northern high latitudes.

3) Finally, a steeper temperature gradient in surface waters between the NGS and those of the adjacent North Atlantic provided excellent preconditions for NADW formation in this area (Henrich et al., in press).

It remains unclear whether all of the processes discussed above were involved and which of them were the most important ones. Ideal preconditions for the production of deep waters capable of entraining into the lower NADW cell, however, were obviously realized during the strong
northern high-latitude cooling period from 3.2 to 2.75 Ma. During this period the ice caps were relative small. Consequently no meltwater discharge or low-salinity surface-water layers were developed (Henrich et al., in press). Because deep-water formation is very sensitive to changes in the salinity balance in the Atlantic (Broecker, 1990), we propose that variations in LNADW circulation prior to ~3.2 Ma were linked to the Atlantic salinity budget, whereas after 2.75 Ma they were primarily controlled by ice-sheet forcing.

4.4 Preservation of planktonic foraminifera in the deep Caribbean: Implications for the Pliocene-Pleistocene deep- and intermediate-water circulation.

In striking contrast to the western equatorial Atlantic, the Caribbean %WTF record (ODP site 999, Fig. 5b) indicates better preservation of planktonic foraminifera during the Pleistocene interval and stronger dissolution during the Pliocene (Fig. 5b). We explain this by an increased entrainment of uppermost UNADW into the Caribbean from the intermediate Atlantic relative to the corrosive AAIW.

A substantial change in the evolution of the deep Caribbean carbonate system occurs at ~3.3 Ma where a shift toward better carbonate preservation is indicated (Fig. 5b). Surprisingly, the timing of this shift corresponds to no other known substantial event in the palaeoclimatic and paleoceanographic history. Therefore, we speculate that this drastic change may be linked to the gradual closing of the Isthmus of Panama. The gradual shoaling of this seaway is of great importance for the thermohaline circulation because it diminishes the Atlantic-Pacific exchange of surface waters. The resulting salinity increase in the Atlantic strengthens the thermohaline circulation (e.g. Haug et al., 1998). However, the final closure that allowed land exchange of mammals between North and South America did not occur before ~2.7 Ma (Marshall, 1988). On the other hand, one might assume that at some time during the long-term, stepwise Panamanian closure a threshold was exceeded that was especially sensitive to the formation of uppermost NADW. If such a threshold was reached at ~3.3 Ma, this would have resulted in an increased flux of UNADW to the intermediate Atlantic and to the Caribbean, and would explain the observed substantial change.

The low resolution of the Pleistocene age model at site 999 limits interpretations inferred from the %WTF record to periods larger than one obliquity cycle (~40 k.y.). Nevertheless, some conclusions will be deduced by comparing the site 999 record of %WTF with those from site 927.

The Pleistocene interval displays three steps of planktonic foraminiferal preservation at site 999 (Fig. 5b). The extraordinarily good preservation between 1.0 and 0.7 Ma indicates that the MPT was a period of enhanced and relative stable entraining of UNADW into the Caribbean. The pronounced long-term shift toward good preservation at site 999 occurs a bit later (1.0 Ma) than the change from Phase Pleist-2 to Pleist-3 at site 927 where the significant decrease in preservation is recorded (1.1 Ma). However, this may be attributed to the uncertainty associated with the Pleistocene age model at site 999.
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On the other hand, the distinct timing of these two events may indicate a stepwise shoaling of the overall LNADW core injected into the Atlantic Ocean. Initially, this would lead to a reduced contribution of northern source waters to the deeper western Atlantic. Later, with continued shoaling, the critical depth of the Caribbean sill front may have been exceeded, and, thus would resulting in abrupt entraining of uppermost NADW to the Caribbean. The lag between the two shifts may then represent the time span during which northern source deep waters are entrained predominantly between the core depth of site 927 and the depth of the Caribbean sill front.

Figure 5b displays highest amplitude fluctuations from 1.5 to 1.0 Ma and between 0.7 and 0.3 Ma. According to previous high-resolution studies from the Caribbean these variations can be clearly related to glacial-interglacial cycles in carbonate preservation with maximum preservation recorded during glacial phases (e.g. Haddad and Droxl, 1996).

Despite the generally good preservation during the Pleistocene, some of the recorded minima match those recorded in the Pliocene. The most extreme minimum is registered around 450 ka (14.50-15.11 mbsf, Fig. 5b). We assume that this interval of intense carbonate dissolution corresponds to interglacial stage 11. This would corroborate the previous results of Ferraro et al. (1996) who reported the most intense carbonate dissolution at ODP-Sites 999 and 1000 (northern Nicaragua Rise) at around stage 11. Furthermore, as indicated by the strongest Atlantic-Pacific benthic foraminiferal δ¹³C gradient (Raymo et al., 1990) LNADW production was at its maximum during interglacial Phase 11. This was likely associated with a reduced UNADW flux to the Atlantic. A resulting predominance of AAIW in the deep Caribbean might explain the prominent decrease in carbonate preservation.

The fact that both the recorded maxima and minima in foraminiferal preservation show higher % WTF values in the Pleistocene records than in the Pliocene suggests an increasing contribution of uppermost UNADW to the Atlantic during both the glacial and interglacials. This suggests a generally increasing production of UNADW toward the Pleistocene, which was deduced earlier from a contemporaneous rise in mean benthic δ¹³C values recorded at ODP site 502 in the deep Caribbean (Oppo et al., 1995).

In contrast to this, the Pleistocene glacial minima in foraminiferal preservation recorded at ODP-Site 927 are drastically decreased compared to the Pliocene. However, no such trend is recognised for the interglacial maxima that remain nearly on the same level. This suggests a persistent high contribution of interglacial LNADW to the Atlantic but a severe reduction of glacial LNADW. In conclusion, the increased flux of interglacial uppermost NADW to the Atlantic (monitored by Pliocene-Pleistocene increase of % WTF minima at site 999) is not paralleled by a corresponding decrease of interglacial LNADW contribution. This argues against the assumption that the reduction of LNADW was compensated linearly by an increase in UNADW production, at least on glacial-interglacial time scales.
Conclusions

Late Pliocene (3.4-2.2 Ma) and Pleistocene (1.6-0.3 Ma) records of mean sortable silt and planktonic foraminiferal preservation indicate a highly variable history of bottom-current strength at the Ceará Rise, western equatorial Atlantic.

Our results for this area indicate a stepwise reduction of glacial bottom-current strength from the Late Pliocene toward the Pleistocene. This is interpreted to reflect a stepwise weakening of the circulation in the LNADW cell with main shifts occurring at 2.75 Ma and 0.95 ka.

The most stable circulation in the LNADW cell, inferred from mean$_{(ss)}$ and planktonic foraminiferal preservation, is found during the initial phase of NHG between ~3.2 and ~2.75 Ma. This is consistent with the "superconveyor model" of Raymo et al. (1996). However, our data do not support this model from 3.5 to 3.2 Ma. We propose that variations in the LNADW flux prior to 3.2 Ma were mainly controlled by variations in the surface-water salinity in the Atlantic Ocean, whereas after 2.75 Ma they are controlled by ice-sheet forcing.

A drastic reduction of glacial bottom-current strength at ODP site 927 (3315 m) is inferred after 2.75 Ma. This shift is synchronous with the first occurrence of larger continental ice shields and with a drastic decrease in deep convection in the NGS (Henrich et al., in press).

An additional impact on the Atlantic deep-water circulation is registered during the mid-Pleistocene climate transition. It is indicated by drastic decreases in bottom-current strength and preservation of planktonic foraminifers.

In agreement with the history of bottom-current strength inferred from the mean$_{(ss)}$ proxy data, a stepwise worsening in the preservation of planktonic foraminifera during glacial at the Ceará Rise indicates a diminished influence of LNADW at the Ceará Rise from the Late Pliocene to Pleistocene intervals. This indicates a general decrease in the contribution LNADW to the Atlantic.

By contrast, an opposing trend is recognised in the Caribbean at ODP site 999, showing poorer preservation of planktonic foraminifera during the Late Pliocene interval moving toward better preservation during the Pleistocene. This indicates an increasing overturn of northern-source deep waters through the Caribbean sill front from the Atlantic Ocean into the Caribbean basins, indicating an increase in the contribution of UNADW to the Atlantic.

Acknowledgements

We thank W. Hale, T. Wagner, and A. Volbers for comments and criticism. We thank Renate Henning and Christian Müller for laboratory and technical assistance. This work was financially supported by the German Science Foundation (DFG-Grant He 1671/10).

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Deep-water circulation during the Pleistocene (0.8-0.25 Ma): inferences from near-bottom-current flow variability and deep-water chemistry in the western equatorial Atlantic

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Abstract

Geochemical proxy records have been widely applied to monitor variations in the flux of northern- and southern-source deep waters to the Atlantic Ocean basins. In this study, grain-size data are used to monitor variations in near-bottom current strength at deep and intermediate depths in the Guyana basin. We present records of the mean grain diameter in the sortable silt fraction ($10-63 \mu m$, mean$_{(ss)}$) from Ocean Drilling Program (ODP) Sites 927 (3315 m) and 929 (4356 m) on the northeastern flank of the Ceará Rise (~5°N, 44°W), which is located about midway between the northern and southern deep-water sources.

Our results indicate that bottom-current induced sediment sorting rather than varying sediment supply is the main control for mean$_{(ss)}$ variations at both waterdepths. Significant inter-site differences in mean$_{(ss)}$ variability reflect the different flow regimes associated with Lower North Atlantic Deep Water (LNADW) at Site 927 and Antarctic Bottom Water (AABW) at Site 929. Reduced bottom-current strength, related to weaker circulation in the LNADW cell is indicated at the shallower site during glacial periods. Spectral analysis of various deep-water proxy records reveals that most spectral power at the shallower Site 927 is concentrated at the Earth's eccentricity frequency band. Cross-spectral analysis indicates that maxima in the inferred bottom-current strength lag ice-volume minima by ~8 k.y. at the Earth's eccentricity frequency band. By contrast, the recorded benthic foraminiferal $\delta^{13}C$ proxy variations are close to being in phase with ice volume. This contrast indicates a lag time between the reconfigurations of deep-water structure and the subsequent changes in the flow velocity of LNADW in the Guyana Basin due to variations in NADW production.

At the deeper Site 929 most of the spectral power is concentrated at the Earth's obliquity frequency band. Maxima in current speed correspond to maxima in the Southern Hemisphere summer insolation. We suggest that changes in bottom-current strength at Site 929 are related to variations in the AABW flux to the Guyana Basin. During periods of low flux the upper boundary of AABW deepens. AABW then has to flow to the east of the Ceará Rise because the sloping topography between the Amazon Fan and the western flank of the Ceará Rise hinders it from flowing west of the Rise. An increased AABW flux, on the other hand, may lead to expansion of the AABW layer in the western equatorial Atlantic. At the higher levels, AABW can pass into the Guyana Basin on both sides of the Ceará Rise by overriding the topographic barrier to the west. As a consequence, the mean flow diameter for AABW passing the Guyana Basin is considerably enlarged, resulting in a slowing of flow and leading to reduced bottom-current vigor at the eastern passage.
Data for inferred bottom-current strength and deep-water chemistry (benthic foraminiferal stable carbon isotope signatures, carbonate corrosiveness of deep water) are compared at Site 927 and Site 929. Our results indicate that substantial changes in both the quantity and quality of LNADW were the main driver for Atlantic deep-water mass reconfigurations during the Pleistocene glacial-interglacial cycles.

In addition, high-frequency fluctuations in mean* during isotope stages 10 and 11 suggest cyclic variations in bottom-current strength on sub-orbital to millennial time scales.

**Keywords:** bottom currents, mean sortable silt, deep-water circulation, equatorial Atlantic.

**1. Introduction**

**1.1 Deep-water regimes in the western Atlantic**

Modern deep-water circulation in the western equatorial Atlantic comprises two principal water masses: (1) the oxygen-rich and calcite-saturated Lower North Atlantic Deep Water (LNADW) expanding southward across the equator, and (2) in the lower deep-water layer (>4000 m), oxygen-depleted and calcite-undersaturated Antarctic Bottom Water (AABW) flowing northward. Located at a central position approximately midway between the source regions of the two deep-water masses, Ocean Drilling Program (ODP) Leg 154 sites at the Ceará Rise are excellently suited to monitor the glacial/interglacial shifts in volume and current strength of the two deep-water masses.

**Figure 1:** Configuration of deep- and intermediate-water masses in the western equatorial Atlantic as indicated by the calculated $\delta$ CO$_3^{2-}$ ion concentration (mmol/kg). The thick line indicates the pressure normalized calcite saturation state ($\delta$ [CO$_3^{2-}$]=0) which deepens northward due to the greater influence of NADW. AAIW=Antarctic Intermediate Water, NADW=North Atlantic Deep Water, AABW=Antarctic Bottom Water. Calculated carbonate-ion distribution refers to GEOSECS data after Bainbridge (1981).
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LNADW is formed by the sinking of nutrient-depleted, saline surface waters in the Norwegian-Greenland Sea (NGS). Thermohaline driven, LNADW flows southward across the equator, and is transported, via the Antarctic Circumpolar Deep Water (ACDW), to the Indian and Pacific Oceans (Reid, 1989). Since NADW contributes large amounts of salt and heat to the other oceans (e.g. Gordon, 1996), LNADW formation in the NGS is a key factor in the maintenance of global thermohaline circulation. One important effect is salt injection into the ACDW, which is a crucial factor for deep-water formation in the Weddell Sea (Reid, 1996).

By contrast, the northward expanding Antarctic Bottom Water (AABW) is a mixture of very cold outflow waters from the Weddell Sea (Weddell Sea Deep Water, WSDW) and very old waters, originating from the ACDW (e.g. Reid, 1989). As an older water mass it is nutrient-rich, has very low $\delta^{13}C$ values of $\Sigma CO_2$, and is enriched in carbon dioxide (Kroopnick, 1985).

Because of the specific initial compositions of their source waters LNADW and AABW are clearly distinguishable in the Atlantic Ocean based on nutrient content and carbonate-ion concentrations (Kroopnick, 1985, Fig. 1).

1.2 Study area and depositional setting
The Ceará Rise lies about 800 km westward from the Amazon River mouth in the Guyana Basin (Fig. 2). The Amazon River discharge is the main source for siliciclastic sediment supply to the Ceará Rise (e.g. Rühlemann, 2001). From the continental shelf the Amazon Fan sediments extend to depths greater than 4700 m, to the northern front of the Ceará Rise, where they merge with the Demerara and Ceará Abyssal Plains (Darmuth et al., 1988; Manley and Flood, 1988). Because of its great offshore extent, wide areas of the Amazon Fan are today exposed to the flow regime of NADW off the NW wedge of the Ceará Rise (Fig. 2).
Located on the NE flank of the Ceará Rise ODP Sites 927 and 929 are protected from direct sediment delivery from the nearby Amazon Fan. However, individual turbidity currents occurring in the Lower Amazon Fan are capable of spreading around the northern wedge of the Ceará Rise and propagating onto deeper parts of the NE flank (Curry et al., 1995).

The Amazon River supplies sediment to the Ceará Rise by injection of the freshwater plumes into surface currents (Rühlemann et al., 2001). Today, fine-grained Amazon sediments can reach the Ceará Rise only via the seasonally eastward-flowing North Equatorial Counter Current (NECC, Fig. 2). The strength of the NECC is controlled by the position of the Intertropical Convergence Zone, which is linked to seasonal variations in the intensity of NE and SE trade winds (e.g., Rühlemann et al., 2001, Tiedemann and Franz, 1997). Accordingly, past variations in the Amazon sediment supply were also strongly influenced by the equatorial surface current system and, hence, by the paleo-intensity of NE and SE trade winds (Tiedemann and Franz, 1997).

The regional flow path of deep waters in the southern Guyana Basin is determined by the NW-SE striking topography of the South-American continental slope and the mid-ocean ridge (Fig 2). The Ceará Rise acts as a natural barrier for deep waters below ~3000 m channeling them along the NE and SW slopes. Because of the sloping topography between the Ceará Rise and the Amazon cone, AABW today is restricted to the northeastern side of the Ceará Rise (Fig. 2, Rhein et al., 1998). By contrast, the shallower LNADW layer is found on both sides of the Ceará Rise (Rhein et al., 1996).

Site 927 (~3300 m) is presently bathed in LNADW (Curry et al., 1995). Site 929 is the deepest site (~4400 m) recovered at the Ceará Rise, and is exposed to the flow regime of AABW. Rhein et al. (1998) inferred the LNADW/AABW boundary from CTD profiles (measuring conductivity, temperature, and density) in the Guyana Basin at roughly 4000 m. This is in agreement with results from current-meter mooring measurements from a more southerly position in South Equatorial Channel at -5°N, 35°W (Hall et al., 1997). These authors reported the northward flow of AABW already at depths between 4100 and 4300 m, even during seasons when the flow of overlying LNADW was intensified. AABW entrains into shallower depths on its way northward (due to decreases in temperature and density), explaining the slightly shallower position of the upper AABW boundary in the study area.

1.3 Results from previous studies

Previous studies have used the δ¹³C concentration in benthic foraminiferal shells as a proxy for the paleo-nutrient content of the deep-water mass, or investigated the carbonate corrosiveness of deep-water using conventional preservation proxies (Bickert et al., 1997a,b, Curry and Cullen, 1997, Oppo et al., 1995, Sarthiein et al., 1994, Raymo et al., 1990, Raymo et al., 1992).

Most of these studies indicate that LNADW production was considerably suppressed during glacial periods (e.g., Raymo et al., 1990, Sarthiein, 1994, Tiedemann and Franz, 1997, Bickert et al., 1997a,b, Curry and Cullen, 1997), which was most likely compensated for by a vertical expansion of AABW in the Atlantic Ocean. This general model has been inferred mostly from geochemical proxy records (benthic foraminifer δ¹³C, carbonate preservation). Many studies have observed that the steep gradients in the benthic δ¹³C values and the carbonate lysocline
that occur at the transition across the LNADW/AABW boundary, were located at much shallower depths during glacial periods (e.g. Bickert et al., 1997a,b; Curry and Cullen, 1997). These features are further supported by corresponding variations of the Cd/Ca ratios in benthic foraminiferal tests (Boyle, 1988) and more recently of neodymium isotope ratios measured in Fe-Mn oxide crusts grown on benthic foraminiferal shells (Rutberg et al., 2000).

Geochemical proxy records can monitor the vertical distribution of deep-water masses, and they provide a powerful tool to reconstruct the water-mass configuration along distinct transects. They can not, however, record variations in physical characteristics of deep-water flow (e.g. near-bottom-current strength). This represents a crucial drawback of many previous studies. A better knowledge of the physical characteristics of geostrophic currents would provide valuable information about the weakening and strengthening of circulation along critical transects, which would allow estimates of changes in the transfer rates of deep water between the oceans.

A substantial problem that remains is the way in which the Atlantic deep-water configuration responds to changes in LNADW production. For example, from the physical point of view there may be two ways to balance the glacial suppression of LNADW production:

1. The glacial loss of large volumes of LNADW can be balanced by a volumetric decrease of the NADW layer in the Atlantic Ocean. This would require a compensating increase of AABW injected into the Atlantic.
2. The LNADW loss could be compensated by a weaker and less efficient circulation of LNADW. This would lead to a slower streaming of LNADW, thus would reducing the export from the Atlantic to the other oceans.

The two models are not exclusive but may be considered as "end member" configurations, allowing various intermediate stages between them.

In recent studies, Gröger et al. (subm.a, b) addressed this question and provided evidence that bottom-current velocities on the Ceará Rise at the core depth of LNADW (Site 927) were much slower during glacial periods compared to interglacials. This finding points to a weaker, and hence, less efficient circulation within the LNADW cell, and supports the idea of an reduced LNADW transfer to the other oceans during glacials.

However, previous studies have verified that changes in deep-water chemistry along a depth transect on the Ceará Rise occurred synchronously (Bickert et al. 1997a,b; Curry and Cullen, 1997). This is surprising considering the completely different chemistry of NADW and AABW. In addition, the two deep-water masses might be influenced by different bottom-current flow regimes. In this study, the influence of varying LNADW fluxes on the Atlantic deep water configuration is examined using both, geochemical and sedimentological proxies. We therefore compare changes in deep-water chemistry (benthic δ13C values, carbonate preservation proxies) with near bottom-current strength (e.g. silt grain-size parameters) at the core depths of LNADW (Site 927) and AABW (Site 929). In particular, the following questions are addressed:

1. Are the variations recorded in deep-water chemistry and bottom-current strength in the individual water masses coherent? If so, is there a positive or negative relationship between the changes in bottom-current strength and deep-water chemistry?
2. Are the changes observed in bottom-current strength and deep-water chemistry synchronous between the LNADW and AABW? If so, are these synchronous shifts positively or negatively related?

1.3.1 Orbital forcing of deep-water circulation

Many paleoclimatic and paleoceanographic records display strong orbital forcing signals, with major components at the precession, obliquity, and eccentricity frequency bands. The climate forcing effect of these orbital parameters is that they control the incoming solar radiation on Earth.

The precession cycle follows roughly a 23 k.y. period and produces its strongest effect in the equatorial regions by controlling wind regimes and surface-water hydrography (e.g. monsoonal precipitation and the strength of trade winds). Eccentricity has its major component at the 100 k.y. periodicity. It has only a negligible effect on the incoming solar radiation and mainly modulates the effect of precession. However, the 100 k.y. periodicity is expressed in many paleoceanographic records, which is commonly explained by non-linear response mechanisms (e.g. Clark and Pollard, 1998, Clemens and Tiedemann, 1997). By controlling the seasonal intensity of summer and winter, the Earth’s obliquity (41 k.y.) cycle produces its strongest climatic effect in the northern and southern high latitudes. Accordingly, it is an important controlling factor for ice volume in the Earth’s polar regions (Imbrie et al., 1984, Imbrie et al., 1992).

The most important controlling factor for the quantity and quality of LNADW formation during the past 3 m.y. was expansion of ice shields in the NGS, which may have "blocked off" the saline surface waters derived from the tropical Atlantic, thus suppressing deep-water formation (Henrich et al., in press). So, in addition to the glacial-interglacially induced changes in deep-water circulation, many proxy records of LNADW flux exhibit a strong component of orbitally induced cyclicity. The predominant frequencies are the eccentricity-related 100 k.y. periodicity and the 41 k.y. obliquity-related periodicity of the Earth’s orbit (e.g. Howard and Prell, 1994, Bickert et al. 1997a,b, Curry and Cullen, 1997).

Throughout the past ~1 m.y., NADW production and its contribution to the Atlantic Ocean was dominated by the 100 k.y. periodicity. Ceará Rise Leg 154 sediment cores display 100 k.y. cycles in records of carbonate preservation and benthic foraminiferal δ¹³C (e.g. Bickert et al., 1997b, Curry and Cullen, 1997). If changes in bottom-current strength were in phase with changes recorded in deep-water chemistry, then we would also expect to find these orbital components in the meanₙₙ signal. To verify this, we analysed the variability of meanₙₙ at Site 927 and Site 929 in the time domain using spectral analysis technics.

2. Material and methods

Age models for the ODP Leg 154 sites were developed by Bickert et al. (1997b) and Tiedemann and Franz (1997). Dating is based on tuning variations of the magnetic susceptibility to orbital parameters (for details see Bickert et al., 1997b and Tiedeman and Franz, 1997).

46 samples were taken from ODP Site 927, from 13.43 to 35.15 meters composite depth (mcd), to investigate the particle-size distribution of the carbonate-free silt fraction. The resulting data
set has been compiled with additional data produced by Gröger et al. (subm.a). The combined record spans the time interval from ~800 to 270 ka at a resolution of ~5 k.y.

In order to achieve an optimal comparison (with respect to the time interval and sample resolution) to the Site 927 record, Site 929 was sampled at 15-cm intervals from 11.67 to 32.96 mcd. In order to avoid taking samples from turbidite deposits identified in Site 929 cores, the 15-cm interval was not kept strictly.

2.1. Particle size data
Prior to grain-size analysis, each sample underwent the following procedure: The fine fraction (<63 μm) was first separated by wet-sieving and then decarbonated with ~12 % HCl. Afterwards it was washed repeatedly until the pH index became neutral. Next, the silt fraction (2-63 μm) was extracted from clay particles by repeated settling procedures after Stoke’s law of settling, using Atterberg settling tubes. The clay residual was identified in the subsequent particle-size analysis, and never exceeded 5 wt % in the analysed silt extracts.

A detailed particle-size analysis was carried out by measurements with a Micromeritics Sedigraph 5100. The Sedigraph determines the particle-size distribution from a dispersed suspension in an analysis cell, assuming Stoke’s law for the settling of particles. It measures the attenuation of a finely collimated X-ray beam as a function of time and height (Stein, 1985). Each sample was analysed within a size spectrum ranging from 100.0 to 0.1 μm. From the raw data we calculated the grain-size distribution of the sortable silt (10-63 μm) spectrum (McCave et al., 1995), which was rescaled to 100%. This spectrum was used to calculate the mean particle size, that is referred here as mean_{ss}.

Since we focus on the determination of bottom currents, we consider only the carbonate-free, lithogenic silt fraction; biogenic silica is mostly absent in the samples or contributes only accessory amounts that can be neglected. In this study only the fraction from 10 to 63 μm is considered. As shown in detail by McCave et al. (1995), particles finer than 10 μm behave cohesively and thus will not be transported as individual particles in the viscous sublayer. Accordingly, sorting effects due to a strong bottom-current can be inferred only from the coarser particle fractions.

2.2 Benthic foraminiferal stable carbon and oxygen isotope data and carbonate preservation
The benthic isotope data (δ^{18}O, δ^{13}C) used in this study are taken from Bickert et al. (1997b). Carbonate preservation is estimated in each sample by the sand content (wt. % particles >63 μm). This proxy is related to the weakening and breakage of foraminiferal shells with progressive dissolution, which leads to a mass transfer from coarser to finer fractions (Berger et al., 1982).

2.3. Spectral analysis
Spectral analysis was performed with the software package AnaLySeries 1.1 (Paillard et al., 1996). Prior to analysis each record was resampled at equal time increments of 3 k.y. We choose the classical Blackman-Tuckey standard method with 50 % lags of the autocovariance series (bandwidth=5.6 cycles/m.y.). Frequency spectra, coherencies, phase angles between geochemical (benthic foraminiferal δ^{13}C) and sedimentological (mean_{ss}) deep-water proxies, and the bent-
hic foraminiferal $\delta^{18}O$ signal as a reference for ice volume were estimated (confidence level of 80%).

Cross-spectral analyses were performed between deep-water proxy records and the benthic foraminiferal $\delta^{18}O$ reference signal for variations in ice volume. To account for the negative relationship between the mean$_{(SS)}$ and benthic $\delta^{13}C$, the $\delta^{18}O$ record was inversed by multiplication with -1 prior to analysis, resulting in a phase shift of $-\pi$.

3. Results

3.1 Particle-size data

The ODP Site 929 mean$_{(SS)}$ record differs significantly from that recorded at the shallower Site 927. Mean$_{(SS)}$ values range from 14 to 22 $\mu$m at Site 929. This is significantly coarser than those recorded at Site 927 (Fig. 3), which range from 11 to 20 $\mu$m. This is in agreement with preliminary results from parasound profiles, which evidence a water-depth-related grain-size sorting, with coarser particles deposited at greater depths on the NE flank of the Ceará Rise (Breitzke and Spieß, 1999).

Among all the Leg 154 sites only Site 929 exhibits turbidites (Curry et al., 1995). Turbidites can be identified in Site 929 sediment cores as 1- to 3-cm thick layers of silt-sized grains, predominantly of quartz with appreciable amounts of feldspar (Curry et al., 1995). Their mineralogical composition is completely different from the downslope-transported carbonate-rich turbidite deposits found in the older lithologic units of Leg 154 sites (Curry et al., 1995). This indicates that the Pleistocene turbidite layers are associated with transport processes occurring in the distal part of the Amazon Fan (Curry et al., 1995).

![Figure 3: Comparison of mean$_{(SS)}$ variability at site 927 (~3300 m, right) and site 929 (~4400 m, left). The two records differ significantly in size range and variability. Black arrows at the site 927 curve mark the extraordinary fine mean$_{(SS)}$ values at the glacial to interglacial transitions. Large arrow indicates a sample taken from a turbidite layer at site 929. Numbers at the y-axis indicate oxygen isotope stage.](image-url)
To test whether the Site 929 mean$_{\text{SS}}$ record is significantly disturbed by turbidite deposits, one sample was taken directly from the basal part of a turbidite layer. This sample (ODP 929A 4H-4-137) can be clearly identified by its extraordinarily coarse mean$_{\text{SS}}$ (large arrow in Fig. 3), which exceeds the average values by about 6 µm and even the recorded maxima by ~3 µm. During the sampling procedure visually identifiable similar turbidite layers were avoided. Therefore, with the exception of this well defined turbidite, we consider the mean$_{\text{SS}}$ curve not to be remarkably influenced by turbidity layers.

The poor covariation between the mean$_{\text{SS}}$ records of Site 927 and Site 929 indicates that there is no inter-site relationship (Fig. 3). Mean$_{\text{SS}}$ variability at Site 927 is related to glacial-interglacial cycles, with finer values observed during glacial stages. Pronounced shifts from the finest values to very coarse values are a regular feature of the glacial to interglacial transitions (with the exception of the stage 20/19 transition, Fig. 3). Superimposed on this glacial-interglacial cyclicity, much higher frequency fluctuations are displayed in the Site 927 mean$_{\text{SS}}$ curve, and these are most obvious during oxygen isotope stages (OIS) 10 and 11.

At Site 929 there is no strict glacial-interglacial cyclicity apparent in the mean$_{\text{SS}}$ record (Fig. 3). However, in contrast to Site 927, mean$_{\text{SS}}$ maxima are predominantly observed during glacial stages, evidencing an inverse phasing compared to that observed at Site 927. This is most evident in the younger intervals during OIS 12, 10, and 8, but is also well expressed during OIS 20.

### 3.2 Carbonate preservation and benthic $\delta^{13}\text{C}$

In striking contrast to the mean$_{\text{SS}}$ variability, variations in sand contents and benthic $\delta^{13}\text{C}$ values are synchronous between the two sites (Fig. 4). The generally lower sand content and benthic $\delta^{13}\text{C}$ values at Site 929 illustrate the greater influence of AABW at the deeper site.

Confirming the previous results of Curry and Cullen (1997) Site 927 and Site 929 sand contents are positively related. Glacial periods are characterized by reduced sand content at both sites, indicating greater deep-water carbonate corrosiveness due to the AABW (Fig. 4a).

As revealed by Bickert et al. (1997), a positive relationship is also observed between the Site 927 and Site 929 benthic $\delta^{13}\text{C}$ variability (Fig 4b). Glacial periods are characterized by lower $\delta^{13}\text{C}$ values, indicating a nutrient-rich, and less well ventilated deep-water mass.

### 3.3 Spectral analysis

Spectral analysis of the Site 927 mean$_{\text{SS}}$ record verifies that most of the spectral power is concentrated within the 100 k.y. eccentricity frequency band (Fig. 5). By contrast, Site 929 mean$_{\text{SS}}$ variability is dominated by the Earth’s obliquity cycle (Fig. 5). Cross-spectral analysis between the Site 927 mean$_{\text{SS}}$ record and the benthic foraminiferal (C.wuellerstorfi) $\delta^{18}\text{O}$ record (as a reference for ice volume) reveals high coherency at the Earth’s eccentricity frequency band (Fig. 6, middle). The phase plot (Fig. 6, bottom) indicates that mean$_{\text{SS}}$ maxima lag benthic foraminiferal $\delta^{18}\text{O}$ minima with a phase shift of about 28.7° (=7.6 k.y., Table 1) at the eccentricity frequency band.
Cross-spectral analysis between the Site 929 mean$_{(ss)}$ record and the $\delta^{18}$O record of Site 927 indicates that mean$_{(ss)}$ maxima are coherent with minima in ice volume with a phase lag of about 3.5 k.y. at the obliquity frequency band (Table 1). Cross-spectral analysis between the benthic foraminiferal $\delta^{13}$C signals from the two sites and ice volume reveals that the benthic $\delta^{13}$ signal is nearly in phase with variations in ice volume at the eccentricity frequency band at both sites.

**a) Sand contents**

**b) $\delta^{13}$C (C.wuellerst.)**

*Figure 4: Intersite comparison of a) sand contents and b) benthic foraminifera $\delta^{13}$C variability. In contrast to the mean$_{(ss)}$ proxy records (Fig. 3) variations in sand content and $\delta^{13}$C occurred synchronously and with similar trend at the two sites.*
4 Discussion

4.1. The control of sortable silt deposition on the NE flank of the Ceará Rise

McCave et al. (1995) established a relationship between mean$_{(ss)}$ size and bottom-current velocity. In general, stronger bottom currents produce coarser mean$_{(ss)}$ sizes. At the Ceará Rise, the applicability of the mean$_{(ss)}$ parameter as a reliable proxy for paleo-bottom-current strength has been demonstrated by Groger et al. (subm. a) for the shallower Site 927.

Three main processes have an influence on the terrigenous mean$_{(ss)}$ variability on the NE flank of the Ceará Rise throughout the Pleistocene: (1) Varying intensity of bottom-current vigor related to changes in the physical flow regime of deep waters (NADW, AABW) is considered to induce sediment sorting (Gröger et al., subm. a,b), (2) episodic deposition from turbidites occurring on the lower Amazon Fan, a pattern only recognized episodically at the deeper Site 929 (Curry et al., 1995), and (3) changes in the equatorial surface current system by controlling the terrigenous sediment supply from the Amazon mouth to the Ceará Rise (Rühlemann et al, 2001).

Comparing mean$_{(ss)}$ variability of the lithogenic and biogenic (calcareous) silt components, Gröger et al. (subm. a) found a good correlation between the two parameters throughout the late Pleistocene. Only depositional processes such as winnowing by strong bottom currents can influence the particle sorting of both the biogenic and lithogenic components in deep-sea sediments (Robinson and McCave, 1994). Thus, the observed good correlation argues for varying bottom-current vigor as the main factor in controlling the mean$_{(ss)}$ variability.

An important constraint on explaining mean$_{(ss)}$ variations at the NE flank of the Ceará Rise comes from comparing the Site 927 mean$_{(ss)}$ record with that of the deeper Site 929. Figure 7 shows the differences in mean$_{(ss)}$ between the two sites. Throughout most of the mid Pleistocene Site 929 mean$_{(ss)}$ values greatly exceed those from the shallower Site 927, with differences of up to ~8 μm (Fig. 7, lower graph). Because of the proximity of the two sites, it is very unlikely that these large intersite differences were controlled by surface water hydrography.
Part II: Deep-water circulation during the Pleistocene (0.8-0.25 Ma): inferences from...

Figure 6: Top: Spectral density and cross coherency between site 927 mean\textsubscript{SS} and benthic foraminiferal (C. wuellerstorfi) $\delta^{18}$O (site 927 Bickert et al., 1997b) as reference for ice volume. Bottom: phase angle (given in degree) vs. frequency plot.

<table>
<thead>
<tr>
<th>reference signal</th>
<th>deep-water signal</th>
<th>coh</th>
<th>$\phi$ (grad)</th>
<th>$\phi$ (k.y.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>927 $\delta^{18}$O vs. $\delta^{18}$C</td>
<td>Site 927 mean\textsubscript{SS}</td>
<td>0.96</td>
<td>-28.7</td>
<td>-7.6</td>
</tr>
<tr>
<td>927 $\delta^{18}$O vs. C. wuellerstorfi</td>
<td>Site 929 mean\textsubscript{SS}</td>
<td>0.75</td>
<td>-28.8</td>
<td>-3.5</td>
</tr>
<tr>
<td>(41 ky band)</td>
<td>Site 929 $\delta^{18}$C</td>
<td>0.89</td>
<td>-8.7</td>
<td>-2.1</td>
</tr>
</tbody>
</table>

Table 1: Coherencies (coh) and phase relationships (expressed in degree and k.y.) for different deep-water proxies with the benthic foraminiferal (C. wuellerstorfi) $\delta^{18}$O signal as reference for ice volume at the eccentricity frequency band. Negative phasing indicates that changes in a given deep-water proxy lag changes in the reference signal.

Only during interglacial maxima of increased NADW flux, when bottom-current vigor and, hence, winnowing was stronger at Site 927 (Gröger et al., subm., a,b) does the 929 - 927 difference becomes negative (Fig. 7). Another important indication for varying intensities of bottom-current vigor as the main controlling factor for the mean\textsubscript{SS} variability is provided by spectral analysis. Rühlemann et al. (2001) have shown that the supply of terrigenous material to the Ceará Rise via the Amazon freshwater plume varies with a strong 23 k.y. precessional periodicity. This was explained by the strong influence of the equatorial surface current system (NECC controlled by trade wind intensity). By contrast, spectral analysis of mean\textsubscript{SS} records from Sites 927 and 929 reveals only weak power in the 23 k.y. frequency band (Fig. 5). Only at Site 929 is the influence of the precession cycle is indicated, but this is not statistically significant (Fig. 5). We propose that the lack of significant power at the precessional frequency band at the two sites argues against equatorial surface water hydrography as the main controlling factor for mean\textsubscript{SS} variability, thus supporting the assumption that sediment sorting occurred due to vigorous bottom-current flow. Furthermore, the predominance of eccentricity (at Site 927) and obliquity (at Site 929) cycles points to a linkage with climatic processes occurring in high latitude regions.
In conclusion, we consider the mean$_{(SS)}$ variability to be mainly controlled by variations in the intensity of bottom-current.

4.2. Orbital response of near bottom-current flow at Site 927 during the mid Pleistocene

Figure 8 illustrates the phase relationships between ice volume (e.g. benthic foraminiferal $\delta^{18}O$) and various deep-water proxies at the eccentricity frequency band as revealed from cross-spectral analysis. Surprisingly, there is a relative large lag time of ~7.6 k.y. in the response of bottom-current strength at site 927 (inferred from the mean$_{(SS)}$ proxy) with respect to changes in ice volume. By contrast, changes in benthic foraminiferal $\delta^{13}C$ at both sites only slightly lag those in ice volume (Fig. 8, Table 1).

Gröger et al. (subm.b) suggested that the changes in the bottom-current strength inferred from the Site 927 sediment cores were related to the circulation strength in the lower NADW cell. This proposal was based on the observed good correlation between the benthic foraminiferal $\delta^{13}C$ record which represents the nutrient content of the deep-water mass, and the mean$_{(SS)}$ record, which is sensitive to the near-bottom flow of deep waters (see above). Because only geostrophic currents should be capable of influencing both, the physical flow and the geochemical properties of deep waters, the good correlation between the two parameters argues for a coupling between the bottom-current velocities at Site 927 and the effective circulation strength within the LNADW cell (Gröger et al., subm.b). In agreement with this, a strong ~100 k.y. periodicity is found in the mean$_{(SS)}$ record at Site 927 (Fig. 5), indicating the linkage to changes in LNADW production.
The observed late response of mean$_{SS}$ to changes in ice volume thus may be interpreted as the lag time between changes in the production rates and quality of NADW and the effective circulation strength within the lower NADW cell.

![Diagram showing phase relationships between ice volume and benthic foraminiferal $\delta^{13}C$ and mean$_{SS}$ at site 927 and 929, and min. ice volume at the eccentricity band.](image)

Fig. 8: "Phase wheel" summarizing phase relationships between ice volume and benthic foraminiferal $\delta^{13}C$ at site 927, and at site 929, and mean$_{SS}$ at site 927 at the eccentricity frequency band. Minimum in ice volume corresponds to minima in the benthic foraminiferal $\delta^{18}O$ variability at site 927.

We speculate that changes in the quality and quantity of northern sourced deep waters during the early periods of interglacials have led to a larger LNADW layer in the Atlantic, which, in a first step, compensated for the excess LNADW produced in the early interglacial. If this process was not sufficient (that is, if the density gradient between AABW and LNADW limited further expansion of the LNADW layer in the Atlantic), the circulation in the LNADW cell would have been enhanced and further compensated for the increased LNADW flux by transferring larger volumes of LNADW to the other oceans. This would have caused stronger bottom currents at the core site of LNADW (Site 927). In turn, the reduced flux of glacial LNADW would lead initially to a smaller LNADW layer. Subsequently, (after AABW and NADW were redistributed balancing the new density gradients in the deep western equatorial Atlantic) the circulation would weaken, again resulting in a reduced flux of LNADW to the other oceans.

4.3. The control of bottom-current vigor at Site 929 - linkage to AABW production?

Presently, AABW is restricted to depths below ~4000m. The sloping topography between the Ceará Rise and the Amazon Fan serves as a barrier for waters below 4250m (Whitehead and Worthington, 1982), whereas east of the Ceará Rise the topography falls below 4700m (Fig. 9). Therefore, and because of the strong southeastward flow of LNADW west of the Rise, the AABW stream today passes through the Guyana Basin mainly through the northeastern passage (Fig. 2, e.g. Rhein et al., 1998).

Given that an increased flux of AABW to the Atlantic would lead to an expanded AABW layer in the western equatorial Atlantic (and a subsequent shallowing of the upper boundary of AABW), this would enable the AABW stream to overrun the topographic barrier between the Amazon cone and the western flank of the Ceará Rise (Fig. 9). Accordingly, AABW would pass through the Guyana Basin on both flanks of the Ceará Rise. In consequence, this would considerably
enlarge the stream diameter for AABW in the Guyana Basin. As a result the mean velocity of flow in the AABW layer would be lowered, producing weaker bottom currents at the NE flank of the Ceará Rise.

![Topographical profile across the Guyana basin at 5°N. Dashed line: Upper boundary of AABW adapted from Rhein, (1998).](image)

Therefore, because of the specific topographic configuration between the Amazon cone and the Ceará Rise in the Guyana Basin we assume that an increased flux of AABW to the tropical western Atlantic would lead to lower current velocities in the Guyana Basin northeast of the Ceará Rise (Site 929).

We consider now the question of what might have caused changes in the AABW flux to the Guyana Basin. AABW production is very sensitive to the climate and in particular to the sea-ice expansion around Antarctica.

Figure 10 compares the summer insolation at 65°S with the Site 929 mean$_{(SS)}$ record. In general, we observe a remarkable positive relationship between the two records with mean$_{(SS)}$ maxima corresponding to maxima in the incoming insolation. Hence, maxima in bottom-current velocity at Site 929 occur during maxima in the incoming solar radiation over Antarctica. Moreover, the strong obliquity component in the southern high latitudes summer insolation is in good agreement with the 41 k.y. periodicity found in the mean$_{(SS)}$ variability at Site 929 (Fig. 5).

It has been suggested that AABW production is enhanced during periods of increased ice production and brine release on the Antarctic continental shelf (e.g., particularly in the Weddell Sea, Gill, 1973). Furthermore, it has been proposed that increased discharge of low-saline meltwaters from Antarctica have the potential to considerably decrease AABW formation (e.g., Seidov et al., 2001). We thus speculate that periods of maximum solar insolation in the Antarctic region may be associated with lowered ice production (and increased mobilisation of meltwaters) leading to a decrease in AABW production in the Weddel Sea. The resulting decrease in AABW flux to the Atlantic would then lead to a smaller AABW layer in the Guyana Basin, thereby strengthening the flow of AABW on the eastern flank of the Ceará Rise.

However, the differences in phasing between the mean$_{(SS)}$ record and the insolation record (Fig. 10) reveal that other factors need to be considered in explaining the regional history of bottom-current strength at site 929.
Part II: Deep-water circulation during the Pleistocene (0.8-0.25 Ma): inferences from...

Fig. 10: Comparison between mean$_{\text{SS}}$ variability at the deep site 929 and Southern hemisphere summer insolation at 65°S showing positive relationship with slight differences in phasing between individual maxima. The two records exhibit ~41 kys cyclicity.

The model discussed above is constrained by the sea-ice expansion around Antarctica and, hence, by the 41 k.y. obliquity cycle in AABW flux to the Atlantic. Interestingly, a strong imprint of 41 k.y. periodicity has been described in some late Quaternary Antarctic climatic and atmospheric records (e.g. Lorius et al., 1990, Jouzel et al., 1987). In particular a strong 41 k.y. component was found in the dust record (e.g., Petit et al., 1999) from the Vostok ice core (78°S, 106°E). The dust mainly originates from the Patagonian Plain in South America (Basile et al., 1997). The dust supply to Antarctica is strongly linked to the sea-ice expansion in the South Atlantic. Petit et al., (1999) suggested that increased sea-ice extent into the South Atlantic causes a colder and drier climate in South America and pushes the belt of westerlies northward over the Andes (due to a more northerly position of the Southern Hemisphere polar front). This increases erosion and results in extensive dust mobilisation in South America (Petit et al., 1999). The strong 41 k.y. periodicity found in the Vostok dust record may therefore be indicative of 41 k.y. cycles in the Pleistocene variability of sea-ice expansion in the South Atlantic.

4.4. Comparison between ODP Sites 927 and 929 mean$_{\text{SS}}$ variability: Implications for Atlantic deep-water circulation.

The differences in near-bottom-current strength at Site 927 and Site 929 as revealed by the contrasting history of mean$_{\text{SS}}$ variability (Fig. 3) display the different flow regime associated with LNADW and AABW. This is in striking contrast to the strong positive intersite relationship observed in deep-water carbonate corrosiveness and benthic $\delta^{13}$C variability (Fig. 4). We thus consider
the question of how changes in the deep-water chemistry of AABW and LNADW could be nearly synchronous and display similar trends.

The history of Atlantic deep-water chemistry (as reflected by the means of benthic $\delta^{13}$C and carbonate corrosiveness) is therefore compared with the history of bottom-current strength at both waterdepths. Since changes in the benthic foraminiferal $\delta^{13}$C and sand content at the two sites are congruent in terms of frequency and tendency (Fig. 4), we take the records from Site 927 as a reference for changes in the equatorial Atlantic deep-water chemistry. In Figure 11 these records (plots c) and d)) are contrasted by the mean$_{(SS)}$ variations at the two sites (plots a) and b)).

![Figure 11: Comparison between mean$_{(SS)}$ variability at a) site 929 and b) site 927 and deep-water geochemical proxy records e.g. c) benthic foraminiferal $\delta^{13}$C and d) sand contents from site 927. Good covariation is displayed between site 927 mean$_{(SS)}$ record and deep water geochemical proxy records. By contrast, covariation with site 929 mean$_{(SS)}$ record is not established.](image)
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It becomes obvious that changes in bottom-current strength at the LNADW Site 927 are positively related to changes in deep-water chemistry. Glacial deep water is characterized by higher nutrient content and higher carbonate corrosiveness (lower sand content) while weaker circulation of LNADW is registered in the Guyana basin (finer mean$_{ss}$ sizes at Site 927, Fig. 11b). In striking contrast, no relationship between deep-water chemistry and the mean$_{ss}$ variations at the AABW core Site 929, is recognized. This indicates that changes in the physical flow of AABW (as inferred from bottom-current variability) are not coupled with changes in the Atlantic deep-water chemistry.

We conclude that changes in the Atlantic deep-water chemistry were accompanied by changes in the physical flow regime of LNADW (but not by changes in the physical flow regime of AABW). We therefore suggest that the synchronicity and similarity in tendency of the recorded geochemical deep-water records (Fig. 4) is related to substantial changes in the overall quantity and/or quality of LNADW production. Below, we address three possible approaches for explaining the glacial-interglacial deep-water reconfigurations driven by LNADW:

1) Due to changes in the production regions glacial LNADW might have had a different initial geochemical composition compared to the interglacial situation. Furthermore, the export to the Southern Ocean was considerably diminished. In consequence, the volume and quality of NADW injected into the Antarctic Circumpolar Deep Water (ACDW) around Antarctica may have completely changed. Since the ACDW is a main source in the production of AABW (Reid, 1989, 1996), the observed shifts in the Atlantic deep-water chemistry could actually be synchronous and display similar trends.

2) LNADW export was reduced during glacial periods but its initial geochemical composition remained unchanged. This would influence only the deep-water chemistry of AABW due to a diminished contribution of NADW to the ACDW. Synchronous changes at the shallower Site 927, would occur due to a vertical expansion of AABW in the water column and may reflect glacial-interglacial gradients in LNADW chemistry.

3) LNADW is diluted by larger quantities of AABW (with a different initial composition) injected into the LNADW body along a broader mixing zone.

The latter two scenarios require an immensely enhanced production of AABW in direct response to the diminished LNADW flux. A slight increase in glacial AABW production has been proposed by model simulations (e.g. Duplessy et al., 1996). However, up to now, no proxy data exist that would suggest such an interdependence between the fluxes of AABW and NADW to the Atlantic.

However, if there had been corresponding changes in the AABW production in direct response to changes in the NADW flux to the the Atlantic Ocean, then they were not accompanied by significant synchronous changes in the AABW stream profile (as inferred from Site 929 mean$_{ss}$ variability, Fig. 11). In consequence, this finding is less consistent with the latter two scenarios because, as we showed above, it is very likely that changes in the AABW flux are accompanied by substantial changes in the regional AABW stream.
In summary, comparison between the variations recorded in inferred bottom-current strength and deep-water chemistry at Sites 927 and 929 indicates substantial changes in quantity and quality of produced LNADW that control the Atlantic deep-water mass reconfiguration at glacial-interglacial time scales.

4.5. Inference for higher frequency fluctuations in near-bottom-current strength from ODP Site 927 and the glacial-to-interglacial transitions

The temporal resolution in the mean(Sss) record (Fig. 3) displays a much higher frequency of bottom-current-strength variations at Site 927. In particular, during OIS 10 and 11 are significant low-order amplitude high-frequency fluctuations in bottom-current strength occur on sub-orbital to millennial time scales. In agreement with this, similar high frequency fluctuations were registered in carbonate-preservation records from Site 927 after OIS 12 (Gröger et al., subm.a). Together, these indications from the tropical Atlantic resemble the high-frequency fluctuations in NADW production that were inferred from benthic foraminiferal δ¹³C records at the North Atlantic ODP Sites 1063 (Bermuda Rise) and 980 (Fenni-Drift) during OIS 12 and 11 (e.g., Poli et al., 2000). It is questionable whether, such high frequency fluctuations in NADW production could have triggered those recorded in near-bottom current flow and carbonate chemistry at the Ceará Rise. Within the limits of the temporal resolution, however, we can neither prove nor exclude a possible linkage between the LNADW production and deep-water circulation in the western equatorial Atlantic on shorter time scales.

However, the extraordinarily fine mean(Sss) values that punctuate the periods of maximal ice accumulation near the glacial-to-interglacial transitions (short arrows in Fig. 3) greatly exceed the above described high-frequency magnitude fluctuations described above. Gröger et al. (subm.a) proposed that these extraordinarily fine mean(Sss) values were caused by an enhanced meltwater discharge into the NADW formation sites, followed by a nearly complete shutdown of circulation in the lower NADW cell, and causing exceptionally weak bottom-current flow at the Ceará Rise (for a detailed discussion see Gröger et al., subm.a).

Our new data set verifies that these extreme conditions were rather episodic and probably persisted over a period of less than 5 k.y. This gives rise to a more catastrophic scenario in which the drastic weakening of circulation in the LNADW cell (and the subsequent "shutdown" in bottom-current flow registered at the Ceará Rise) was caused by a strong meltwater impact into the NADW formation area triggered by massive ice-shield decomposition during the initial deglaciation phase. However, we can not exclude the possibility that the meltwater discharge strengthened more linearly with ice-sheet growth and only during maximum ice-sheet expansion became large enough to suppress deep-water formation completely, as proposed by Gröger et al. (subm.a).

Testing the two hypotheses and the possible linkage between the observed high-frequency fluctuations in the mean(Sss) record and those from deep-water proxy records at North Atlantic sites requires higher resolution records that will be obtained in a future research project focused on OIS 12, 11, and 10.
Conclusions

Late Quaternary records of mean sortable silt (10-63 μm fraction) from the NE flank of the Ceará Rise (ODP Sites 927 and 929) indicate a water-depth-related grain-size sorting with coarser particles deposited at greater depths. Site 929 - 927 differences in mean sortable silt range up to 8 μm and are most likely controlled by cyclic changes in the flow regime of deep-water masses (NADW/AABW). Inter-site differences decrease (and sometimes even become negative) during interglacial periods when the mean sortable silt at Site 927 coarsens due to stronger NADW flow. The lack of significant power in the precessional frequency band in Site 927 and 929 mean sortable silt records and the large intersite mean(ss) differences indicate sediment sorting by the physical flow regime of deep waters rather than by variations in the equatorial surface-current system.

Spectral analysis of the mean(ss) record at the shallower Site 927 reveals that most of the spectral power is concentrated in the eccentricity frequency band, which is consistent with geochemical proxy records. Cross-spectral analysis indicates that changes in near-bottom-current strength lag those in ice volume by ~8 k.y. at the eccentricity frequency band. This is likely related to the interaction between changes in the depth distribution of the LNADW layer and flow velocity in the LNADW cell in response to substantial changes in the quality and quantity of NADW production around the glacial-interglacial transitions.

Besides the orbitally induced variations, ODP Site 927 mean(ss) values exhibit higher frequency fluctuations, especially during OIS 12, 11, and 10, resembling analog millennial-scale changes in NADW production (e.g., Poli et al., 2000).

By contrast, at the deeper Site 929 the variations in mean sortable silt are dominated by a strong 41 k.y. obliquity periodicity, which is a common feature in many climatic and atmospheric record from the Antarctic (Vostok ice core, 78°S, e.g. Petit et al., 1999). Covariation with the record of Southern Hemisphere summer insolation at 78° S is well established. We propose that the mean(ss) variability at the deeper Site 929 is related to changes in the AABW flow regime, possibly linked to climatically induced changes in AABW flux to the Atlantic Ocean that change its flow path through the Guyana Basin.

Changes deep-water chemistry are synchronous between the two sites and display similar trends at both water depths. This pattern is not recognized in the variability of inferred bottom-current strength. However, bottom-current strength at the LNADW Site 927 correlates well with the Atlantic deep-water chemistry. This points to a substantial role of changes in the quantity and quality of LNADW flux in the control of Atlantic deep-water mass reconfigurations at glacial-interglacial time scales.

We thank W. Hale, and T. Wagner, for comments and criticism. We thank Renate Henning and Christian Müller for laboratory and technical assistance. This work was financially supported by the German Science Foundation (DFG-Grant He 1671/10).
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Part III: Summary and conclusions

Changes in oceanic circulation have greatly influenced climate variability on a global scale. In this thesis reconfigurations of deep-water circulation have been investigated in the Atlantic Ocean and the Caribbean Sea. Deep-water chemical and physical properties have been investigated to reconstructed deep-water circulation over the last three million years. Variations in the vertical distribution of deep-water masses have been inferred from changes in carbonate chemistry and the stable carbon isotopic composition in benthic foraminiferal shells. Changes in the physical flow regime of circulating deep waters were estimated by interpreting the paleointensity of bottom-current flow as inferred from grain-size analyses of the terrigenous silt fraction. For this purpose, core locations were selected in regions that are sensitive to changes in the main water masses, e.g., UNADW in the Caribbean (ODP Site 999), and LNADW (ODP Site 927) and AABW (ODP Site 929) in the western equatorial Atlantic.

Results from ODP Sites 927 and 929 at the Ceará Rise depth traverse (western Atlantic)

Detailed grain-size analyses of the terrigenous silt fraction were carried out on sediment cores from ODP Sites 927 (~3300 m water depth) and 929 (~4400 m water depth). Bottom-current induced particle sorting is considered to be the primary factor controlling mean grain size in the 10-63 μm fraction (mean sortable silt = mean_{ss}). The main arguments for this assumption are:

1. The good covariation observed between the mean_{ss} sizes recorded in the terrigenous and the biogenous (calcareous) silt components,
2. The large differences in average mean_{ss} sizes between Sites 929 and 927,
3. The dissimilarity of variability in mean_{ss} with respect to the trends and frequency of recorded changes at the two sites.

Because of the proximity of the two sites, arguments (2) and (3) rule out the possibility that varying sediment supply from the Amazon river via the regional surface currents (e.g. North Equatorial Counter Current) has significantly influenced the mean_{ss} variability at the two sites.

At Site 927 (~3300 m) on the Ceará Rise, downcore records of the terrigenous mean_{ss} reveal a highly variable history of bottom-current intensity at the LNADW core depth. The deduced current intensities are most likely controlled by the climatically induced weakening/strengthening of circulation within the LNADW cell. This is indicated by the excellent covariation between the physical mean_{ss} proxy and the benthic δ^{13}C proxy, which monitors changes in the deep-water nutrient content. Throughout the Pleistocene (~1.6-0.3 Ma) the inferred bottom-current strength and, hence, LNADW circulation was generally weaker in glacial compared to interglacial periods. In agreement with this, lower glacial benthic δ^{13}C values and poor preservation of planktic foraminifera indicate reduced ventilation and a higher carbonate corrosiveness of deep-water at the core depth of modern LNADW. Whether the glacial increase in carbonate corrosiveness is due to a glacial shallowing of the LNADW/AABW boundary or, alternatively, may be simply explained by an "older", more CO₂-rich and thus more corrosive LNADW mass alone, remains to be resolved. In conclusion, the observed glacial slowdown of circulation must have been associa-
Part III: Summary and conclusions

ted with a strong reduction in meridional heat transfer, thus amplifying the Pleistocene glaciations.

The most fundamental change during the Pleistocene occurred at the mid-Pleistocene climate transition centered around ~1 Ma. Here, a drastic decrease in glacial LNADW circulation and ventilation is inferred from a drastic decrease in mean$_{ss}$ and benthic $\delta^{13}C$ values. This is paralleled by a substantial increase in deep-water carbonate corrosiveness as indicated by a considerable worsening of planktic foraminiferal preservation during glacial periods. Moreover, the finer mean$_{ss}$ values indicate that bottom-current intensity was generally weaker compared to glacial periods of the earlier Pleistocene (1.6-0.95 Ma). It is proposed that the observed shifts in circulation strength and water chemistry represent a direct response to intensified glacial ice-sheet build up in the Northern Hemisphere.

In contrast to the slowdown scenario of glacial periods, a shutdown scenario is proposed at the glacial-to-interglacial transitions of the younger Pleistocene (~1.0-0.3 Ma). Here, the lowest mean$_{ss}$ values of about ~12 μm point to a total absence of vigorous bottom currents at Site 927, indicating a complete shutdown of circulation in the LNADW cell. Our results show that each of these short-term shutdowns was followed by a rapid shift to very high bottom-current intensities. This indicates a substantial rebalancing of Atlantic deep-water circulation due to a rapid reinitiation of LNADW circulation during the early periods of interglacials. These pronounced changes at the glacial-to-interglacial transitions are a unique feature of the younger Pleistocene (~0.8-0.3 Ma), after the mid-Pleistocene climate transition. They are not observed during the early Pleistocene when more gradual changes of bottom-current intensity are indicated.

The late Pleistocene mean$_{ss}$ variability has been analyzed in the time domain using spectral analysis techniques. Most of the spectral power is concentrated at the Earth's eccentricity frequency band. There, changes in the inferred bottom-current intensity occur about 8 k.y. later than the changes in ice volume. It is proposed that, in a first step, the glacial decrease in LNADW flux is compensated for by a reduction of the LNADW layer in the Atlantic. In a second step, the LNADW circulation slows down, thereby reducing the export rates of LNADW to other Oceans.

In contrast to the Site 927 mean$_{ss}$ variability, which exhibits a strong 100-k.y. periodicity, the deeper Site 929 mean$_{ss}$ reveals obliquity cycles. In general, it covaries well with the Southern Hemisphere summer insolation. It is assumed that these variations are controlled by the AABW flux to the western tropical Atlantic and the special topography of the Guyana basin. There, increased flux may lead to a rise of the upper AABW boundary, enabling AABW to flow west of the Ceará Rise, providing a larger stream diameter and thus slowing the circulation within the Guyana basin.

The Pliocene (3.5-2.2 Ma) deep-water circulation has been investigated at Site 927, revealing a three-phase evolution with major steps at 3.1 and 2.75 Ma. This time interval comprises the main steps of Northern Hemisphere glaciation. The results indicate that the highest bottom-current intensity (= highest mean$_{ss}$ values) and, hence, the strongest circulation of LNADW occurred during the Northern Hemisphere cooling transition between 3.1 Ma and 2.75 Ma. This corroborates the super conveyor model for this time interval. The exact relationship with cooling
of the Northern Hemisphere is unclear. A positive effect may have been provided by increasing pole-to-equator pressure and temperature gradients, which would have strengthened the zonal atmospheric circulation and water vapor export from the Atlantic to the Pacific Ocean.

Our data, however, do not support a super conveyor in the interval between 3.5 Ma and 3.2 Ma. During this period, high-amplitude fluctuations in bottom-current strength and in planktic foraminiferal preservation are registered. Hence, a long-term, persisting super conveyor obviously did not exist. The cause of fluctuations in LNADW circulation has not yet been resolved. Variations in the salinity difference between the Atlantic and the other oceans (which drives the thermohaline circulation) triggered by changes in the hydrological cycle or atmospheric circulation may be responsible.

Synchronous with the first occurrence of large-scale continental ice sheets on the Northern Hemisphere, a significant decline in bottom-current strength and planktic foraminiferal preservation is observed. This documents the termination of the super conveyor at around 2.75 Ma. From then onward increasingly pronounced glacial/interglacial fluctuations dominate the LNADW circulation. During colder periods a considerable decline in bottom-current intensity and planktic foraminiferal preservation point to a significant reduction in the overall volume of NADW.

Results from ODP Site 999

At Site 999 planktic foraminiferal shell preservation has been investigated to portray the evolution of Atlantic intermediate water circulation throughout the Pliocene-Pleistocene. Better preservation was found in the Pleistocene interval and stronger dissolution in the Pliocene. This is explained by an increased overturn of uppermost UNADW from the intermediate Atlantic into the deep Caribbean and a decreased import of corrosive AAIW during glacial in the Pleistocene. By contrast, the opposite trend of progressively decreasing preservation from the Pliocene to the Pleistocene glacial was observed at ODP Site 927, indicating an overall decrease in LNADW production.

At Site 999 the best preservation is registered around the mid-Pleistocene climate transition between ~1.0 and 0.7 Ma. This indicates that the deep Caribbean was almost exclusively occupied by non-corrosive UNADW during this period. After 0.7 Ma, a shift back to a more glacial-interglacial related preservation pattern is recognized. By contrast, the most intense carbonate dissolution is registered around 450 ka when LNADW production was at its maximum. This was likely associated with a reduction of UNADW flux to the Atlantic. A resulting predominance of corrosive AAIW in the deep Caribbean might explain the pronounced decrease in carbonate preservation.

The Pliocene (3.5-2.3 Ma) evolution is characterized by a long-term trend toward progressively improving carbonate preservation. This indicates an increasing volume in overturn of non-corrosive intermediate waters through the Caribbean sill front and an increase in the overall volume of UNADW contributed to the Atlantic Ocean, and may be interpreted as a response to the gradual closure of the Central American Gateway (CAG).
The most pronounced shift toward better planktic foraminiferal preservation is registered at ~3.3 Ma, indicating a considerable increase in UNADW overturn from then onward. It is suggested that this marks a threshold during the long-term, stepwise closure of the CAG, which led to an increase in the formation of uppermost NADW.

**Outlook**

This thesis has improved the current knowledge of Atlantic deep-water circulation throughout the past ~3 m.y. During recent decades, intense research efforts have been applied to this topic by studying the ocean’s past chemistry. Presently, a rapidly growing number of studies investigating nutrient concentration in deep waters (as preserved in the $\delta^{13}C$ signals in benthic foraminiferal shells) are being published in scientific journals. However, geochemical gradients primarily portray the vertical deep-water mass distribution and do not provide information about current strength within the deep-water regime. As this thesis illustrates, the reconstruction of bottom-current intensity may serve as a powerful tool in future research for the reconstruction of deep-water physical flow and, hence, for estimating changes of transfer rates along geostrophic deep-sea currents.

The subject of further studies will be to combine geochemical and physical proxy records in studying deep-water circulation. This will provide new insights on actual research activities concerning deep-water circulation that may help in further resolving the role of the deep ocean in the earth’s climate system.

**Presentation at national and international conferences**


Danksagung

Ich danke Herrn Prof. Dr. Henrich für die Vergabe dieser Arbeit und deren Betreuung während der letzten drei Jahre. Herrn Prof. Dr. Flemming danke ich für die freundliche Übernahme des Zweitgutachtens.


Herrn Walter Hale danke ich dafür sein Engagement an drei eingerichteten Manuskripten, meine "verrückten und konfusen" Ideen in sauberes und verständliches Englisch zu bringen.