Terrigenous Signals in Sediments of the Low-Latitude Atlantic - Indications to Environmental Variations during the Late Quaternary: Part II: Lithogenic Matter

M. Zabel[1*], T. Wagner[1] and P. deMenocal[2]

[1] *Universität Bremen, Fachbereich Geowissenschaften, Postfach 330 440, D-28334 Bremen, Germany*
[2] *Lamont Doherty Earth Observatory, Columbia University, PO Box 1000, Palisades NY 10964*
*Corresponding author: mzabel@uni-bremen.de

Abstract: The inorganic terrigenous fraction of marine sediments offers a great number of different and well established proxy parameters to investigate the development of Earth's climate. Our present knowledge on climate variability through time is based, to a large part, on these proxies. This study presents a synthesis of multidisciplinary investigations which have been applied to late Quaternary sediments recovered from the low-latitude Atlantic during the Bremen Special Reseach Project 291. In the equatorial Atlantic terrigenous matter is supplied by eolian and fluvial pathways. In addition to the dust input from African deserts, the catchment areas of the three major rivers Amazon, Niger and Zaire (Congo) are the dominant sources. Small river systems are of local importance. Terrigenous records from near-continental and open pelagic depositional settings are discussed. The main questions we focused on are a) the control of climate change and b) the identification and timing of rapidly occurring events. Results from the low- latitude Atlantic support the suggestion that both high-latitude and low-latitude forcing influence tropical climate and marine sedimentation. Apparently, the frequency of climate variability in the tropics during the late Quaternary is controlled by the precessional insolation cycle, whereas amplitudes and timing of climate change are mainly determined by the high latitudes in the Northern Hemisphere. Within the phase relationships, however, regional differences arise. Furthermore, there is evidence for climate instability during glacials and interglacials which probably occurred on decadal to centennial time scales.

Introduction

In manifold ways the equatorial Atlantic represents a particularly suitable key position for investigations on climatic development, its fluctuations and land-ocean interrelations. This region represents a key corridor for the global water mass circulation, the dominant process of the interhemisphere and latitudinal heat transfer on Earth. On the other hand, the equatorial Atlantic is characterised by the contact of meteorological cycles between Northern and Southern Hemisphere at the Intertropical Convergence Zone (ITZC). In a very simplistic description, there are mainly the contrasting temperatures between land and ocean, or on global scale, between polar regions and low latitudes, combined with air pressure gradients which drive the atmospheric circulation, and therefore control climate conditions and marine sedimentation. As simple as this system may appear, its function is highly complex because interacting sub-processes strongly influence this system. During the last decades numerous studies on

marine and lacustrine sediments have improved our knowledge about these processes, their cause, and their effect on climate change (e.g. Parkin and Shackleton 1973; Street and Grove 1976; Sarnthein 1978; Kolla et al 1979; Kutzbach 1981; Pokras and Mix 1985; Mix et al. 1986; McIntyre et al. 1989; deMenocal et al. 1993; Foley 1994; Hughen et al. 1996; Ganopolski et al. 1998; Zabel et al. 1999; Mulitza and Rühlemann 2000). One emphasis of this research was placed on the investigation of variations in the African monsoon system which primarily controls the transport of water vapor onto the West African continent. Despite the large scientific progress in this field, there are still open and intensively discussed questions which concern, for example a) the link between fluctuations in the African climate and evaporation in the tropical Atlantic, b) the interplay between high and low latitude forcing of African climate variability, and c) the cause of rapid climate changes, especially during late Quaternary.

Sediments from the equatorial Atlantic represent outstanding archive material. Although terrestrial records offer more direct, yet only temporally limited insights into regional climatic developments, continuously settled marine deposits permit reviews back to the Mesozoic (e.g. Wagner 2002). The region of the tropical Atlantic is one of the most important depot centers for the input of terrestrial source material. Particles are supplied to this area by eolian and fluvial transport from both adjacent continents (Fig. 1). Related to the affected sea-floor area, the eolian dust input from the African Sahara and Sahel regions may possess the greatest importance for the composition of the marine sediments. Estimates for the terrestrial dust deposition rate range between 100-400 Mt/yr (Prospero 1981). The largest quantity is, however, supplied by the Amazon River. Its discharge of suspended particulate material is estimated to amount approximately to 1200 Mt/yr (Gaillardet et al. 1997). Depending on the ocean current pattern at present, the bulk of this material is carried parallel to the coastline in northwestern direction to the Caribbean (Milliman et al. 1975). Nevertheless, there is evidence that Amazon suspensates may constitute the dominant portion of the terrigenous fraction as far as the Mid- Atlantic Ridge (Zabel et al. 1999).

However, in contrast to this tremendous input, the wash- outs of the Niger River and the Zaire River are comparably small (each approx. 40 Mt/yr; Gaillardet et al. 1999). Apart from these four main sources, some smaller rivers of local importance additionally supply their load of suspended material.

With this synthesis paper we summarize some collaborative geoscientific studies on variations of the inorganic terrigenous fraction in marine sediments which were conducted between 1997 and 2001 within the previous German Special Research Project 261. On this occasion, we particularly want to put out their contribution for an improvement of the understanding of the climate history within the low-latitude Atlantic and the adjacent continents. First, short overviews are given on the most common methods to investigate the lithogenic fraction and its input to the ocean and on the state of knowledge from outside studies. Related aspects concerning the terrigenous organic matter in sediments from the low-latitude Atlantic are reviewed in a separate contribution (Wagner et al. this volume). In addition, further studies on the terrigenous fraction from other regions of the Atlantic Ocean are summarized by Diekmann et al. (this volume).

Methods to investigate the inorganic terrigenous fraction

There is a large number of well established approaches to investigate the inorganic terrigenous fraction in marine sediments. Although it is not the purpose of this paper to review them all in detail, we briefly turn our attention to some of these methods, or rather proxy parameters, because they may differ substantially in their force of expression. In extreme cases, two different proxies, applied to the same samples, can lead to apparent contradictions. Besides, individual approaches may occasionally contain risks of misinterpretation.

The first group of research methods uses concentrations or accumulation rates (AR) of specific particulate sediment constituents which are considered to be exclusively associated with the terrigenous fraction. The variety of parameters essentially concerns individual minerals or characteristic mineral suits. For example, feldspar, quartz, iron oxide, certain clay minerals or clay mineral assem-
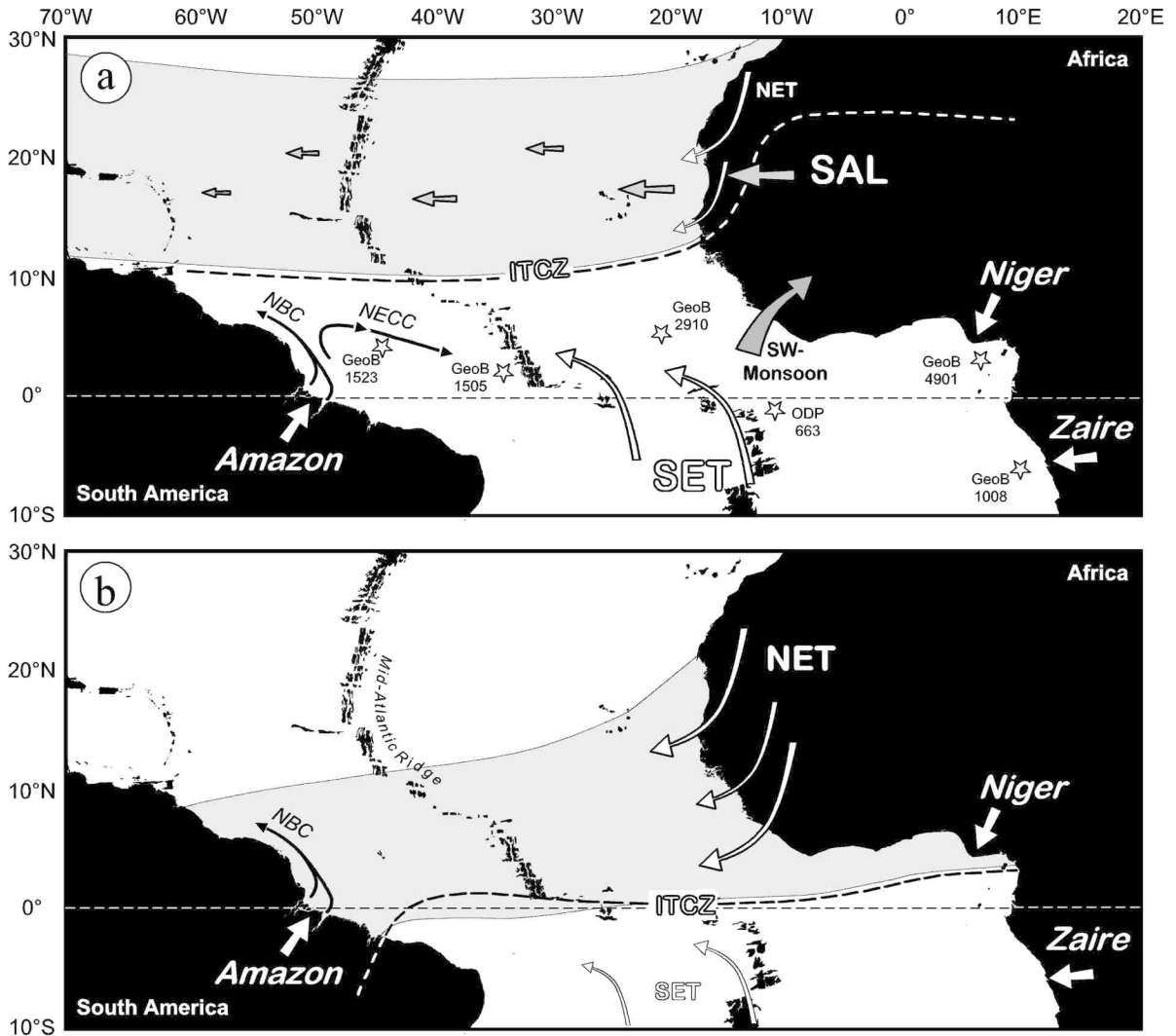
Fig. 1. The equatorial Atlantic and source areas of terrigenous input. Current low, mid-tropospheric and underlying wind regimes and main river systems are additionally shown. Shaded areas indicate the seasonal positions of the dust plumes (modified after Sarnthein et al. 1981). Stars mark locations for which records are presented in Figs. 2 to 4. During the boreal summer season **a)** strong SE trade winds (SET) move the Intertropical Convergence Zone (ITCZ) to about 10°N. African dust is mainly transported by the Saharan Air Layer (SAL). Because the enhanced retroflection of the North Brazil Current (NBC) which accelerates the North Equatorial Countercurrent (NECC), suspended matter supplied by the Amazon can drift eastwards (Zabel et al. 1999). During the boreal winter season **b)** dust- loaded NE trade winds (NET) are dominant and the ITCZ is located close to the equator. River-suspended matter supplied by the Amazon is mainly transported in northwesterly direction.

blages have been used to record the terrigenous input (e.g. Delany et al. 1967; Damuth and Fairbridge 1970; Parkin and Shackleton 1973; Windom 1975; Kolla et al. 1979; Lange 1982; Baslam et al. 1995; Schneider et al. 1997; Gingele et al. 1998; Harris and Mix 1999; Rühlemann et al. 2001; Diek-

mann et al. this volume). Quartz and feldspar contents may be the most reliable indicator of these proxies, because clay mineral assemblages or iron oxide contents are often much more difficult to interpret. On account of several factors, like the very slow soil formation rates, clay mineral assemblages

may provide only integrated records of overall climatic impacts, from which it follows that their distribution patterns rather reflect the great, supraregional changes than variations in specific local climate conditions (Thiry 2000). Also not to be neglected is the possible influence of a geochemical alteration of the primary signal due to authigenic mineral formation and/or dissolution. Hence, clay mineral distribution has been used more often to trace ocean currents (e.g. Biscaye 1965; Petschick et al. 1996; Diekmann et al. 1999).

Quite similar to the use of specific minerals, individual element concentrations have been interpreted as characterizing terrigenous constituents (e.g. Matthewson et al. 1995; Schneider et al. 1997; Zabel et al. 1999, 2001; Haug et al. 2001; Bozzano et al. 2002). One uncertainty of this assumption is that bulk chemical analyses of sediment do not naturally reveal which sedimentary phases add to the concentration of a particular element (e.g. van der Weijden 2002). Another risk stems from the possible distortion of the primary terrigenous signal by secondary processes during particle settling through the water column, like scavenging effects (e.g. Orians and Bruland 1985). We will return to this point in the next paragraph. However, interpretations of the element contents in marine sediments are manifold. While in some studies elements like Al, K, Rb, Ti, or Zr are considered to be indicators for terrigenous matter derived from a defined area and reflect the climate conditions therein (e.g. Matthewson et al. 1995; Schneider et al. 1997), others also use the elemental composition of bulk sediments to identify terrigenous quantities from different source areas, providing that the raw materials differ significantly from each other (e.g. Zabel et al. 1999, 2001). A description of the technical and analytical methods to determine element concentrations in marine sediments which were also applied for this study is given in Zabel et al. (1999).

A frequently used modification of this method focuses on element ratios. Besides the previously mentioned restriction regarding the allocation of single elements to specific mineral phases, element ratios may be suitable especially for reconstructions of the sediment's provenance and the paleoclimate (e.g. Boyl 1983; Matthewson et al. 1995; Schnei-

der et al. 1995; Jansen et al. 1998; Arz et al. 1998, 1999; Martinez et al. 1999; Zabel et al. 1999, 2001). According to conditions in the sedimentation regime, they can reflect climate variations more sensitively than the AR of terrigenous particles (Zabel et al. 1999). Nevertheless, studies from the equatorial Pacific have shown that caution is required when marine particles dominate the sedimentation flux and the terrigenous input is low. However, sedimentary Ti/Al ratios, for example, can extremely deviate from the natural composition of terrestrial source material. The underlying enrichment of Al has been interpreted in terms of scavenging on biogenic particles (e.g. Murray et al. 1993; Dymond et al. 1997). As a result, element/Al records can reflect variations in paleoproductivity instead of such related to the terrigenous signal.

When specific measurements are not available, the quantity of the non-biogenic, terrigenous fraction ($Terr_{tot}$) is often calculated as the residual from biogenic carbonate and opal analyses (e.g. deMenocal et al. 1993; Tiedemann et al. 1994; deMenocal 1995; Rühlemann et al. 1996; Ruddiman 1997). But due to the mutual dilution of the marine and the terrigenous fractions, this generalized method can at least result in an estimation of the latter, however, only producing reciprocal values of the marine components in summary. Additionally, effects due to variations in carbonate production or dissolution would have inevitable consequences for the interpretation of the terrestrial record (e.g. Bloemendal and deMenocal 1989). Information inherent in the terrigenous material itself as investigated by the specific methods described above, may not be observed. In contrast to individual concentrations and element ratios, AR records are much more sensitive with regard to the age model.

An unspecific but nevertheless expressive sedimentological approach is to look at the lithogenic grain-size distribution as representative for the energy which transported the terrigenous particles (e.g. Parkin and Shackleton 1973; Sarnthein et al. 1981; Matthewson et al. 1995; Grousset et al. 1998). The relation is simple: The coarser the particles, the higher the wind velocity or the discharge of river water.

Recently, geophysical sediment parameters were also used for the investigation and interpretation of the terrigenous fraction (Frederichs et al. 1999; Schmidt et al. 1999; Funk et al. this volume). First results obtained from the magnetic characterization of marine sediments are very promising and indicative of the high potential of this new approach. A future task of great importance lies in the calibration of the complex geophysical measurements using geochemical and mineralogical data.

State of knowledge from outside studies

Fundamental work investigating the export of African dust into the equatorial Atlantic originates from the end of the sixties and beginning of the seventies. First indication of the extent to which African dust is carried across the Atlantic Ocean was made by Delany et al. (1967). Three years later, Prospero et al. (1970) identified considerable amounts of African dust particles within the Caribbean as well. Details of the meteorology associated with the transport mechanisms were elucidated by Carlson and Prospero (1972) and Prospero and Carlson (1972). Accordingly, long range transport occurs by the mid-tropospheric African easterly jet stream (Saharan Air Layer - SAL) during boreal summer season, whereas winter dust plumes are predominantly carried by the northeast trade wind system (Sarnthein et al. 1981; Fig. 1). However, these studies have not only shown the spatial and quantitative dimensions of the dust transport from West African deserts for the first time, but can also be seen as an important inspiration for the paleoceanographic and paleoclimatic studies of the last 30 years. Today, the input introduced by the NE trade wind during winter is described as the dominant pathway for the lithic fraction in sediments of the northeastern tropical Atlantic (Chester et al. 1972; Chiapello et al. 1997; Ratmeyer et al. 1999). Against earlier speculation (Kolla et al. 1979), there is a lot of evidence that the position of the trade-wind belt has not shifted substantially between glacials and interglacials (e.g. Sarnthein et al. 1981; Tiedemann et al. 1989; Baslam et al. 1995; Ruddiman 1997; Grousset et al. 1998).

Indication for Low-Latitude Forcing of the West African Monsoon System

The general availability of erodible soils depends, first of all, on the humidity of the respective climate. In Central and West Africa precipitation is controlled by the West African monsoon which drives moisture into the continent during boreal summer (Fig. 1). Apart from the highly seasonal pattern of this system, there is also plenty of evidence that its intensity has periodically varied responding to low-latitude insolation on the precessional frequency bands (19 and 23 kyr; e.g. Kutzbach 1981; Pokras and Mix 1985; Tiedemann et al. 1989). Consequently, orbitally induced variations of the low-latitude monsoon intensity are described as the primary driving force for the West African terrestrial climate (e.g. deMenocal et al. 1993; Matthewson et al. 1995). It inevitably follows that dry episodes must have been related to a general attenuation of the monsoon. Furthermore, it has been stated that monsoon intensity and precipitation over Central Africa is strongest, when the boreal summer perihelion coincides with the maximum summer insolation on the Northern Hemisphere (deMenocal et al. 1993 and references therein). However, this interferential effect indicates that, apart from precessional insolation, eccentricity, i.e. the variation in the elliptical course of the Earth around the sun, may also at least occasionally influence the tropical climate (cf. McIntyre and Molfino 1996).

The concept of enhanced aridity on the African continent during glacial periods was first developed for terrestrial samples by Fairbridge (1964). Meanwhile, this concept has been confirmed by a large number of mineralogical, geochemical, faunal, and palynological studies on marine and lacustrine paleoclimate records (e.g. Damuth and Fairbridge 1970; Parkin and Shackleton 1973; Williams 1975; Street and Grove 1976; Sarnthein 1978; Kolla et al. 1979; Sarnthein et al. 1981; Pokras and Mix 1985; Tiedemann et al. 1989; Street-Perrott and Perrott 1990; deMenocal et al. 1993; Tiedemann et al. 1994; Leroy and Dupont 1994; Matthewson et al. 1995; Ruddiman 1997; Gasse 2000 and references therein). The approximately simultaneous decrease in precessional forcing in the tropics is

suggested as one reason for the dominance of dry conditions during glacials (e.g. deMenocal et al. 1993).

Indication for high-latitude forcing of African Aridity/Humidity cycles

Apart from the frequently documented link between terrigenous input and variations in the monsoon system, there are various studies on marine and lacustrine records which indicate that fluctuations in the Saharan and Sahelian aridity, as well as the precipitation cycles in tropical South America, were essentially synchronous with cold events at high latitudes (e.g. Parkin and Shackleton 1973; Kolla et al. 1979; Sarnthein et al. 1981; Stein 1985; Gasse et al. 1989; Street-Perrott and Perrott 1990; Tiedemann et al. 1994). Based on fluctuations in benthic oxygen isotope records which are sensitive to ice volume variations in the Northern Hemisphere, this global climate signal is dominated by the 100-kyr orbitally eccentricity cycle since about 1Ma (deMenocal 1995) and is associated with an increased variance at the precession bands (e.g. Imbrie et al. 1984). According to Harris and Mix (1999) this nonlinear amplification of insolation forcing drives latitudinal shifts of the ITCZ which could explain the dominant 100-kyr component. However, comparison with the previous paragraph makes it clear that the control mechanisms of African aridity are still being controversially discussed.

Indications derived from sea surface temperatures

Valuable information to fathom this apparent contradiction result from reconstructions of variations in sea- surface temperature (SST). As mentioned above, the thermal land-sea contrast and accompanying pressure gradients are important factors for climatic development and variability. For example, results of circulation models predict greater monsoonal precipitation due to larger land-ocean pressure gradients acting in response to increased boreal summer insolation (e.g. Kutzbach 1981; Prell and Kutzbach 1987). SSTs themselves depend on the thermohaline circulation of the ocean which is clearly influenced by the production of North Atlantic Deep Water (e.g. Zhao et al. 1995; Manabe and Stouffer 1997; Mulitza and Rühlemann 2000). Hence, meltwater induced changes in the strength of the North Atlantic thermohaline circulation have been proposed quite early to explain fluctuations of the African monsoon (e.g. Mix et al. 1986; Street-Perrott and Perrott 1990; deMenocal et al. 1993). Accordingly, arid conditions prevail when North Atlantic SSTs are relatively cool and the South Atlantic, or in this case tropical, SSTs are relatively warm (e.g. Lough 1986; deMenocal and Rind 1993). Consequently, the African climate seems preconditioned for aridity during ice growth in high latitudes and full glacial periods. The buildup of heat in the equatorial region was clearly established by comparing alkenone-derived temperature records from ODP site 658 (NW Africa) and core GeoB 1007 recovered from the Congo fan (Zhao et al. 1995; Mulitza and Rühlemann 2000). Similar to other paleoclimate proxies, equatorial SST records show strong precessional variance with lower amplitudes in the west (McIntyre et al. 1989). However, variations in the strength of deep water ventilation and therefore in the cross-equatorial heat transport certainly may help to understand changes in monsoonal precipitation over Africa, but terrestrial surface fresh water indicatorscast doubt on the fact that changes in the thermohaline circulation can exclusively explain all the periods that evidence weakened monsoon. Especially during the Holocene, there still are considerable discrepancies in the number, timing and duration of the century-scale dry episodes (Guo et al. 2000; see below).

Rapid climate changes

A significant criterion for climate control issues is represented by the timing and amplitudes of climate changes. In particular, short-living and abrupt climatic changes are of special interest. At least the climatic instability in low latitudes during the Holocene and late Pleistocene were first proven by retreating lake levels in arid, semiarid and equatorial Africa (e.g. Street and Grove 1976; Talbot et al. 1984; Street-Perrott and Perrott 1990 and references therein). These high-amplitude events lasted over decades and occasionally over several

centuries and are comparable with climatic changes which are documented in high-latitude marine sediments (e.g. Bond et al. 1993) and Greenland ice cores (e.g. GRIP 1993; Dansgaard et al. 1993). Equivalent variations in high-resolution marine records from the tropical Atlantic region are sparsely documented and were only observed for the most part in most recent times (Peterson et al. 1991; Hughen et al. 1996; deMenocal et al. 2000a, b; Maslin and Burns 2000; Haug et al. 2001; Marret et al. 2001). So, in the eastern subtropical Atlantic (ODP site 658) the Holocene cooling events were described as synchronous with changes in the SSTs of the subpolar North Atlantic which document a link between high- and low-latitude climate (deMenocal et al. 2000a). Similar correlations were also documented for the laminated deposits of the Cariaco Basin off Venezuela (ODP site 1002; Haug et al. 2001). In contrast to Maslin and Burns (2000), who have postulated an approximately constant increase of the effective moisture at the Amazon Basin throughout the Holocene, Cariaco Basin deposits revealed a period of enhanced precipitation between the global Younger Dryas event and about 5.4 kyr BP. This has been attributed to a northward shift of the ITCZ (Haug et al. 2001) which generally corresponds to palynological studies form this region (e.g. Ledru 1993), although the forest of the Amazon Basin does not seem to be replaced by an extensive savanna vegetation during glacial periods (Haberle and Maslin 1999). Additional support for Amazonian climate change is given by the large-scale variations in the Atlantic thermohaline circulation which could also be documented in western tropical Atlantic sediments for the last 10 kyr (Arz et al. 2001). However, its a fact that the instability of the Holocene climate is a global phenomenon and that slow orbital insolation forcing alone cannot explain the abruptness of the aridity/humidity changes. In this context, deMenocal et al. (2000b) discussed a climate-threshold response as being responsible for the timing of climatic transitions.

In summary, the essence of all these studies is that the tropical Central African and South American climate is sensitive to both high- and low-latitude forcing. Therefore, frequently formulated questions remaining are a) how does the climate

engine work and b) what is the cause for abrupt climate variations?

Improvements made by Geoscience Research in Bremen

Climate forcing in the low-latitude Atlantic as inferred by variations in the lithogenic fraction

In this section we want to compare and discuss time series of terrigenous matter from six cores which cover the whole tropical Atlantic, resolving the last 250 kyr (Fig. 1). A first generalized view on the records indicates that the accumulation rates of the estimated total terrigenous fraction ($Terr_{tot}$ AR) and Ti flux rates (Ti AR) are expectedly almost parallel (Fig. 2). This definitively does not apply to time series of $Terr_{tot}$ AR and the Al/Ti ratio (Fig. 3). The records seem to be largely independent of each other. Figure 7 documents that this cannot be attributed to an age model effect. Records of the total terrigenous content ($Terr_{tot}$) and Al/Ti are nearly anticyclical, especially in cores that are influenced by a dust input from North Africa and suspensates from the Amazon River (GeoB2910, 1505, 1523). For sediments off the African River estuaries (GeoB1008 and 4901), this relationship reveals an inconsistency which could indicate changes in the interactions among underlying processes. However, the significant differences between the signals of terrigenous parameters consequently imply that their individual variations must have different causes. In the following, cycles and phase relationships in the lithogenic material of the individual cores will be discussed.

Variations in the African Dust Input (ODP site 663, GeoB2910): Based on $Terr_{tot}$ from ODP site 663 (Figs. 2a and 4a), deMenocal et al. (1993) have deduced that AR records of Sahelian dust vary predominantly at orbital periodicities of 100-kyr and 41-kyr and that spectral phase estimates would implicate high-latitude forcing. Provided that sediments from this locations and core GeoB2910 are influenced by the same wind field or by rather continental climate conditions, parallel oscillations in $Terr_{tot}$AR and Ti AR of core GeoB2910 gener-
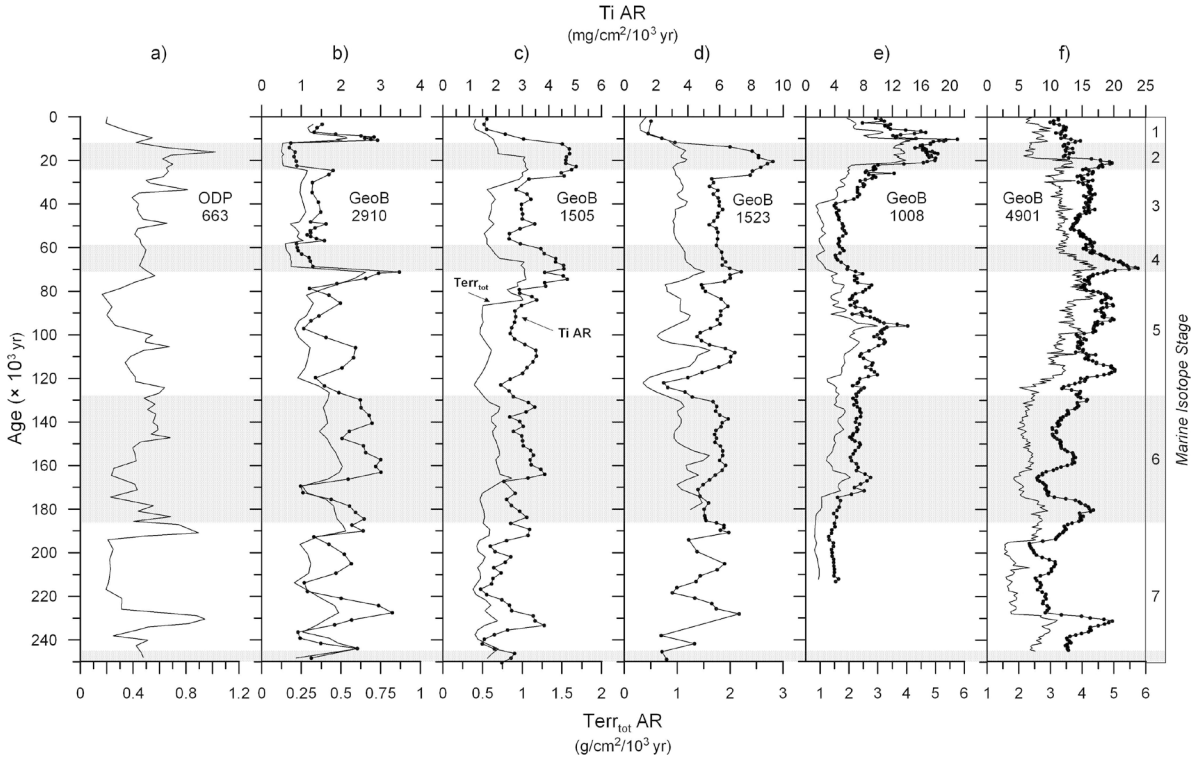
Fig. 2. Records of accumulation rates (AR) of the total terrigenous matter (Terr$_{tot}$) and Ti from six cores of the equatorial Atlantic. Terr$_{tot}$ was estimated by subtraction of biogenic carbonate, opal, and organic carbon contents from the total sediment. All age models are based on δ^{18}O-stratigraphy. **a)** ODP site 663 - western equatorial Atlantic, 1°12'S, 11°53'W, (deMenocal et al. 1993); **b)** GeoB2910 - Sierra Leone Rise (Zabel et al. 1999; cf. Fig. 4, Tab.1); **c)** GeoB1505 - central equatorial Atlantic (Zabel et al. 1999; cf. Fig. 4, Tab. 1); **d)** GeoB1523 - Ceara Rise (Zabel et al. 1999; cf. Fig. 4, Tab.1) Terr$_{tot}$AR based on ^{230}Th-normalization; **e)** GeoB1008 - Zaire deep-sea fan, 6°35'S, 10°19'E (cf. Schneider et al. 1997); **f)** GeoB4901 - Niger deep-sea fan (Zabel et al. 2001; cf. Fig. 4, Tab. 1)

ally contradict this observation (Fig. 2b). Resembling the variations observed in the Al/Ti ratio (Fig. 3b), these records reveal a much stronger precessional 23-kyr component which is nearly in phase with the high-latitudinal insolation signal in the δ^{18}O record of the planktonic foraminifera *G. sacculifer* (Zabel et al. 1999). By contrast, the marine rain rate (total org. carbon/carbonate) in core GeoB2910 clearly fluctuates in tune with orbital eccentricity and subordinate obliquity cyclicity. Due to the potential and the reciprocal dilution effect of the terrigenous and biogenic marine fractions mentioned above, it seems obvious that the assumed domination of the eolian transport to the tropical western Atlantic at the 100-kyr periodicity is rather an artifact. Nevertheless, the Al/Ti record in GeoB

2910 gives strong evidence to an eccentricity modulation of the prevailing precessional term. These overlying frequencies were also documented by the occurrence of the freshwater diatom *Melosia* in ODP site 663 (deMenocal et al. 1993) and in other cores recovered from this region (Pokras and Mix 1985). In this context it is very interesting that *Melosira* variations, in contrast to the Al/Ti ratio, lag precession by about 9 kyr, which was interpreted on account of a lake desiccation in response to climate transitions rather than arid conditions in general (Pokras and Mix 1985). However, the results presented clearly indicate that while the frequency of African dust input and its composition during late Quaternary depends on Northern Hemisphere insolation, the
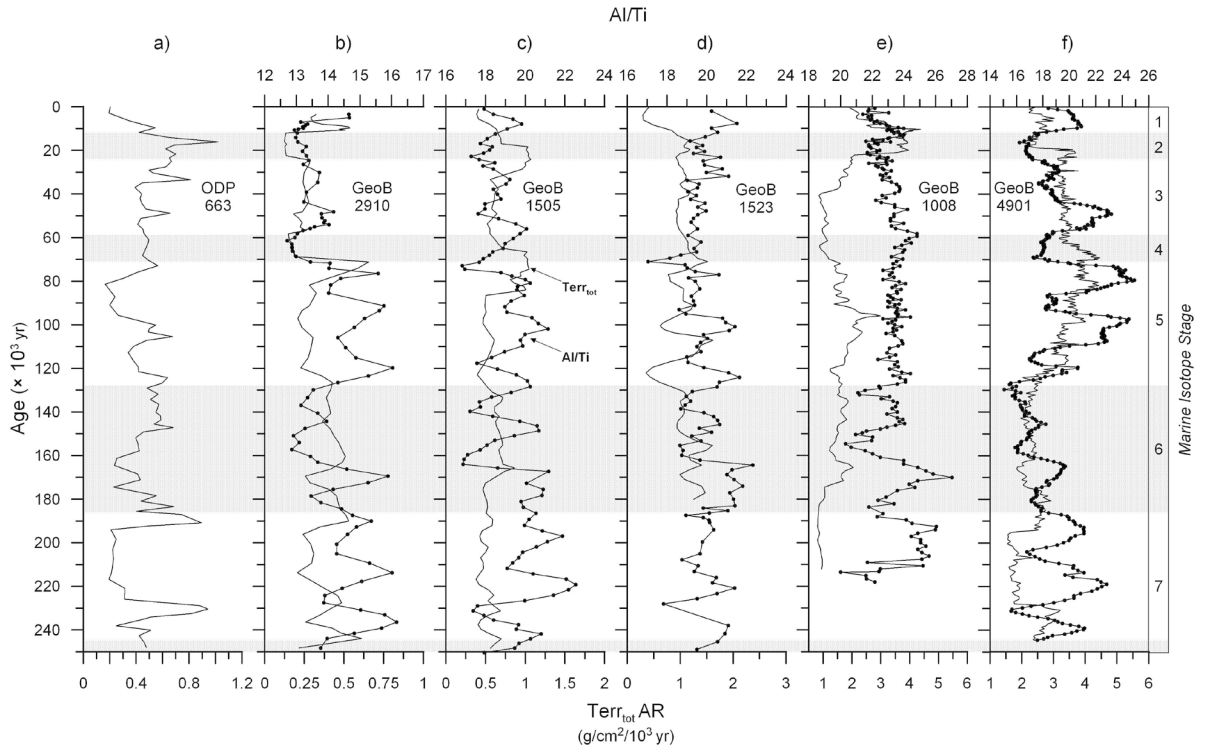
Fig. 3. Records of Terr$_{tot}$AR and the Al/Ti ratio (For information on the cores see caption of Fig. 2)
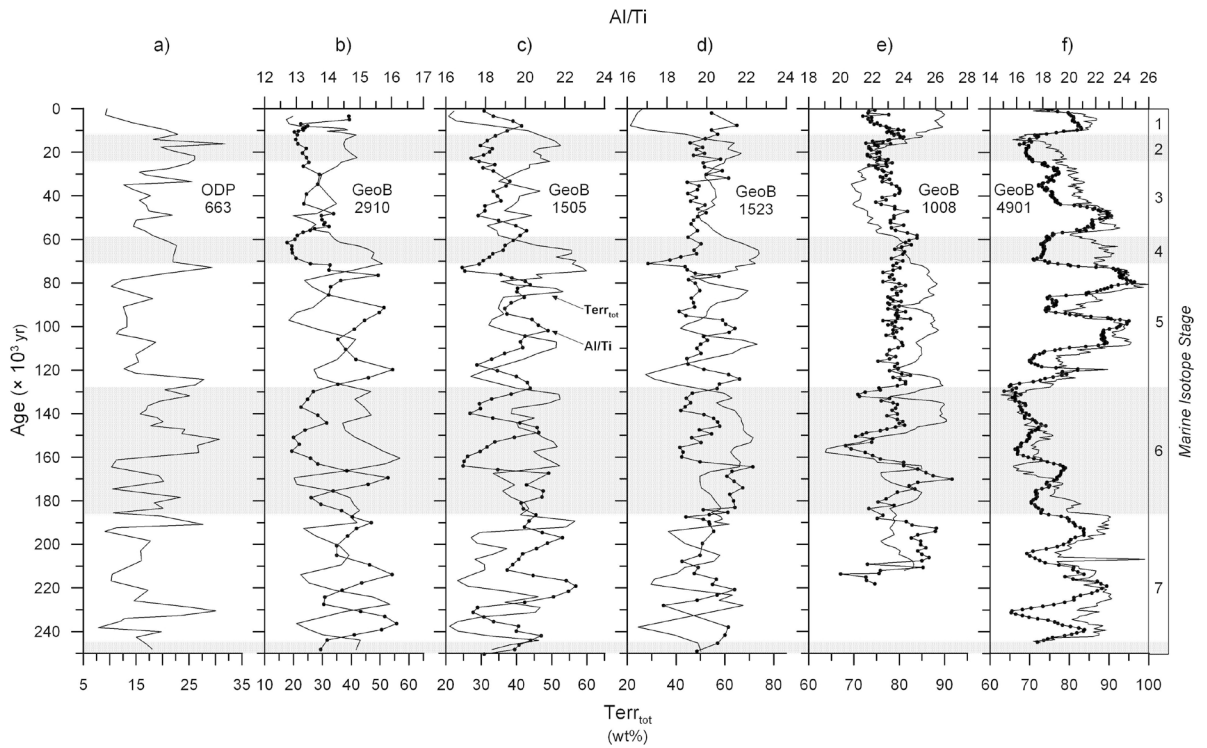
Fig. 4. Records of Terr$_{tot}$ and the Al/Ti ratio (For information on the cores see caption of Fig. 2)

amplitudes are governed by variations in the global ice volume.

Variations in the Amazon River Input (GeoB1523 and 1505): The terrigenous fraction on the Ceará Rise (GeoB1523) consists almost exclusively of river-suspended matter (RSM) that is supplied by the Amazon River (Zabel et al. 1999; Rühlemann et al. 2001). Both, the total terrigenous input (Terr$_{tot}$AR) to the Ceará Rise and its composition as indicated by the Al/Ti ratio are dominated by precessional periodicity (Figs. 2d and 3d). In comparison, the clay mineralogy (illite/smectite ratio) in core GeoB1523 shows a inconsistent and partly divergent picture (Fig. 5), which is probably due to the artifacts on clay mineral assemblages previously discussed (cf. above). However, despite the last glacial amplitudes are most pronounced during interglacials as is particularly documented in the flux records. Therefore, Rühlemann et al. (2001) attributed changes in the supply of terrigenous matter to global sea level variations. Accordingly, the flat topography of the shelf off the Amazon estuary causes the main effect of shelf erosion and direct transport of RSM to the Ceará Rise via canyons to occur when sea-level oscillations only vary between present-day level and such being 40-50 m lower than today. This implies that the flux of Amazon suspensates to the tropical Atlantic Ocean indicates a major influence of high-latitudinal forcing. On the other hand, changes in the surface circulation patterns are described as being additionally responsible for variations in the terrigenous supply to the Ceará Rise and further to the east (Zabel et al. 1999; Rühlemann et al. 2001). Zabel et al. (1999) have therefore deduced an intensification of the North Equatorial Counter Current (NECC) (Fig. 1) as a result of strengthened SE trade winds which explain the relatively high Ti AR and corresponding low Al/Ti ratios in core GeoB1505 at the western flank of the Mid-Atlantic Ridge during glacials and cold interstadials (Figs. 2c and 3c). Significant leads of the terrigenous records against the precessional signal in oxygen isotope records as documented by phase shifts in cores GeoB1523 (Terr$_{tot}$AR: 1.4 kyr, Al/Ti: 1.9 kyr) and GeoB1505 (Al/Ti: 3.0 kyr) may additionally support previous studies which demonstrated that sequences of the Southern Hemisphere lead the
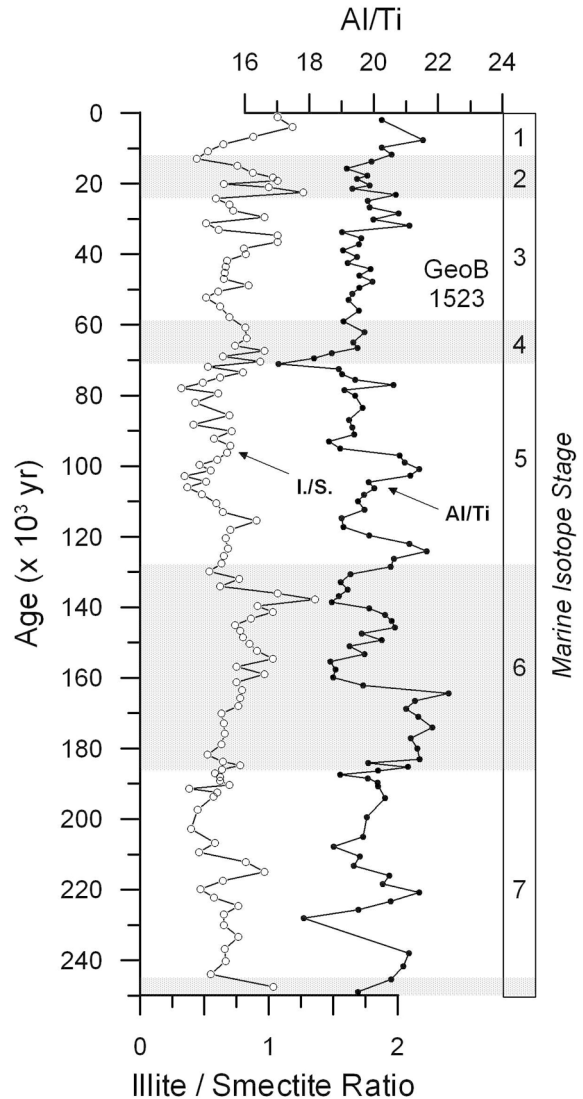

Fig. 5. Comparison between records of the illite/smectite ratio and the Al/Ti ratio in sediment core GeoB1523. Clay data were taken from Rühlemann et al. 2001.

northern circulation by 2-3 kyr (e.g. Hays et al. 1976; Imbrie et al. 1989; Zabel et al. 1999). However, interpreting the Al/Ti ratio as an indicator of the climate conditions in the source area (see below), terrigenous records would also support the assumption of Harris and Mix (1999), who have argued that Amazonian aridity is to be assigned to the chain of events leading to ice ages, rather than being a response to glacier oscillations.

Variations in the Zaire River Output (GeoB1008): RSM output by the Zaire River was discussed by Schneider et al. (1997) and Gingele et al. (1998). Element ratios like K/Al and mineralogical investigations like the kaolinite/feldspar ratio, both to be interpreted as geochemical weathering indices, indicate to the expected larger input of kaolinite as compared with feldspar during warm and humid periods (cf. van der Gaast and Jansen 1984; Bonifay and Giresse 1992; Gingele 1996). Correspondingly, variations in the composition of the lithogenic fraction and its constituents and hence in the Central African climate are again dominated by orbital precession (Schneider et al. 1997). At least during the last 130 kyr, this signal in the 1/23 kyr^{-1} frequency band is less pronounced in the Al/Ti ratio (Fig. 3e) and completely absent in the Ti AR record as well as in the collective parameters Terr$_{tot}$ AR (Fig. 2e) and Terr$_{tot}$ (Fig. 4e). While potential problems with the total terrigenous fraction were already discussed before as a convincing indicator for climate conditions, the lesser significance of single element proxies could be connected with the composition of the soils in the source area. However, the strong precessional cyclicity in the terrestrial signals was described as having been more or less in phase with changes in Southern Hemisphere SST and boreal summer insolation in low latitudes, leading changes in Northern Hemisphere SST and continental ice volume (Schneider et al. 1997). Accordingly, as with the Amazon input, climate variability in the Zaire catchment area seems to be governed by the SE trade wind system which is known to lead the circulation in the Northern Hemisphere (e.g. Zabel et al. 1999). This scenario is consistent with results of clay mineralogy studies that were carried out on sediments from core GeoB1401 (6°56'S, 9°00'E; Gingele et al. 1998; Fig. 6). Smectite crystallinity and illite chemistry revealed that the freshwater discharge of the Zaire River is fostered by an intensified SW African monsoon system during times of maximal insolation in the Northern Hemisphere.

Variations in the Niger River Input (GeoB4901): Time series in the composition of the terrigenous fraction at the Niger fan (GeoB 4901) also showed considerable oscillations (Figs. 2f, 3f, 4f), but the connection to global climate conditions is much
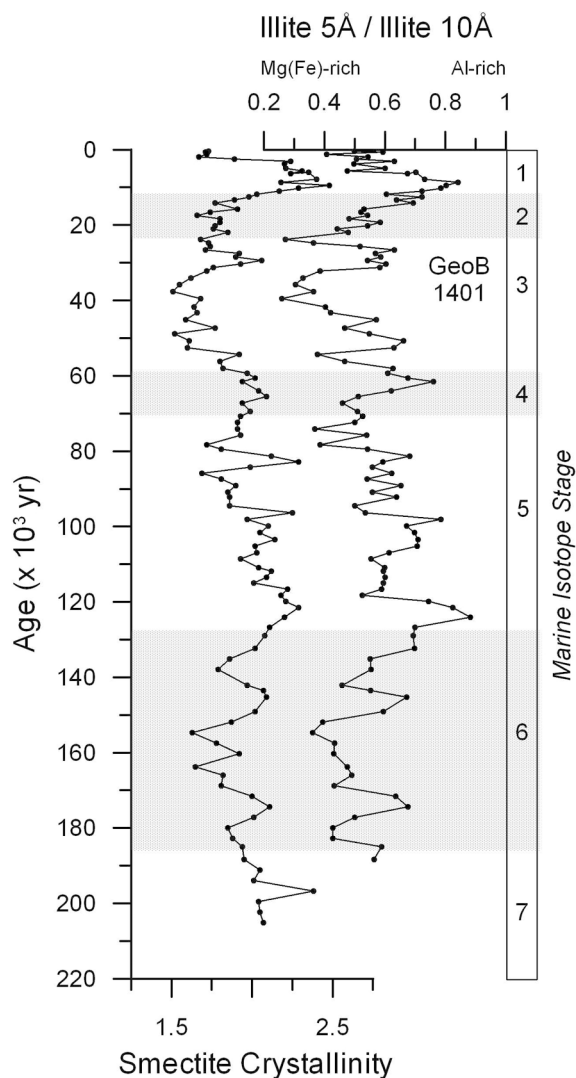

Fig. 6. Records of the smectite crystallinity and of the chemical character of illite (Fe, Mg- or Al-rich) in core GeoB1401 recovered from the Zaire River deep-sea fan at 6°56'S, 9°00'E. The clay mineralogy was analysed by Gingele et al. (1998). Whereas well crystalled smectite originates mainly from the continental shelf, poorly pedogenic crystalls are rather supplied to this region by RSM of the Zaire River. The chemistry of illites reflect the intensity of chemical weathering in the source area which is recently high (Al-rich) in the drainage area. Mg, Fe-rich illites can be traced to the eolian pathway from SW-African deserts. Therefore both parameters indicate to increased runoff during interglacials 1, 5 and 7 and record a high-latitude forcing of river runoff at 100 kyr periodicities reflecting glacial aridity.

more pronounced than for Zaire sediments (Zabel et al. 2001). Consequently, the wrapping curve of the Al/Ti record, indicating relative decreases in Al concentrations during cold interstadials of both penultimate interglacials and glacials, already reveal the typical saw- tooth pattern (Fig. 3f). These oscillations additionally denote that the heavy minerals (the Ti-carrier) are relatively reduced in sediments from warm periods. Based on the fact that the formation of kaolinite (Al) is favored by intensive chemical weathering in a humid climate, Al/Ti ratios corroborate the frequently documented response of African aridity to changes in glacial boundary conditionsdisplaying dry conditions during cold periods. However, based on spectral estimates for harmonic variances, Ti AR and Ti/Al time series are strongly controlled by precession-modulated insolation. In this clarity nothing similar can be determined for the bulk parameters $Terr_{tot}$ AR and $Terr_{tot}$ (Figs. 2f and 4f).

To study the link between orbital climate forcing and its documentation by terrestrial proxies Zabel et al. (2001) have applied cross-spectral analysis to the marine and terrigenous records from the Niger fan (GeoB 4901). Figure 7 shows the result of the relation between Ti AR, Ti/Al, maximum boreal summer insolation at 20°N as potentially reflecting the variability of the monsoon intensity in central equatorial Africa (e.g. Pokras and Mix 1985; Dupont and Leroy 1995), and the precessional signal in the oxygen isotope record of the benthic foraminifera Cibicidoides wuellerstorfi as representing high-latitude climate change. The latter was extracted from the raw data by digital filtering. Zabel et al. (2001) discovered a significant lag of fluctuations in the terrigenous fraction against variations in low-latitude solar radiation (Fig. 7c and e). Although delays are not constant over time, this observation implies that a direct response of terrigenous supply and composition to the monsoon cycle does not exist. Terrestrial signals fluctuate closer in tune with the 23-kyr orbital portion of global ice volume cyclicity. This concerns both chronology and magnitude of the amplitudes (Fig. 7d and f). Considering the well-known time lag of the global isotope response to insolation forcing (Imbrie et al 1984), sediments from the Niger fan confirm the frequently postulated considerable influence of

high-latitude forcing on tropical African climate. Additional strong evidence for this concept is given by variations in the phase shifts (Fig. 7g). They show a clear modulation of the precessional period by the 100-kyr cycle which dominates high-latitude climate change and associated processes like the thermohaline circulation of the ocean. In general, this overlay of frequencies may be applicable to the tropical South American climate, where a dominant 100-kyr cyclicity in compositional variations of Amazon clay minerals has been documented (Rühlemann et al. 2001).

In summary, the results presented underline that the terrigenous input to the tropical Atlantic and its composition generally fluctuates during late Quaternary on the 23-kyr orbital cycle. A lot of studies have given evidence that the same applies to the African monsoon system, which mainly controls the eastern supply of terrigenous matter to the tropical Atlantic (cf. above). Consequently, the strong influence of the high-latitude insolation component on the terrigenous fraction of marine sediments at low latitudes reveals that precessional climate variations in tropical Africa and South America of late Quaternary were modulated by mechanisms operating at the subpolar North Atlantic, which are dominated by the 100-kyr eccentricity cycle. Time series going back further substantiate that the orbital constellation and associated interferences are subjected to nonlinear temporal variations (e.g. deMenocal 1995). This may indicate that the question, whether tropical climate were mainly influenced by high or low latitude processes, could only be answered for limited intervals.

The period from the last glaciation to the Holocene

To consider the last glacial-interglacial change in more detail, we examined the upper sections of nine sediment cores recovered from the tropical Atlantic. Figure 8 shows the individual locations. All sediments are well dated by monospecific $\delta^{18}O$ records, a close correlation with adjacent ^{14}C-dated cores or by radio carbon measurements (Tab. 1). With the exception of the Niger sediments (GeoB 4901), all concentration profiles show significantly increased contents of the terrigenous source ele-
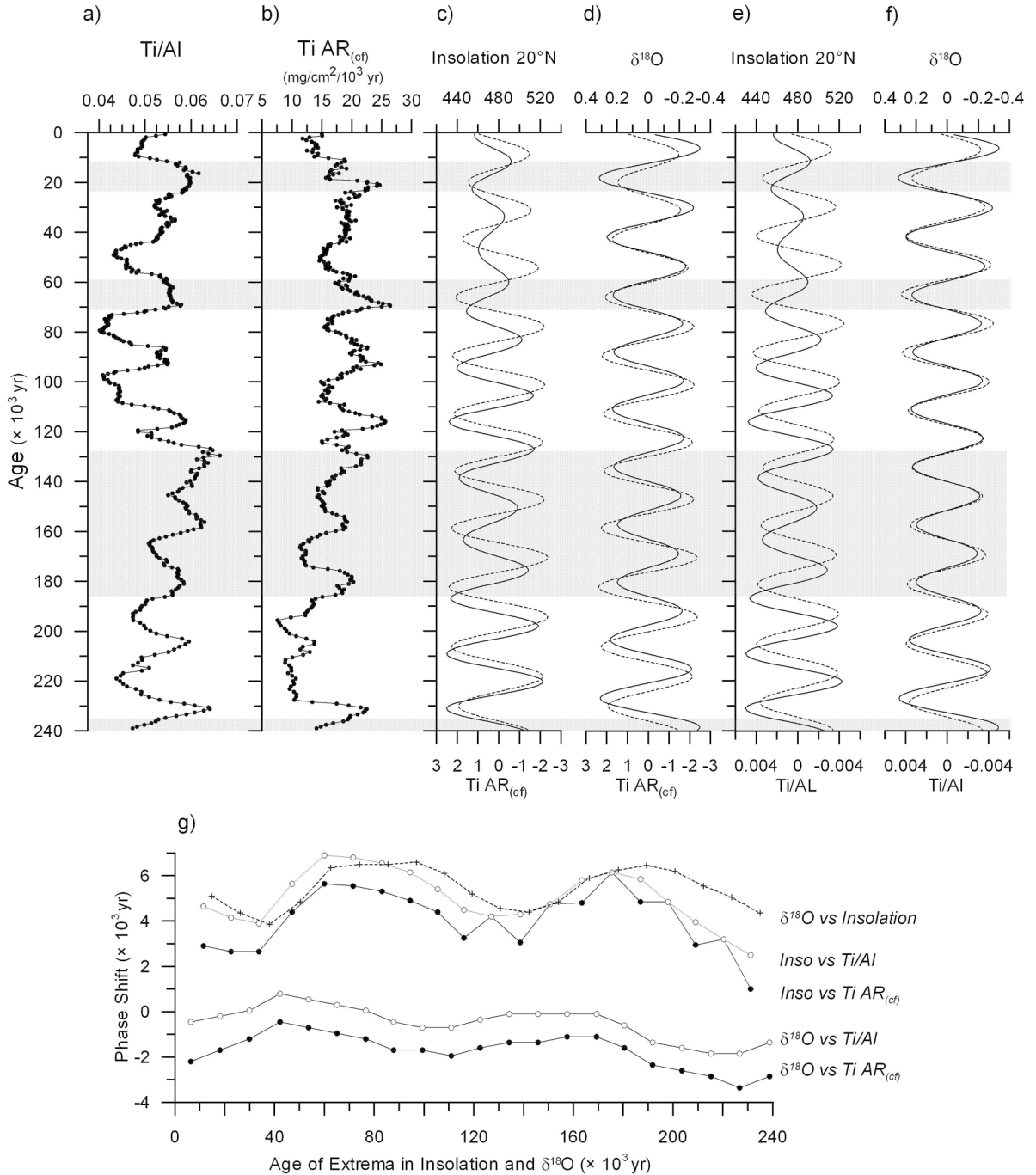
Fig. 7. Results from cross-spectral analysis on core GeoB4901 records. Comparison of the δ^{18}O record of the benthic foraminifera *C. wuellerstorfi*, the insolation cycle for 20°N (W/m²), Ti/Al, and Ti AR at a 23-kyr periodicity. Dashed lines trace changes in the elemental variables. Phase and magnitude of amplitudes indicate that variations in the terrigenous input show a better match with changes in the Northern Hemisphere ice volume than with low-latitude solar radiation. Variations in the phase shifts reflect the overlay of the 100-kyr periodicity. (after Zabel et al. 2001)
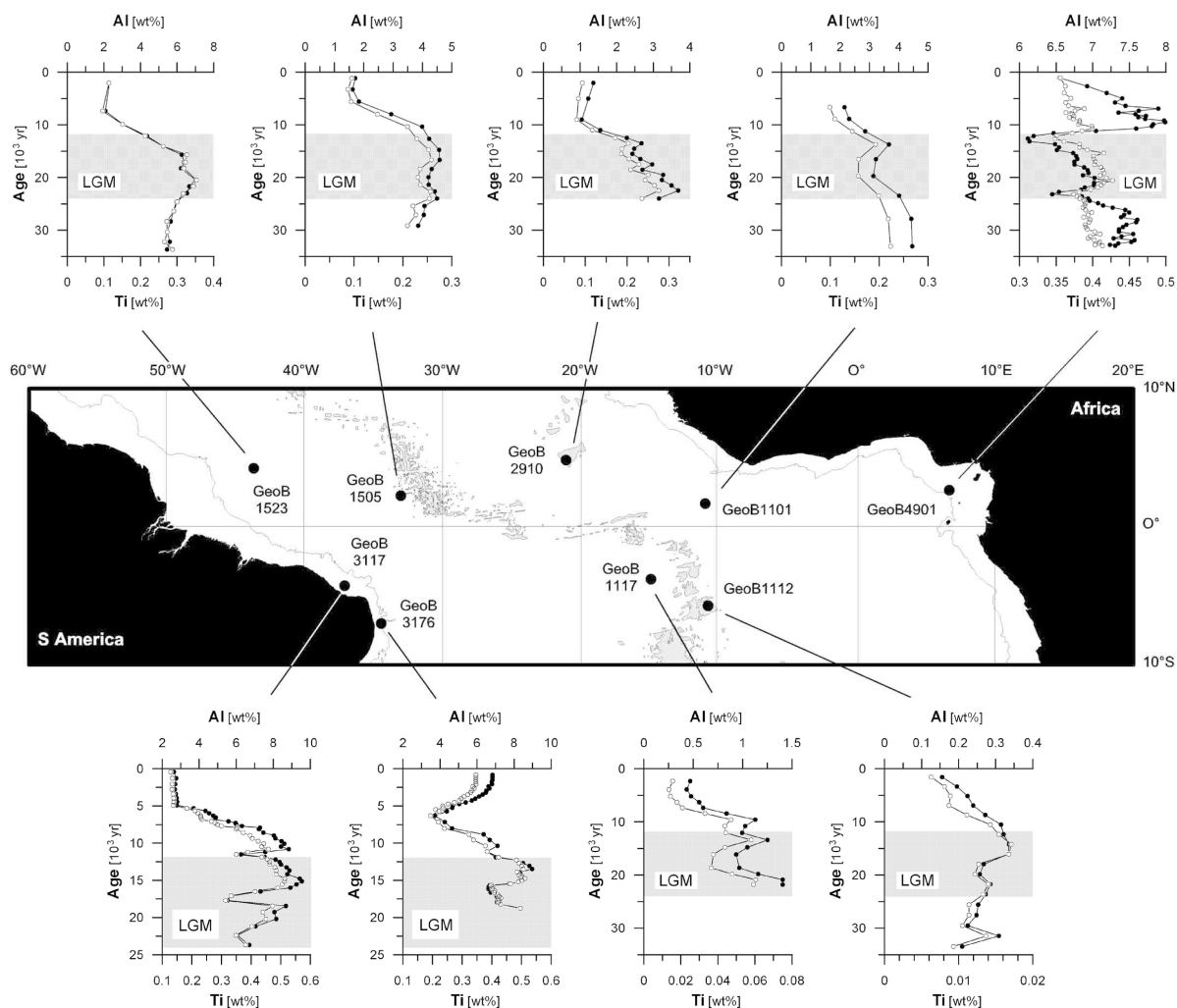
Fig. 8. Records of Al and Ti concentrations in 9 cores analyzed for this study. Al - closed cycles, Ti - open cycles. The terrigenous components in these sediments originated from different source areas adjacent to the equatorial Atlantic (Tab.1) The period of last glaciation is hatched (LGM – last glacial maximum). Age models are based on δ^{18}O-stratigraphy from monospecific samples, transfer of accelerator mass spectrometry (AMS), radio carbon dating of monospecific samples from adjacent cores by correlation using records of several parameters, or new AMS data (Tab. 1).

ments Al and Ti during last glaciation, as compared with the Holocene. Based on isotope stage averages, the enrichment factors range from 1.3 to 2.2 (abs. 1.2-3.6). Highest concentrations were found at near-shore locations (GeoB 3117, 3176, 4901), where the terrigenous fraction is dominated by fluvial input (Arz et al. 1999; Zabel et al. 2001).

Calculation of the element AR agrees with this observation in nearly all cores (Fig. 9). Distinctive maximum flux rates can be noted in most records during Last Glacial Maximum (LGM) and close to

deglaciation. This is consistent with the concept of predominantly arid glacials (cf. above). High AR can be associated with some interacting processes. Depending on the source area and transport mechanisms they indicate (a) intense deflation of dust favored by strong winds and a reduced vegetation coverage due to low precipitation rates, (b) low retention capacity of soils under fluvial erosion which also depends mainly on the extent of root penetration, (c) an intensification of ocean currents when these serve as carriers of the terrigenous

	Longitude	Latitude	Water depth [m]	Stratigraphy	Main Source Area
Core					
GeoB1101-5	01°40'N	10°59'W	4588	δ^{18}O - *C. wuellerstorfi* [1]	Sahara [6]
GeoB1112-4	05°47'S	10°45'W	3125	δ^{18}O - *C. wuellerstorfi* [1]	African Deserts
GeoB1117-2	03°49'S	14°54'W	3984	δ^{18}O - *C. wuellerstorfi* [1]	African Deserts
GeoB1505-2	02°16'N	33°01'W	3706	δ^{18}O - *C. wuellerstorfi* [2]	Amazon Basin [2]
GeoB1523-1	03°50'N	41°37'W	3292	δ^{18}O - *G. sacculifer* [3]	Amazon Basin [2,3]
GeoB2910-1	04°51'N	21°03'W	2703	δ^{18}O - *G. sacculifer* * [2]	Sahel Zone [2,6]
GeoB3117-1	04°11'S	37°08'W	930	AMS ^{14}C ** [4]	Local Brazilian Rivers [4]
GeoB3176-1	07°01'S	34°27'W	1385	AMS ^{14}C ** [4]	Local Brazilian Rivers [4]
GeoB4901-8	02°41'N	06°43'E	2184	AMS ^{14}C [5]	Niger Catchment Area [7]

[1] Bickert and Wefer 1996; [2] Zabel et al. 1999; [3] Rühlemann et al. 1996, 2001; [4] Arz et al. 1999; [5] Zabel unpubl.
[6] Frederichs et al. 1999; [7] Zabel et al. 2001
* via CaCO$_3$ correlation; ** via δ^{18}O (*G. sacculifer* and *G. ruber*), XRF data, and color correlation

Table 1. Core locations, depths, methods for stratigraphy, and main source areas of the terrigenous fraction.

fraction. Absolute enhancement factors of flux rates during oxygen isotope stage 2 in comparison to the Holocene range from 1.5 to 13.5, where maximum differences are documented for the African dust input at station GeoB 2910 and for the local RSM input at station GeoB 3117. However, similar flux patterns were also reported for Terr$_{tot}$ in equatorial Atlantic sediments by Ruddiman (1997). But, his theory according to which stronger NE trade winds are more important than glacial hyperaridity for the dust influx to the tropical Atlantic can neither be corroborated nor disproved by our data set. However, special interesting features are the differences in the occurrence of the maximum ARvalues for dust. While the northernmost coring site GeoB 2910 is located under the center of the African dust plume, this is definitely not the case for the two cores south of the equator (GeoB 1112 and 1117; cf. Fig. 1). But, similar records and amplitudes in flux rates still indicate that GeoB 1101 and 1117 may be supplied by the same trajectory. In contrast to GeoB 2910, the other three records show significant variations in the dust input which took place during the last glaciation. Although distinct maxima at the transition to the Holocene and the lead of the prominent peak in core GeoB 1112 could be interpreted as caused by fluctuations of

position of the ITCZ, the geochemical composition of the terrigenous fraction is rather supportive of variations in the zonal wind strength (cf. Sarnthein et al 1981 and references given above). So, maximum AR are parallel to minima in Al/Ti (Fig. 10) which indicate strongest atmospheric circulation. However, the interstage extrema substantiate that variations in the corresponding supply of terrestrial material to the low-latitude Atlantic, and more in general terms climate variations in the adjacent source areas, cannot sufficiently be explained by a simple glacial-interglacial contrast (cf. above). For example, on core GeoB 4901 Zabel et al. (2001) was able to demonstrate that the terrigenous input from the Niger River is mainly governed by the intensity of precipitation and the associated vegetation coverage. Nevertheless, interpretation of AR records with regard to the terrestrial input seems difficult. For example, AR maxima in the near-shore deposits GeoB 3117, 3176, and 4901 appear similar to the prominent North Atlantic melt-water discharge events recorded by Fairbanks (1989) on coral reefs off Barbados. This permits the assumption that temporally limited inputs due to shelf erosion during periods of rapid sea-level rise have affected these records significantly (Arz et al. 1999). Variations in the composition of the terrigenous
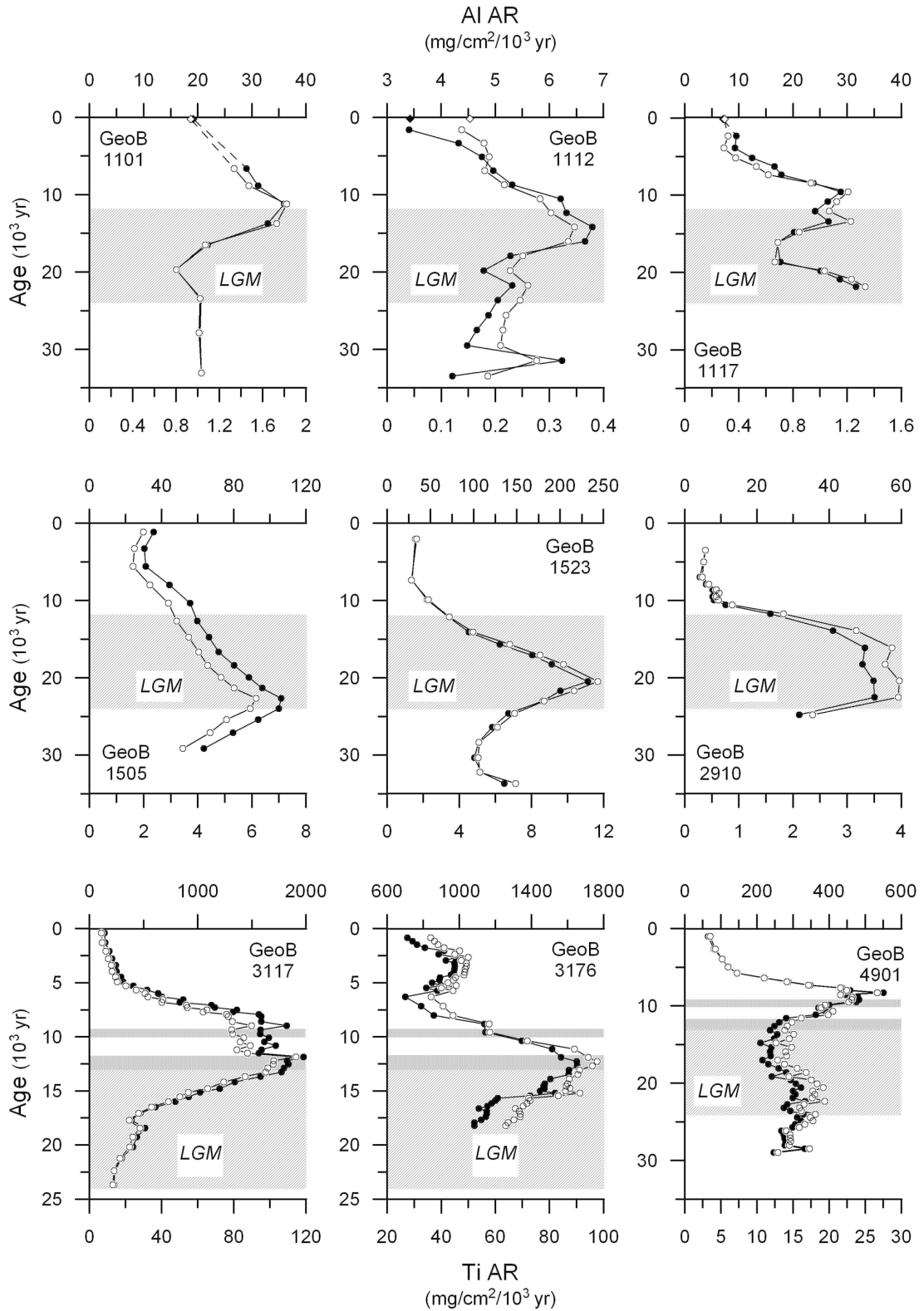
Fig. 9. Records of Al and Ti accumulation rates (AR). For signs and symbols see Fig. 8. Bars mark North Atlantic meltwater events mwpIA and mwpIB (Fairbanks 1989). Dry bulk densities for the estimation of AR were calculated via weight/volume by PJ Müller (unpubl. data).
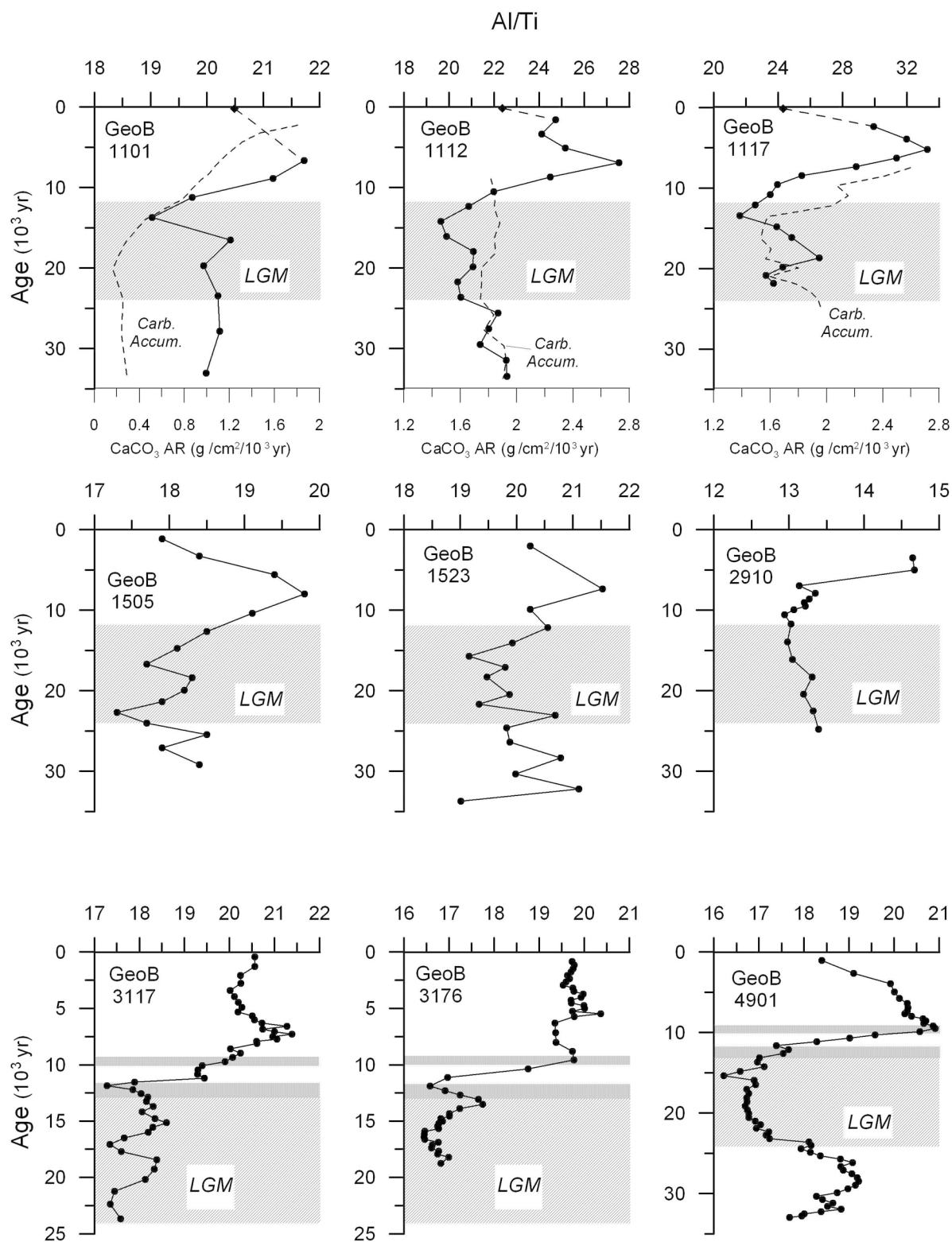
Fig. 10. Records of Al/Ti ratios. For signs and symbols see Figs. 9 and 10. Carbonate contents were measured by Bickert and Wefer (1996).

fraction support the occurrence of this effect at least in both cores off NE Brazil (Fig. 10). While distinct decreases in the Al/Ti ratio during the first meltwater peak (mwp-IA) at around 12 kyr BP could be caused by redeposition of older shelf sediments to the continental slope, the second steep sea-level rise (mwp-IB) is documented by relatively constant ratios which would point to the focusing of material with similar geochemical signatures. An alternative interpretation of this period in Al/Ti records off Brazil is given by pollen analysis, indicating exceptionally strong rainfall between 15.5 and 11.8 kyr BP (Behling et al. 2000), which would correspond to the nearly coinciding local Al/Ti maxima (see below).

Despite these possible artifacts due to sea-level change, records of element ratios are less sensitive to age models and may thus elucidate differences in climate conditions easier than AR. Based on the well established assumption that the Al/Ti signature of dust is an indicator for the wind strength (e.g. Zabel et al. 1999), representative records of African dust input (GeoB 1101, 1112, 1117, 2910) indicate stronger atmospheric circulation during last glacial by significantly lower ratios. Al/Ti ratios at the Sierra Leone Rise (GeoB 2910) resemble the composition of African dust samples (Zabel et al. 1999 and references therein), whereas carbonate-rich off-shore sediments (up to 95 wt% $CaCO_3$) reveal relative enrichments of Al. Decoupling with carbonate AR records indicates, however, that the potential influence of Al-scavenging (Murray et al. 1993) may be of minor importance. The concept of predominant aridity during glacials is also supported by sediments in which RSM dominates (GeoB 1505, 1523, 3117, 3176, 4901). According to Zabel et al. (2001) the Al/Ti ratio of RSM can be interpreted as a chemical weathering index, representing the product of the interplay of precipitation rate, vegetation coverage, type and intensity of weathering, and erosion capacity. Due to preferentially chemical weathering during warm and humid climates, when percolated water permits hydrolytical processes, somewhat more Al (kaolinite) than Ti (heavy minerals) is eroded, a fact which is expressed by high Al/Ti ratios during interglacial periods. In contrast to the eolian pathway, transport energy might be of sub-

ordinate importance for the composition of RSM, when sediment discharge and runoff are inversely correlated due to the retention effect of vegetation. However, following our argumentation it becomes clear why the terrigenous AR records and Al/Ti ratios presented here show roughly inverse patterns. The slight shifts between maxima and corresponding minima may be mainly the result of the particular response time in plant growth and decay to changes in rainfall intensity.

In summary, all records provide strong evidence that generally dry conditions prevailed during last glacial. Additionally, they reveal that significant changes in terrestrial flux rates often occurred on relatively short time scales. Depending on depth resolution and age model, some of these changes lasted only a few centuries. This agrees with the general opinion that fluctuation in orbital insolation cannot be the only driving force for the climate variability in the tropics.

Conclusions

In accordance with most outside studies, the presented results concerning the variations of terrigenous signatures in sediments from the tropical Atlantic reveal a strong precessional cyclicity in general, which is indicative of a close link between continental aridity fluctuations and evaporation in the ocean. But apart from this dependence on changes in orbitally produced solar radiation, paleoclimate records also clearly indicate that oscillations in high latitudes are necessary to explain the major features of late Quaternary climate change at centurial, millennial or longer time scales. Beyond that, the highly complex interplay between high- and low-latitude forcing is subject to regional differences. In particular, land-ocean interactions may be of crucial importance for this observation. These are mainly controlled by the thermocline circulation which could be one explanation for the predominately latitudinal differences. The additional sensitivity of the monsoon system to changes in the vegetation cover (e.g. Foley et al. 1994; Ganopolski et al. 1998; Claussen et al. 1999) implies that the timing of climate change is also influenced by the response of vegetation to significant changes in precipitation. However, the close connection be-

tween SSTs, temperature and pressure gradients, and the orbital insolation cycle may explain why the precessional frequency of terrigenous input variations and material compositions revealed a modulation by ice volume fluctuations in the Northern Hemisphere. At least during late Quaternary, the high-latitudinal 100-kyr periodicity determines the amplitudes of fluctuations in the terrigenous climate proxies, and therefore seems to have a dominant influence on the sum of all local parameters controlling climate change each probably working on different time scales.

Implications and perspectives for future research

Owing to the effectiveness of high-resolution studies on marine sediments, future approaches should rely on a much closer association between terrestrial and marine investigations. These should not only include conventional comparisons between time series from lacustrine and marine deposits, but also interdisciplinary projects on such specific terrigenous source materials like soils and dust particles. At least today's interpretations of most terrigenous climate proxies which are based on causal connections, may be well-founded, but they are not really understood in detail. This is definitively the case in regard to regional differences and for processes of particle transport. Studies concentrating on the geochemical and mineralogical alteration of the particle load from their primary signature to the imbedding at the sea floor are extremely rare. This also includes investigations on the influences of lateral particle drift in the water column and redistribution processes near to the sea floor. In this context, an important but only sparsely discussed question concerns the preservation potential of distinct short-lasting peaks in marine sediments related to benthic bioturbation.

Due to the highly complex connections among all the processes involved, further improvements of our understanding of the climate control from the results of coupled climatic models are to be expected. Last but not least, little is known about the anthropogenic disturbances taking an effect on natural climate variations.

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