SOIL CLAY MINERALS IN NAMIBIA AND THEIR SIGNIFICANCE FOR THE TERRESTRIAL AND MARINE PAST GLOBAL CHANGE RESEARCH

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ABSTRACT We delineated seven soil clay mineral provinces in Namibia. Many individual clay mineral assemblages occur in fluvial, pan, cave and other environments. Previous researchers have used clay mineral compositions as evidence for palaeoenvironmental reconstructions, often without analyzing the formation, the transport and the deposition of these clay minerals. In Namibia, rates of erosion and denudation by water and wind have been very small since early Quaternary times. During the Quaternary, the clay mineral assemblages of the seven provinces and of individual clay mineral deposits did not change significantly. Palaeoenvironmental reconstructions have to consider these small rates of erosion, especially if clay minerals were transported by water and/or wind from their source area to distant regions (e.g., the ocean). Changes in marine clay mineral compositions may not reflect climate change, but can be caused by changes in the ratio of fluvial to aeolian transport. If the changes in the transport mode are known, these changes can be interpreted palaeoenvironmentally. Future researchers have to decipher quantity and quality of the fluvial and aeolian dust transport (clay minerals, pollen, etc.) over southwestern Africa and the Benguela Current area.

Key Words: Namibia; Clay minerals; Terrestrial and marine geoarchives; Quaternary palaeoclimate.

INTRODUCTION

Clay minerals are the most common components of all sediments and soils. Clay minerals are found in the soils and sediments from polar to equatorial regions, from sea level to high mountains, from deserts to rain forests and in marine sediments from coasts to deep seas. Clay minerals are also trapped in the ice of mountain glaciers and polar ice caps. Clay minerals are produced by the transformation of parent rocks by physical and chemical disaggregation without chemical modification of the minerals, and by chemical weathering causing a transformation of primary minerals with the formation of secondary clay minerals. These secondary clay minerals make up the weathering complex and result in soil formation. The intensity of weathering depends on the characteristics of the parent rock (lithosphere), the climate (atmosphere), the water (hydrosphere), and the organisms (biosphere). Clay minerals can be eroded, transported and deposited by water and wind. The development of soils and clay minerals is influenced by climate, vegetation and fauna, lithography, landforms, interflow water, time, and human activities. Therefore, clay minerals provide clues to their parent rocks and to the climatic conditions during their formation.

Past-Global-Change researchers use clay minerals to reconstruct past environments on land and in water. However, these reconstructions will only succeed if the origin and conditions of formation of these clay minerals are known. Until now, there has been no detailed description of the clay minerals from soils and sediments in Namibia, although many palaeoenvironmental reconstructions refer to clay minerals from terrestrial and marine sediments. Without fundamental knowledge of the source areas, formation and distribution of clay minerals in Namibia, many assumptions based on terrestrial and marine clay mineral assemblages remain questionable. Here, we describe clay mineral provinces in Namibia. The clay mineral provinces refer to the occurrence of certain clay minerals and clay mineral assemblages in near-surface sediments and soils (colluvia, soils, fluvial and lacustrine sediments, etc.). The clay minerals of these near-surface substrates are important archives of palaeoenvironmental data, even if they are eroded, transported and deposited, and no longer found at the place of their formation.

River discharge and aeolian input are the main processes supplying terrigenous material to the southwestern African continental margin. Both processes reflect climate (aridity and humidity) in the source area (Gingele, 1996). In our study, clay mineral records from Namibia are described. We discuss the importance of transport processes reflecting climatic conditions of the respective source areas. We evaluate the importance of clay mineral assemblages with respect to the Past-Global-Change research. We address the climatic interpretations of fluvial silt accumulations, the age of the red longitudinal dunes in northern Namibia, the origin of palygorskite, the dust transport to the SE Atlantic Ocean, drainage systems and denudation rates, and the trade wind system in the Benguela Current region.

METHODS

We obtained 205 sediment and soil samples from the surface, from shallow profile pits, from bore holes, and from natural exposures in many different regions and (palaeo) environments of Namibia (e.g., slopes, valleys, pans, plains, caves) (Fig. 1). We collected material from sediments and soils of different ages (recent, subrecent, Holocene, late Pleistocene etc.). The clay minerals were recovered by sieving and settling. They were identified by X-ray analyses. Morphological features of some samples were investigated by using SEM (scanning electron microscopy, Joel JSM 840) to prove the presence of the hormite minerals sepiolite and palygorskite (e.g., Buch et al., 1992; Ott, 1994).

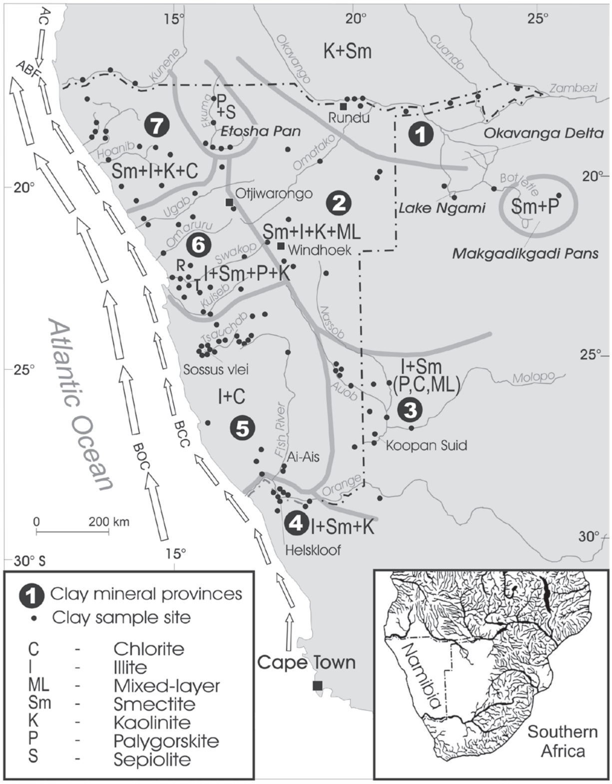

Fig. 1. Clay mineral provinces of Namibia and selected sample sites. Inset map shows perennial rivers in southern Africa.
ABF = Angola-Benguela-Front; AC = Angola Current; BCC = Benguela Coastal Current;
BOC = Benguela Oceanic Current; R = Rössing Cave; T = Tinkas Cave.

Until 1987, clay minerals were determined on carbonate-free (acetic acid) samples of the <2µm fraction by Rothe (Mannheim). Settling methods were applied and the <2µm fraction pipetted on glass slides. Subsequently the samples were smeared to avoid selective settling of smectite. Samples were scanned at 1°2ø/min with a Philips APD-10 diffractometer, using Ni-filtered Cu-Kα radiation. Peak areas were measured with a planimeter and weighted peak areas were calculated to obtain the concentrations of specific clay minerals. To distinguish kaolinite from chlorite, a slower scanning speed of ¼°2ø/min was used to separate the 3.58Å peak of kaolinite from the 3.54Å peak of chlorite (Diester-Haass & Rothe, 1987). Rothe's method probably results in excessively high smectite values.

After 1987, samples were analysed by XRD (by Chamley, see Pletsch et al. 1996). Clays were deflocculated by successive washing with demineralized water after removing carbonates from the crushed rock with 0.2n HCl. The <2µm size-fraction was separated by sedimentation according to Stokes' law. After centrifugation, the resulting paste was smeared onto glass slides. The XRD analysis was performed using a Philips PW 1730 diffractometer with Cu-Kα radiation and a Ni filter. All samples were analysed after air-drying, solvation in ethylene glycol (24h in vacuum at ambient temperature) and after heating at 490°C for 2h. Clay minerals were identified according to the position of the basal reflections on the three X-ray patterns. Semi-quantitative estimations were based on intensity ratios (peak height times a factor relating to peak shape and a mineral-specific factor) of the 001 reflections of the respective clay species. % values in the text are based on these analyses.

After 2000, Völkel analyzed clay samples by XRD (see Völkel, 1995). The fine fraction was chemically pre-treated. Organic materials were removed with hydrogen peroxide (6% H_2O_2) and iron oxides were removed with the dithionite-citrate-bicarbonate- (DCB) method. From the clay fraction (<2μm) oriented glass slides were prepared and four treatment steps were measured with a Siemens D5000 X-ray diffractometer (XRD) using Cu-Kα or Co-Kα radiation: (1) Mg^{2+} saturated clay; (2) Mg^{2+} saturated clay after ethylen glycol salvation; (3) K^+ saturated clay; (4) K^+ saturated clay stepwise heated to 110°, 200°, 300°, 400° and 550°C. 2Θ-angle varies stepwise (step scan mode) from 2°–40° (step size 0.05°, step time 2sec.).

Rose analyzed powder and texturated (air dried and glycolated) samples of clay fractions (<2μm) from the Etosha area by XRD (Philips PW 1729/1710, Cu-Kα radiation). Details of the method are presented in Buch et al. (1992) and Ott (1994).

STUDY AREA

The country of Namibia covers an area of about 823,680km^2. The country is situated between 17° and 29°S latitude and 12° and 25°E longitude. Western Namibia is characterized by a great variety of rock formations, which usually are exposed in a rugged landscape of valleys, escarpments, mountains and large plains. In eastern Namibia, Tertiary and Quaternary sands and other sediments cover most of the surface (Mendelsohn et al., 2002; Hüser et al., 2001). In the west, dominant soils are arenosols, gypsisols, leptosols, together with dune sands, gravel plains, and rock outcrops. In the escarpment areas and mountains, soils consist mostly of leptosols and regosols. On calcareous rocks, calcisols are common. Arenosols are widespread in the Kalahari basin, together with cambisols in the northwestern part of the basin. Fluvisols are found along the margins and valleys of larger river courses. Pan soils are characterized by solonchaks and solonetzes (Mendelsohn et al., 2002).

Namibia's climate is heavily influenced by its location. The country is exposed to air movements of the Intertropical Convergence Zone (ITC), of the Subtropical High Pressure Zone, and of the Temperate Zone. The relative positions of these systems determine the rainfall pattern. The cold Benguela Current modifies the subtropical climate of Namibia. As a result, the coastal regions see little rainfall, relatively low temperatures, strong winds, frequent fogs, relatively high humidity, less radiation and no frost along the Atlantic coast. The regional significance of thermo-topographic airflows over the central Namib Desert frequently equals or exceeds that of the general circulation. The mean annual rainfall is less than 20mm yr^{-1} along the coast and reaches >600mm yr^{-1} in the northeastern parts of the country. Vegetation patterns mostly depend on climate. The more moist and tropical areas in the northeast are dominated by tall subtropical broadleaved tree-and-shrub savanna. To the west and south the vegetation types change progressively to Acacia tree-and-shrub savanna, dwarf shrub savanna, and desert.

RESULTS

I. Clay Mineral Provinces of Namibia

We identified seven clay mineral provinces in Namibia (Fig. 1). Many clay mineral compositions contain quartz, feldspars, Fe-oxides (goethite), calcite, dolomite and traces of other non-clay species. These minerals are not covered in this article.

Clay mineral province 1. In northeast Namibia, kaolinite and smectite are characteristic of clay mineral compositions. The crystallization of the clay minerals usually is good to excellent. The clay mineral compositions document the weathering conditions of a tropical Aw-climate (Köppen/Geiger classification) and the long time period for clay mineral formation since the Tertiary on the old African surface (peneplain).

The intense red-coloured longitudinal dunes of the area between the Okavango delta, the Okavango River and the Etosha Pan are characterized by approx. 85% kaolinite, in addition to mixed-layer clay minerals. This spectrum documents the old weathering age of the longitudinal dunes.

Clay mineral province 2. In the northwestern Kalahari, smectite (55%) is dominant, followed by illite (20%) and kaolinite (15%), as well as illite/smectite/mixed-layer clay minerals (10%).

Clay mineral province 3. In the southwestern Kalahari, the clay mineral compositions mainly consist of illite (10–60%) and smectite (40–70%), in addition to palygorskite (15–30%), chlorite (10%) and mixed-layer clay minerals (5%). The clay mineral assemblages of provinces *2* and *3* document the transition to more arid climatic conditions from the northeast to the southwest.

Clay mineral province 4 covers the southern Namib Desert south of the Orange River. Illite (ca. 40%), smectite (ca. 40%) and kaolinite (ca. 20%) are characteristic of its clay mineral spectrum.

Clay mineral province 5 is situated between the Orange and Kuiseb Rivers, and comprises the Namib Erg, the area of the Great Escarpment, and the adjacent western part of the Namibian Highland. Illite dominates the clay mineral compositions and attains values from 40 to 70%. Chlorite is ubiquitously present with high values as well (ca. 25%). The proportion of smectite (up to 25%) to kaolinite (up to 5%) varies extremely. Up to 10% palygorskite occurs in the clay minerals of this province.

Clay mineral province 6. In the area between the Kuiseb and Ugab valleys, illite dominates (20–50%). In addition, smectite (15–30%) and kaolinite (10–15%) are important components. Mixed-layer clay minerals reach up to 15%. Palygorskite and sepiolite can attain values of up to 30%; the latter two clay minerals document an arid environment.

Clay mineral province 7 consists of the northern Namib Desert and the adjacent areas in the east (Great Escarpment and western Highland). There, illite (30–35%) and smectite (30–60%) dominate; both are well crystallized. Kaolinite and chlorite values each can reach 10%. Mixed-layer clay minerals (chlorite-smectite-forms) regularly contribute to the composition with a few percent. Palygorskite is always present, often well crystallized, and sometimes values reach as much as 35%.

II. Clay Minerals of Different Environments

Apart from the clay mineral provinces, samples were taken from characteristic environments, such as valleys (Kuiseb, Swakop, Molopo/Auob-Nossob, Orange etc.), caves (Rössing Cave, Tinkas Cave), and pans (Sossus vlei, Koopan South, Etosha, Makgadikgadi, etc.).

1. Valleys

River catchments can be part of several clay mineral provinces. The lower reaches of the Orange River run through the southern Namib Desert (clay mineral provinces *4* and *5*), which show a dominance of illite + chlorite and illite + smectite + kaolinite, respectively. However, the Orange River sediments yield 75% smectite with relatively low percentages of illite (10%) and kaolinite (10%) as well as mixed-layer clay minerals (0 to 5%). The Orange River clay sediments represent the clay mineral provinces of the river's upper reaches, where smectite is abundant in soils and sediments as a product of the weathering of the Drakensberg basalts and the Karoo sedimentary rocks (Compton & Maake, 2007). Severe soil erosion (Heine, 1987; Chakela, 1981) contributes smectite to the Orange River floods. In the Namib Desert area, the clay mineral compositions of the slackwater deposits of the Orange River differ from local flood sediments (e.g., Helskloof valley) in their high smectite percentages.

In the southwestern Kalahari, clay mineral compositions from the Auob and Nossob valleys differ considerably from those of the Molopo valley. The Molopo River catchment stretches to the more humid highland in the southeast of the Kalahari Desert. The illite content reaches only 5%, whereas smectite reaches >60%. In the Nossob valley, illite is dominant (60%), and smectite and kaolinite contribute only about 20% each. On the other hand, the Auob valley sediments show not only 45% smectite, but also 30% palygorskite and 10% chlorite + illite.

In the Fish River Canyon, the flood sediment clays mostly consist of illite (±85%) and, secondary, chlorite (15%). The sediments of the main valley (Fish River) often show a higher content of illite than the sediments of the minor tributary valleys. In a tributary valley near Ai-Ais, the percentage of chlorite increases to >30%, whereas the illite content decreases to <65%.

The sediments of the Kuiseb floods contain about 40% smectite and 40% illite, in addition to 10–15% kaolinite and up to 5% mixed-layer clay minerals and chlorite. Palygorskite is not present. Palygorskite is also absent in the late Quaternary sediments of the Kuiseb. This shows that little aeolian dust is transported from the Namibian Highland to the Namib Desert. Erosion processes are mainly confined to the gramadulla area (severe eroded Damara shists). Material of the Namib plain (Namib Unconformity Surface) was not washed to the Kuiseb valley. This is corroborated by geomorphologic-pedological evidence (Heine & Walter, 1996), which documents extremely slow denudation rates. From the Namib Desert, the Namibian Escarpment, and the adjacent Namibian Highland, surface exposure ages have been useful in revealing erosion rates since Tertiary times: denudation of the surface of ~0.5–1.0m/myr (van der Wateren & Dunai, 2001) and ~3.5m/myr (Bierman & Caffee, 2001) confirm that the desert surface is very stable. Fission track analysis of rocks suggests that Namibian erosion rates have reached a steady state and are changing little over time (Bierman & Caffee, 2001; Cockburn et al., 2000).

The Swakop valley clay mineral composition differs from that of the Kuiseb valley, because the Swakop catchment stretches to the Namibian Highland in the east. Illite (50–90%) dominates. Smectite only contributes 15–25%, and, as a result of the influence from the highland, kaolinite is present with 10–20%. Even though palygorskite always is present in the sediments of the surrounding Namib plains, it occurs only occasionally in Swakop sediments. We suppose that denudation rates by water of the Namib Desert surface have been very low and/or that palygorskite was unstable and was transformed into smectite under the influence of groundwater in the sediments, and therefore, it cannot be identified by XRD analyses.

The Omaruru sediments contain up to 10% palygorskite. Apart from this, the Omaruru sediments resemble the Swakop sediments. The similar clay mineral compositions of these distinct catchments confirm their classification in the same clay mineral province.

The valleys of the Skeleton Coast show high smectite contents (up to 60%). Small valleys with catchments exclusively in the Etendeka basalts display almost exclusively smectite with only minor proportions of mixed-layer clay minerals.

The clay mineral composition of the Kunene River sediments reflects the origin of the clays in the tropical wet Angolan Highland. Kaolinite (±30%) and smectite (±60%) dominate the samples (with some illite: ±10%). This is also true for the Okavango and the Cuando River sediments. While the clays of the Okavango sediments contain about 50% kaolinite and 50% smectite, the smectite content increases to 80% in the Cuando deposits. The clay mineral formation under a tropical climate controls the clay mineral composition.

The Ekuma Valley sediment clays north of the Etosha Pan are rich in illite and smectite, in addition to relatively high amounts of palygorskite and sepiolite.

2. Pans

Generally, pans differ in their characteristic clay mineral composition from other sites (gypsum, sulphur, sepiolite etc.; see e.g., Mees, 1999; 2002; Eckardt & Spiro, 1999; Bao et al., 2000). In the Etosha area, Ott (1994) analyzed the clay minerals of the soils, the sediments and the rocks. The pan clays are characterized by relatively high amounts of sepiolite (in some samples between 80 and 100%) and palygorskite. The clay minerals of the soils in the Etosha area also are rich in sepiolite and palygorskite, which are the main clay minerals of the underlying parent rock (Etosha Limestone). The clay mineral compositions are greatly influenced by the geological, geomorphological and (palaeo-) pedological conditions (Buch et al., 1992; Heine, 1995).

In the Lake Ngami sediments, smectite (45%) and kaolinite (40%) are the most important clay minerals. Palygorskite is only observed in traces. The high kaolinite values together with the low illite content (15%) point to weathering conditions under tropical humid to semi-humid climates.

In the Makgadikgadi Pans, the clays of the sediments are characterized by high percentages of smectite (80%) and low percentages of palygorskite (10%), as well as illite and mixed-layer clay minerals (5% each). The sediments were deposited by flood waters and by wind. They indicate a semi-humid climate with a strong dry season.

In the Koopan Suid Pan of the southwestern Kalahari, illite is dominant in the clay mineral compositions.

3. Caves

We collected blown-in sediments in two caves. In the Rössing Cave, late Quaternary sediments show clay mineral compositions with smectite and palygorskite (35% each), illite (15%), kaolinite and mixed-layer clay minerals (5% each). Sediments older than 350 kyr have clay mineral compositions with remarkably low palygorskite values (15%), but high smectite values (60%). These observations point to more intense weathering in the Namib Desert before ca. 350kyr BP and/or persisting remnants of older (Tertiary/early Pleistocene) soils.

The clay minerals of the most recent (Little Ice Age) sediments of the Tinkas Cave consist almost exclusively of palygorskite (95%). Illite, kaolinite and smectite appear only in traces.

DISCUSSION AND CONCLUSIONS

For a discussion of the palaeoclimatic interpretation of the soils and clay mineral assemblages see Heine (1995) and Eitel (1994). Here we discuss the implications of the clay mineral compositions for the terrestrial and marine Past-Global-Change research. It is important to note that in Namibia, soils of recent to subrecent age cannot be distinguished from palaeosoils of early Holocene and Pleistocene age (Heine, 1995; Buch, 1996). Moreover, there is no difference in clay mineral assemblages between glacial and interglacial soils and sediments.

I. Terrestrial Past-Global-Change Research

1. Origin of the silts of the Namib valleys

Thick fluvial silts were deposited in many valley locations in the Namib (Heine & Völkel, 2009). Some of these are interpreted as *slack water deposits* (SWD), documenting extreme flood events (Heine et al., 2000; Heine & Heine, 2002; Heine, 1998; 2004; Leopold et al., 2006). Other authors interpret the same silts as deposits of reduced water discharge (river end deposits) (Rust & Vogel, 1988; Vogel & Rust, 1987; Rust & Vogel, 1990; Blümel et al., 2000a; 2000b; Eitel et al., 2005). The disagreement extends not only to the sedimentary processes but also to the origin of the silts. Heine (2004) explains the origin of the silts by weathering processes in the associated catchment area and by subsequent fluvial transport from the slopes into the valley bottoms. This points to a local origin of the silts. Contrasting this, Blümel et al. (2000a) concluded that the silts were transported by wind over large distances, then sedimentated on the slopes and washed into the valleys.

In the Namib valleys, the clay mineral compositions of the silts often show characteristic trends, which correspond with the geological and petrographic features of the associated catchment of the valley. The silts (slackwater deposits) of the Orange River are characterized by a dominance of smectite (75%). In the central Namib Desert, the silts (slackwater deposits) of the Kuiseb, Swakop and Omaruru valleys show individual features with respect to their clay mineral compositions (Kuiseb: 40% illite, 40% smectite, 12% kaolinite; Swakop: 60% illite, 20% smectite, 20% kaolinite; Omaruru: 50% illite, 20% smectite, 10% kaolinite, 10% palygorskite). The area of Palmwag is situated in the Etendeka basalt region. There, the clay mineral compositions of the valley silts are dominated by smectite. This reflects the proximity of the basalts. Contrasting this, in the nearby Khowarib Gorge area (Hoanib valley), illite dominates the clay mineral assemblages, as is characteristic for this province. The older Pleistocene fluvial silts contain higher values of smectite than the late glacial and Holocene silts.

The different clay mineral compositions of the silts document the great influence of local conditions on their origin. These observations indicate that the aeolian transport over large distances (Blümel et al., 2000a) cannot be the main agent for the distribution of the silts in the Namib valleys. Furthermore, the clay mineral assemblage contains very little palygorskite. Eitel (2000) argues that palygorskite dominates in the clay fractions of calcretes and that calcretes were 'recycled' by aeolian processes. The low palygorskite values show that recycled calcretes (and that means aeolian long distance transport) do not markedly influence the clay mineral composition of the valley silts. Unfortunately, no detailed scientific analyses of the quantity and quality of the Namibian dust events exist to-date (Eckardt et al., 2001). Therefore, we cannot evaluate the amount of dust from long-distance transport and its influence on the origin of the valley silts in the Namib.

Furthermore, the slackwater deposits show that discharge varied extremely during the late Quaternary and that the last period with more frequent flash floods and extreme discharges into the Atlantic occurred during the Little Ice Age (Heine, 2004; Heine & Völkel, 2009).

2. The age of the 'red dunes' in northeast Namibia

In northeast Namibia, East-West-trending longitudinal dunes occur from the Zambezi River in the east to the Ovamboland in the west. They are characterized by a bright red colour. These longitunal dunes are part of a dune field system that stretches far into the Congo Basin in the North. The orientation of the longitudinal dunes was correlated with late Quaternary glacial wind systems over southern Africa (Partridge, 1999: last glacial maximum; Lancaster, 1989: prior to 32 kyr BP; Thomas et al., 2000; Thomas & Shaw, 2002). Many authors argue that the longitudinal dune systems of northern Namibia, Angola, Zambia, Zimbabwe and southern Congo are evidence for an extreme aridity during the last glacial maximum (compared to late Holocene climatic conditions) (e.g., Lancaster, 1988; Partridge, 1999). We question the age and, hence, the palaeoclimatic interpretation of the longitudinal dunes. The red colour is evidence for intensive weathering of the dunes. The clay mineral composition of the red dunes near Rundu/Okavango (northern Namibia) shows a characteristic kaolinite dominance (85%) which is typical for old (Tertiary) soils. The kaolinite is well crystallized. Additional clay minerals are mixed-layer minerals (10%) and illite (5%). This composition together with the crystallinity and the red colour speaks against an intense sand movement and reforming of the dunes during the last glacial maximum (LGM). The palaeoclimatic reconstruction of LGM wind systems has to be revised.

In the area of the Etosha Pan, the age of the red longitudinal dunes is assumed to be considerably older than the LGM (Ott, 1994; Buch, 1996). Soil development on the red longitudinal dunes (Rhodi-/Chromi-Ferralic Arenosol) and their geochronologic/geomorphologic situation indicates that the longitudinal dune systems were formed during the late Tertiary/early Quaternary (Buch, 1996).

Surface soils and sediments south of the Etosha Pan in areas of local watersheds provide further evidence that no or little erosion occurred during the Quaternary. In these locations, the clay mineral composition of dark red soil remnants indicates that these soils were formed a long time ago. Their clay fraction contains 50% kaolinite and 50% well-crystallized illite. The quartz content is relatively high. Only some 100km further south on the divide near Otjiwarongo, illite increases to 70% and kaolinite decreases to 20%, providing evidence for the arid to semi-arid character of this region since early Pleistocene times.

3. Origin of the palygorskite

The clay mineral palygorskite is formed in alkaline conditions and at high magnesium activities in soils. Pedogenic palygorskite appears to be more common in arid soils (<300mm mean annual rainfall). It is transformed into smectite in wetter conditions. Detailed investigations of the clay minerals were carried out by Ott (1994) and Buch et al. (1992) in the Etosha area (see also Heine, 1995). South and southwest of the Etosha Pan, in the area of the Etosha Limestone, the soils are rich in palygorskite. The palygorskite content is exclusively a result of inherited palygorskite from the Etosha Limestone, in which palygorskite is the main component (Ott, 1994). REM/SEM images of palygorskite from the soils and from the Etosha Limestone (Ott, 1994; Buch et al., 1992) show the detritic nature of palygorskite in the soils. If palygorskite and sepiolite (hormite) in the soils are inherited to a large degree from the parent rocks, a palaeoclimatic interpretation of the palygorskite remains questionable, unless a pedogenic origin of palygorskite can be documented (Ott, 1994). In the Etosha area, leptosols contain more palygorskite than smectite, whereas vertisols contain more smectite than palygorskite (Ott, 1994), because palygorskite dissolutes in favour of smectite formation. Palygorskite values in calcretes decrease with the age of the calcretes (from the Tertiary to the late Pleistocene) (Eitel, 2000). Eitel (2000) explained this observation with the 'multiplication of calcretes' (Kalkkrustenmultiplikation). However, Eitel (2000) does not differentiate between authigenic and detritic palygorskite (see also Pletsch et al., 1996).

II. Marine Past-Global-Change Research

Petschick et al. (1996: 226) wrote: 'Material from *West- and Southwest Africa*, which dominates in sediments within the Guinea Basin, Angola Basin, and northern Cape Basin, originates from distinct regions of kaolinite, smectite, and illite dominance. These regions are related to the climate, weathering regime, and type of soil formation. The transport to the deep sea results from a complex interaction of river and wind input and distribution by ocean currents' (Fig. 2).

1. Drainage systems and denudation rates

Dingle & Hendy (1984) used marine sediments to reconstruct drainage basins and their denudation rates. Today, the Orange River carries at least 20 times more sediments to the Atlantic Ocean (>6.95km^3 yr^{-1}) than on average during the Neogene (0.3km^3 yr^{-1}). The increase is the result of anthropogenic activities (Dingle & Hendy, 1984). Gingele (1996) attributes peak values of sediment input to the Atlantic Ocean from the Kunene River (mean value today: 5.8km^3

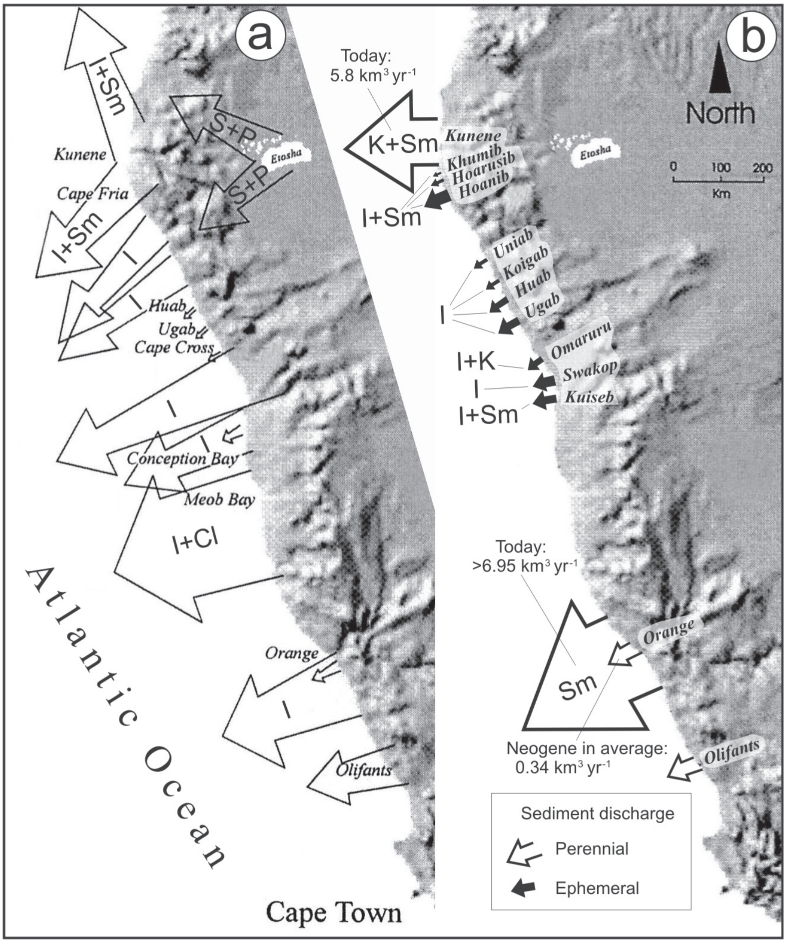

Fig. 2. Attempt to show the typical clay minerals that reach the Atlantic Ocean by wind and water. (a) Map of dust outbreak corridors for the southwest coast of Africa as identified from space-borne imagery and photography (After Eckardt et al., 2001). Abbreviations for clay minerals see Fig. 1. (b) Transport of fluvial sediments (clay minerals) into the southeast Atlantic Ocean.

yr^{-1}) between 15 and 10 cal kyr BP to increased runoff caused by a strengthening of the monsoonal system. A second period of increased runoff from 9 to 5 cal kyr BP shows a distinct shift in clay mineralogy towards river-derived material (increase in smectite and kaolinite). Moreover, Gingele (1996) assumes that the balance between fluvial and aeolian input, represented by the smectite/illite ratio, varied only slightly since 4 kyr BP.

Our results show that the clay mineral compositions of fluvial deposits did not change from glacial to interglacial periods. The clay minerals were eroded by water and wind from the same source regions (surface of the Namib Desert, of the Namibian Highland, of pans and of river deltas, etc.) throughout the Quaternary, independent of climatic fluctuations. Only the vegetation cover changed from glacial to interglacial periods. The changes of marine clay mineral compositions (e.g., increase in kaolinite/smectite or increase in illite) are caused only by changing ratios of fluvial *versus* aeolian input. A shifting of the source areas of wind-derived clay minerals, caused by changing wind systems during the Quaternary, may have influenced the marine clay mineral composition, too. Therefore, changes in clay mineral assemblages of marine sediments by themselves do not represent evidence for climate change.

2. Ocean currents

Variations of the Benguela Current were the driving factor behind the Quaternary climatic development in Namibia. The Benguela Current, which is part of the global oceanic conveyor belt circulation, influences not only the climate of southern Africa, but also the global climate. Variations of the Benguela Current have been inferred from the clay minerals of the marine sediments (Diester-Haass et al., 1986; 1988; Bremner & Willis, 1993). From the occurrence of smectite in the marine sediments off the Namibian coast, Diester-Haass et al. (1986; 1988) infer that sediments of the Orange River were transported northward by the Benguela Current. Bremner & Willis (1993) disagree with this interpretation. The clay mineral compositions of the Kuiseb, Swakop and Omaruru Rivers show smectite values which can explain the marine clay mineral compositions. Petschick et al. (1996) published simplified clay mineral provinces, similar to many conceptions of other authors, about the relationships between marine and terrestrial sediments. A marine clay mineral province with illite dominance between 10–35°S off the Namibian coast correlates with the illite content up to 70% of the Namib Desert surface sediments. Erosion processes are responsible for the transport of the clay minerals from the desert to the ocean (Petschick et al., 1996: 216, 226). Our clay mineral analyses show similar values for the clay mineral province *5* and corroborate the concept of Petschick et al. (1996). The marine cores analyzed by Petschick et al. (1996) do not allow a distinction between fluvial and aeolian deposition (Fig. 2). The ephemeral rivers transport relatively smectite-rich sediments from the central Namib Desert and the hinterland to the Atlantic Ocean. The Hoanib River catchment study (Leggett et al., 2001) quantifies the amount of sediment movement within the catchment area through the combined effects of wind and water erosion during the 1999–2000 rainy seasons. The results show that sheet erosion was observed at 70% of the sites, while gully and wind erosion were observed at 50% and 25% of the sites, respectively. Since discharge decreases downstream and varies from flood to flood, the floods of the Namib Desert valleys rarely reach the Atlantic Ocean (Jacobson et al., 1995). Therefore, the individual rivers carry varying amounts and types of suspended sediments into the ocean. The lack of detailed information on the nature and amount of clay transport by water and wind to the Atlantic Ocean prevents a precise correlation between the source areas of terrestrial clay minerals and their corresponding marine clay minerals. The role of the ocean currents remains unclear as well.

3. Aeolian dust transport to the southeast Atlantic Ocean

Many publications discuss dust transport processes from land to sea (e.g., McTainsh, 1999; Nash, 2000), but only a few refer to studies in southwestern Africa and the southeast Atlantic Ocean.

For the region of southwestern Africa, many authors assume that the SE trade winds are responsible for the majority of aeolian transport of dust (and clay minerals) into the ocean (e.g., Petschick et al., 1996: Fig. 13; Gingele, 1996: Fig. 1; Stuut & Jansen, 2000; Stuut et al., 2002). Chester et al. (1972) note that the input into the south Atlantic Ocean, compared to the north Atlantic Ocean (between 27° and 34°N), is very low with mainly illite deposition. Tyson et al. (2002) mention an annual mass flux of aerosols of ~29Mt a^{-1} from southern Africa to the south Atlantic.

Observations about the dust export from southwestern Africa to the SE Atlantic Ocean during the late Quaternary (Wilkinson, 1988; Diester-Haass et al., 1988; Eckardt et al., 2001) show that SE trade winds off the Namibian coast do not contribute to the dust transport. This is corroborated by the wind streaks on the rock outcrops in the Namib Desert that were produced by winds from NE and E (Diester-Haass et al., 1988; Eckardt et al., 2001). The NE and E winds can reach high velocities, and they often carry large dust plumes to the southeastern Atlantic Ocean. Only in the extreme north of Namibia, SE and S winds can contribute to the dust transport to the ocean (Eckardt et al., 2001).

Satellite images clearly show the source areas of the dust and the 'corridors' of the plumes (e.g., Wilkinson, 1988; Eckardt et al., 2001; Mendelsohn et al., 2002). Near-coastal pans, dry river deltas with wide-spread fluvial sediments, dry valleys, areas of severe soil degradation and overgrazing, dry inland pans (especially the Etosha and Makgadikgadi Pans) are the main source areas for aeolian dust. This is corroborated by the interpretation of satellite images (Eckardt et al., 2001) that document dust outbreak events and their variety and major characteristics. We conclude that in the Namibian Highland, desertification led to increased aeolian dust entrainment (see Andreae, 1996). During the recent centuries, and especially during the last decades, dust (and clay minerals) from degraded and devastated soils may show different clay mineral compositions compared to those of the Pleistocene and early to middle Holocene. We suggest that the cultivated land (arable land of northern Namibia and pasture land of the Namibian Highland) became a source area for dust plumes since the first cattle breeders invaded from the north about 2000 years ago (Kuper, 1999). This process increased in intensity after the European colonization, which started about one hundred years ago (Bubenzer et al., 2007). Eckardt et al. (2001) used space-borne imagery and photography to construct a map of dust outbreak corridors for the southwest coast of Africa (Fig. 2a). Off the west coast of southern Africa, relatively short, narrow individual dust plumes extend only short distances offshore before subsiding into the ocean surface. (This contrasts with the situation off the east coast, where aerosol and trace gas plumes are more integrated, coherent and massive) (Tyson et al., 2002).

Recent analyses of atmospheric aerosols found a high degree of recirculation in the transport plumes over southern Africa (Tyson et al., 2002). These recent studies of dust transport pathways strongly disagree with model conceptions (McGowan et al., 2000; Swap et al., 1996). This necessitates a different interpretation of marine sediments. For example, these results may affect previous assumptions about pollen source areas and transport agents (Shi et al., 1998), about the mid-Pleistocene African C_3 to C_4 plant vegetation changes (Schefuß et al., 2003), and about the calculations of marine high-resolution sedimentation rates (Gorgas & Wilkens, 2002). Dupont & Wyputta (2003) reconstruct the pathways of aeolian pollen transport to the marine sediments along the coastline of SW Africa based on wind trajectories for the LGM using the ECHAM 3 model. Their reconstructions of the LGM vegetation changes and associated palaeoclimatic implications may be improved by considering these results (see also Dupont et al., 2007). To date, palaeoenvironmental reconstructions from marine sediments have been unable to distinguish between intensity and direction of the trade winds (e.g., trade winds and berg winds; Stuut et al., 2002).

In Figure 2, we attempt to show the characteristic clay mineral compositions that reach the Atlantic Ocean via different transport pathways. We distinguish between fluvial and aeolian transport. In this study, we did not examine the extent of clay mineral transport by ocean currents. The influence of ocean currents on the transport and mixing of clay minerals and therefore on the clay mineral compositions of the marine core sediments remains unclear (Petschick et al., 1996: 226).

4. Reconstruction of the trade wind system in the Benguela Current region

Many authors reconstruct the atmospheric circulation in the region of the Benguela Current by interpreting variations of the clay mineral compositions (e.g., Stuut & Jansen, 2000; Gingele, 1996; Petschick et al., 1996; Jansen, 1994). These reconstructions overlook that clay mineral assemblages of the fluvial and aeolian sediments individually did not change in their composition during the major Quaternary climatic changes (glacial – interglacial). However, changes did occur in the ratio of aeolian to fluvial transport of the clay minerals, requiring a different approach to palaeoclimatic reconstructions based on clay mineral assemblages. Furthermore, the denudation rates are extremely low in most parts of Namibia (van der Wateren & Dunai, 2001; Bierman & Caffee, 2001). A denudation rate of 0.5–3.5m/myr suggests that only small amounts of aeolian and fluvial sediments can contribute to the marine deposits off the southwestern African coast.

SUMMARY

We delineated seven soil clay mineral provinces in Namibia. Many individual clay mineral assemblages occur in fluvial, pan, cave and other environments. Previous researchers have used clay mineral compositions as evidence for

palaeoenvironmental reconstructions, often without analyzing the formation, the transport and the deposition of these clay minerals. In Namibia, rates of erosion and denudation by water and wind have been very small since early Quaternary times. During the Quaternary, the clay mineral assemblages of the seven provinces and of individual clay mineral deposits did not change significantly. Palaeoenvironmental reconstructions have to consider these small rates of erosion, especially if clay minerals were transported by water and/ or wind from their source area to distant regions (e.g., the ocean). Changes in marine clay mineral compositions may not reflect climate change, but can be caused by changes in the ratio of fluvial to aeolian transport. If the changes in the transport mode are known, these changes can be interpreted palaeoenvironmentally. Future researchers have to decipher quantity and quality of the fluvial and aeolian dust transport (clay minerals, pollen, etc.) over southwestern Africa and the Benguela Current area.

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