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Significance of clay mineral assemblages in the Antarctic Ocean

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ABSTRACT

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Typical examples from different morphological and geological settings in the Antarctic Ocean are reviewed in order to discuss the value of clay mineral assemblages for reconstructing the glacial history of Antarctica, the paleoceanographic history of the Antarctic Ocean and the sedimentary processes at the Antarctic continental margin. The significance of clay minerals for paleoenvironmental reconstructions strongly varies with both the position of the sites under investigation and the age of the sediments.

In late Mesozoic to Paleogene sediments clay mineral assemblages are sensitive tools for reconstructing climatic conditions. For example, the shift from smectite-dominated assemblages to illite- and chlorite-dominated assemblages in the earliest Oligocene clearly documents the transition from chemical weathering conditions under a warm and humid climate to physical weathering under cooler conditions. Submarine elevations such as Maud Rise and Kerguelen Plateau give the best record for direct paleoclimatic and paleoceanographic studies. At the proximal sites of the continental slope and shelf, as well as in the deep sea, the paleoclimatic information normally is masked by a variety of processes resulting in sediment redistribution. At those sites, in contrast, the clay mineral assemblages bear a wealth of information on different sedimentary processes.

After the establishment of a continental East Antarctic ice sheet, physical weathering prevailed. Variations in the clay mineral records predominantly reflect the influence of different sediment sources resulting from different glacial, hydrographic or gravitational transport processes. Because these sedimentation processes are generally linked to climatic variations, the clay mineral assemblages in most of the Neogene and Quaternary sediments provide indirect paleoclimatic information. The processes are best documented in the clay mineral composition in those areas where changes in source regions with distinct petrographic differences are expected and where distances from the source region are low.

Introduction

A large part of the clay minerals accumulating in the ocean close to continents is derived from land. There they were provided by physical or chemical weathering processes from a variety of lithologies. The clay mineral types and the proportions of the individual clay minerals in marine sediments therefore depend on the climatic conditions on land and on the nature of the source rocks. The distribution of different clay minerals in the present-day oceans reveals a latitudinal zonation that strongly reflects the pedogenic zonation and climatic conditions on the adjacent continental land masses (Biscaye, 1965; Griffin et al., 1968; Lisitzin, 1972; Windom, 1976). Clay mineral assemblages in marine sedimentary sequences are, therefore, useful tools for reconstructing the paleoclimate through time. However, the small size of the clay minerals makes them prone to erosion, transport and redistribution by different media, such as wind transport, fluviatile transport, as well as transport and erosion by bottom currents or gravitational sediment movements. Thus, clay minerals may also be useful tools for deciphering and reconstructing sedimentary processes.

In high latitudes Cenozoic climatic variations

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and erosional processes both on land and at the continental margin were specially pronounced. Therefore, in these regions clay minerals are predestinated as indicators of modifications in the environment and complement the paleoclimatic information provided by other indicators.

To assess the long-term record of the development of paleoenvironmental conditions, glacial history and paleoceanography, the recovery of long sediment cores is required. Therefore, studies of Mesozoic and Cenozoic conditions mainly rely on sediment cores from the drilling ships of the Deep-Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP). The investigation of clay mineral assemblages on these cores has become a standard method. In contrast, in almost exclusively Quaternary sediments sampled by gravity, piston, phleger and box corers from the Antarctic Ocean, only few clay mineral analyses were carried out. One reason for that may be that the Antarctic Quaternary sediments were often described to reveal only minor fluctuations in the clay mineral composition (Anderson et al., 1980; Elverhøi and Roaldset, 1983; Pudsey et al., 1988; Wessel, 1989).

This paper discusses the significance of clay mineral assemblages in the Antarctic Ocean in respect to decipher the paleoceanographic history of the Antarctic Ocean, the glacial history of Antarctica and the sedimentary processes at the Antarctic continental margin. However, it does not intend to discuss the climatic evolution of the southern high latitudes, which already has been reconstructed in great detail (e.g. Robert and Maillot, 1990; Grobe et al., 1990a; Ehrmann, 1991). For evaluating the significance of clay minerals, typical examples from different morphological and geological settings, such as the continental shelf, the continental slope, the adjacent deep-sea and isolated submarine elevations are investigated or reviewed. The material and examples presented in this study mainly come from several expeditions of the Ocean Drilling Program and of the Alfred Wegener Institute for Polar and Marine Research (Fig. 1; Table 1).

Methods

Clay mineral studies based on X-ray diffraction (XRD) often present semiquantitative data gained by different approaches (McManus, 1991). One approach is to calculate ratios between peak areas or peak intensities of two minerals. Another possibility is to calculate relative percentages based on weighted peak areas. Both methods, however, do not provide absolute proportions of individual minerals. An approach to gain an independent data base for each mineral would be to calculate accumulation rates. However, especially in the southern high latitudes, this approach is hampered by the presence of additional minerals in the clay fraction (< 2 µm), such as several types of feldspar, which cannot be quantified easily. Hence, we have chosen an internal standard method in order to quantify the minerals in the clay fraction.

Bulk sediment samples were oxidized and disaggregated by means of a 3–10% H_2O_2 solution. After sieving the samples through a 63 µm mesh, the clay fraction was isolated from the fine fraction by the Atterberg method (settling time based on Stoke's Law). 10–30 ml of a 50% $MgCl_2$ solution was added to the clay suspension (up to 5 l) in order to charge the clay minerals and make them sink by agglomeration. Subsequently, excess ions were removed by double centrifugation with destilled water, and the samples were dried at a temperature of 60°C. In case larger amounts of carbonate or amorphous silica were present, these components were removed by 10% acetic acid, respectively a three minutes treatment with a boiling 2 *M* Na_2CO_3 solution.

After grinding the clay in an agate mortar, 40 mg were dispersed in an ultrasonic bath and mixed with 1 ml of a 1% MoS_2 suspension (0.3 µm grain-diameter). We preferred MoS_2 rather than the often used talc standard (McManus, 1991), because talc is a component of the <2µm fraction in sediments of the southern high latitudes (Melles, 1991), whereas MoS_2 does not occur in sediments. Texturally oriented aggregates were produced by rapidly filtering the suspension with a vacuum pump through a membrane filter of 0.15 µm pore width (Lange, 1982). The filter cakes were dried at 60°C while being pressed between waxpaper and a porous plate. Subsequently, they were mounted with double-sided adhesive tape onto 3 cm^2 aluminium tiles and placed into aluminium sample holders. The samples were analysed by XRD after

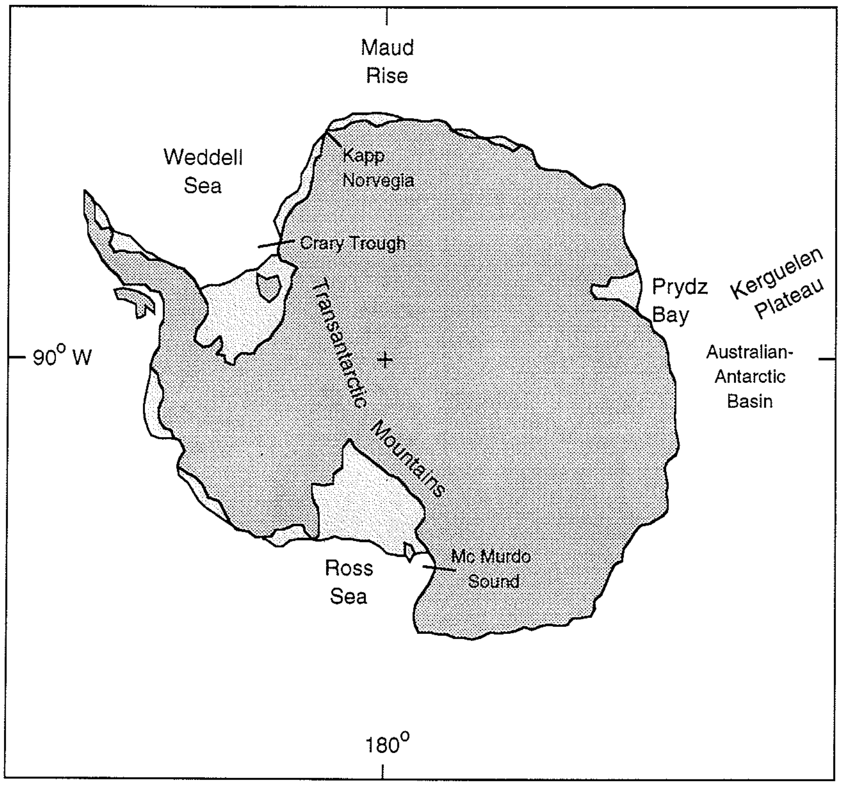

Fig. 1. Schematic map of Antarctica with main areas reviewed and studied.

solvating them for about 18 h with ethylene-glycol vapor in an evacuated exicator at 60°C. The measurements were conducted on an Philips PW 1700 automated powder diffractometer system with CoKα radiation (40 kV, 40 mA), a graphite monochromator and an automatic sample changer. Scans were performed from 2° to 40° 2θ with a speed of 0.02° 2θ/s.

In this paper we concentrate on the main clay mineral groups smectite, illite, chlorite and kaolinite. Compositional differences within these groups are not considered. The individual clay minerals were identified by their basal reflections at $\approx$17 Å (smectite), 10 Å (illite), 14.2, 7, 4.72 and 3.54 Å (chlorite), and 7 and 3.57 Å (kaolinite). Semiquantitative evaluations of the mineral assemblages were made on the integrated peak areas. The relative percentage of each clay mineral was determined using empirically estimated weighting factors (Biscaye, 1964, 1965; Brindley and Brown, 1980).

In order to get independent distribution patterns of each mineral, the calculated peak areas were set in relation to the peak area of the MoS_2 standard. The MoS_2 basal reflection is always well developed, well separated from the reflections of the investigated minerals and lies at 6.15 Å. Distribution patterns of amphibole (at 8.52 Å), quartz (at 4.26 Å), feldspar (at 3.24 Å and 3.19 Å), and talc (at 3.13 Å) were also identified and quantified by relating the peak areas of their basal reflections to that of the MoS_2 standard.

Six samples were prepared and analysed five times with and without a MoS_2 standard in order to reveal possible interferences between the MoS_2 standard and other minerals (Table 2). Comparable mean values and standard deviations were gained by both methods and thus support the applicability of the MoS_2-standard method. The standard deviations characterize the accuracy by which the parameters may be discussed (Table 2).

In order to detect possible dilution effects in the

TABLE 1

Sites studied and reviewed, site location, water depth and references to existing clay mineral studies. ODP= Ocean Drilling Program legs; ANT= Antarctic expeditions of the Alfred Wegener Institute

Site no.	Expedition	Location	Geographic setting	Position	Water depth (m)	Author
689	ODP 113	Maud Rise	elevation	64°31.01'S 03°06.00'E	2080	Robert and Maillot, 1990; Ehrmann and Mackensen, 1992; this study
690	ODP 113	Maud Rise	elevation	65°09.63'S 01°12.30'E	2914	Robert and Maillot, 1990; Ehrmann and Mackensen, 1992; this study
693	ODP 113	Kapp Norvegia	slope	70°49.89'S 14°34.41'W	2359	Grobe et al, 1990b; Robert and Maillot, 1990; this study
694	ODP 113	Weddell Basin	deep sea	66°50.82'S 32°26.76'W	4653	Robert and Maillot, 1990
738	ODP 119	Kerguelen Plateau	elevation	62°42.54'S 82°47.25'E	2253	Ehrmann, 1991; Ehrmann and Mackensen, 1992
739	ODP 119	Prydz Bay	shelf	67°16.57'S 75°04.91'E	412	Hambrey et al., 1991
742	ODP 119	Prydz Bay	shelf	67°32.98'S 75°24.27'E	416	Hambrey et al., 1991
744	ODP 119	Kerguelen Plateau	elevation	61°34.66'S 80°35.46'E	2307	Ehrmann, 1991; Ehrmann and Mackensen, 1992
745	ODP 119	Ant.–Austr. Basin	deep sea	59°35.71'S 85°51.78'E	4082	Ehrmann et al., 1991; Ehrmann and Grobe, 1991
746	ODP 119	Ant.–Austr. Basin	deep sea	59°32.82'S 85°51.78'E	4059	Ehrmann et al., 1991
CIROS-1		McMurdo Sound	shelf	77°34.55'S 164°29.56'E	200	Claridge and Campbell, 1989
PS1400	ANT-IV/3	Crary Trough	shelf	77°33.05'S 36°24.10'W	1061	Melles, 1987; this study
PS1606	ANT-VI/3	Weddell Sea	slope	73°30.08'S 34°01.24'W	2938	Melles, 1991
67 surface samples	ANT-IV/3, ANT-V/4, ANT-VI/3	eastern Weddell Sea	continental margin	various	140 to 4541	this study
72 surface samples	ANT-IV/3, ANT-V/4, ANT-VI/3	southern Weddell Sea	continental margin	various	369 to 2933	Melles, 1991; this study

samples investigated for this paper, we graphically compared the clay mineral percentage curves with the mineral/MoS_2 curves. In general, the visual correlation was convincing. We also calculated correlation coefficients between the percentages and the mineral/MoS_2-ratios. In the case of smectite, the correlation coefficients varied between 0.70 and 0.94. Poorest correlation was found in sequences with smectite contents >90%, where the integration of the smectite peak areas was most inaccurate. In the case of illite, correlation coefficients were 0.80–0.90; in the case of kaolinite, they were 0.87–0.96. For chlorite we calculated correlation coefficients of 0.67–0.83. In contrast to smectite, here we do not know the cause for the occasionally poor correlation. Because of the relatively good correlations between the two methods, we decided to present the clay mineral composition

TABLE 2

Mean values ($\bar{x}$) and standard deviations (σ) of clay mineral analyses of six samples. The samples come from different cores from the Weddell Sea and were taken from various core depths. Each sample was prepared and analysed five times with a MoS_2 standard (A) and five times without a MoS_2 standard (B)

		Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6	
Statistic		$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Smectite (%)	A	5.8	0.25	5.4	0.65	5.9	0.73	5.9	0.67	11.4	3.15	5.8	0.51
	B	5.9	0.51	4.9	0.32	6.2	0.57	5.5	0.80	8.5	0.78	7.5	1.54
Illite (%)	A	62.1	3.91	68.0	3.64	60.3	4.72	50.1	1.95	49.0	1.95	49.4	1.46
	B	62.0	2.49	66.0	1.70	59.3	0.95	50.8	0.66	48.6	1.71	51.2	1.90
Chlorite (%)	A	28.9	4.05	24.8	6.13	29.4	6.92	35.3	2.94	29.8	3.94	34.4	1.62
	B	30.8	2.75	28.0	2.05	31.5	2.48	34.8	1.83	31.9	2.96	32.0	3.18
Kaolinite (%)	A	3.2	0.51	1.7	2.15	4.4	2.07	8.7	1.76	9.9	1.32	10.4	2.15
	B	1.3	1.44	1.1	0.55	3.0	1.17	8.9	1.12	11.0	1.29	9.4	2.18
Smectite/MoS_2	A	0.70	0.04	0.68	0.08	0.66	0.08	0.66	0.10	1.34	0.37	0.59	0.06
Illite/MoS_2	A	7.56	0.64	8.51	0.53	6.76	0.30	5.61	0.18	5.79	0.18	4.99	0.17
Chlorite/MoS_2	A	3.51	0.47	3.10	0.78	3.37	0.96	3.96	0.35	3.53	0.52	3.48	0.20
Kaolinite/MoS_2	A	0.39	0.06	0.22	0.27	0.49	0.21	0.98	0.21	1.16	0.14	1.05	0.22
Talc/MoS_2	A	0.20	0.05	0.26	0.06	0.13	0.03	0.01	0.01	0.01	0.02	0.00	0.00
Amphibole/MoS_2	A	0.07	0.01	0.10	0.02	0.05	0.00	0.02	0.00	0.01	0.01	0.02	0.01
Quartz/MoS_2	A	0.16	0.05	0.12	0.05	0.19	0.07	0.27	0.05	0.39	0.09	0.37	0.15
Feldspar/MoS_2	A	0.64	0.14	0.71	0.28	0.49	0.15	0.29	0.06	0.40	0.09	0.35	0.15

in relative percentages, in order to give the reader a better idea of the actual composition of the clay fraction.

Origin of minerals in the clay fraction

Chlorite and illite are especially common in marine sediments of high latitudes (Biscaye, 1965; Griffin et al., 1968; Windom, 1976). These clay minerals are mostly detrital, being the products of physical weathering on land and glacial scour, particularly of crystalline rocks, such as those that are widespread in East Antarctica. Chlorite is a characteristic mineral for low grade, chlorite-bearing metamorphic and basic source rocks, but is not very resistant against weathering and transport. Chlorite can form in the marine environment only under rather restricted conditions (Griffin et al., 1968). In contrast, illite tends to be derived from more acidic rocks, and is relatively resistant. There is no evidence that illite can form in situ in the open marine environment.

High concentrations of kaolinite are normally restricted to temperate to tropical regions, where intense chemical weathering, especially of granitic source rocks, and lateritic soil formation occurs on land. However, kaolinite occurring in polar regions may be derived from the weathering of older, kaolinite-bearing sediments and erosion of paleosols, because kaolinite is a very resistant mineral (Naidu et al., 1971; Darby, 1975; Chamley, 1989; Hambrey et al., 1991; Ehrmann, 1991). Kaolinite cannot form under glacial conditions. In several high-latitude settings a correlation between recycled kaolinite and smectite has been found and a common source could be reconstructed. In Baffin Bay, for example, kaolinite and smectite originated from offshore coastal plain sediments of Mesozoic to Tertiary age, whilst on the margin of Nova Scotia they were derived from Carboniferous to Triassic red beds (Piper and Slatt, 1977).

The origin of smectite in marine sediments is still under debate. In the present-day oceans, smectite does not reveal a latitudinal distribution pattern as clear as that of the other clay minerals, and no relationship to weathering regimes on land can be detected easily. Maximum smectite concentrations occur in the temperate to subarid regions of the South Atlantic, the central North Atlantic, the central and southern Pacific, and the northeastern Indian Ocean. It thus seems that smectite forms by hydrolysis under climatic conditions between those necessary for the formation of kaolinite and those for chlorite and illite, i.e. between warm-humid and cold-dry conditions (Chamley, 1979, 1989; Chamley et al., 1984). Often, however, smectite is assumed to be derived as a result of submarine weathering (halmyrolysis) of volcanic material (e.g. Biscaye, 1965; further references in Kastner, 1981). This hypothesis is supported by the fact that smectite commonly is found in marine regions where volcanic activity providing the source rocks is high, and where at the same time sedimentation rates are low, resulting in long exposure times for volcanic rocks and ashes, and where the input of terrigenous material is low and therefore dilution is reduced (e.g. in the central Pacific Ocean).

For most of the smectite in sediments drilled in the Antarctic Ocean a continental origin is assumed (Piper and Pe, 1977; Barker et al., 1988; Ehrmann and Mackensen, 1992). Evidence of chemical weathering with smectite formation, however, have been reported from a few soils in Antarctica (Claridge, 1965; Claridge and Campbell, 1989; compilations in Campbell and Claridge, 1987, pp. 130 ff. and Chamley, 1989, pp. 26 ff.). Some Antarctic tills also contain smectite (Bardin et al., 1979; Bardin, 1982).

In addition to the main clay mineral groups chlorite, illite, kaolinite and smectite, many other minerals and amorphous components contribute to the composition of the clay fraction. The quantification of these components, even if they occur in very low concentrations, may provide important information on the environmental conditions. For example, high amounts of talc and amphibole may indicate magmatic and especially metamorphic source rocks and by this may give further information on transport paths, transport processes and the geology of the source area (Melles, 1991).

Examples from the Antarctic continental shelf

The Antarctic shelf area best investigated by deep drilling is Prydz Bay, an embayment in East Antarctica that opens to the Indian Ocean (Fig. 1). The Lambert Glacier and the Amery Ice Shelf drain through Prydz Bay about a tenth of the East Antarctic ice sheet. Four sites were drilled in Prydz Bay along a S–N transect (Barron et al., 1989). Sites 739 and 742 (Table 1) are at a distance of about 140 km to the edge of the present-day ice shelf and may serve as typical examples for a glacial shelf setting. The clay minerals in this special type of setting were investigated in order to study the glacial influence on the clay mineral assemblages. Another point of interest was the value of clay minerals in such a proximal position for reconstructing glacial history and sedimentary processes (Hambrey et al., 1991).

The sediments recovered at Sites 739 and 742 are glacially influenced throughout. Mainly massive waterlain till and some lodgement till build up most of the sequence. Some intervals of weakly stratified and well stratified diamictites also occur and are interpreted as proximal and distal glaciomarine sediments, respectively (Hambrey et al., 1991). The age of the sediments ranges from early Oligocene (possibly late Eocene) to Holocene. The total lack of microfossils in parts of the core and the lack of age-diagnostic microfossils through extended core intervals allowed only a rough dating of the sedimentary sequence (Barron et al., 1991).

In the deepest part of Sites 742 and 739, kaolinite concentrations average around 60%, but decrease continuously upcore to ca. 140 mbsf at Site 742 and ca. 280 mbsf at Site 739 (Fig. 2; Hambrey et al., 1991). Higher in the core kaolinite concentrations remain constant at about 20%. The kink in the concentration curves has an early Oligocene age. The illite and chlorite concentrations show an opposite trend to that of kaolinite. In the lower part of the two sites, chlorite concentrations range from 5 to 15%, in the upper part they reach 30%. Illite concentrations fluctuate around 20 and 60% in the lower and upper parts of both sites, respectively. Smectite shows concentrations fluctuating between 2 and 20%. The highest smectite values are found in the Oligocene part of the sites (Fig. 2; Hambrey et al., 1991).

The most striking feature in the clay mineral distribution at Sites 739 and 742 is the high content

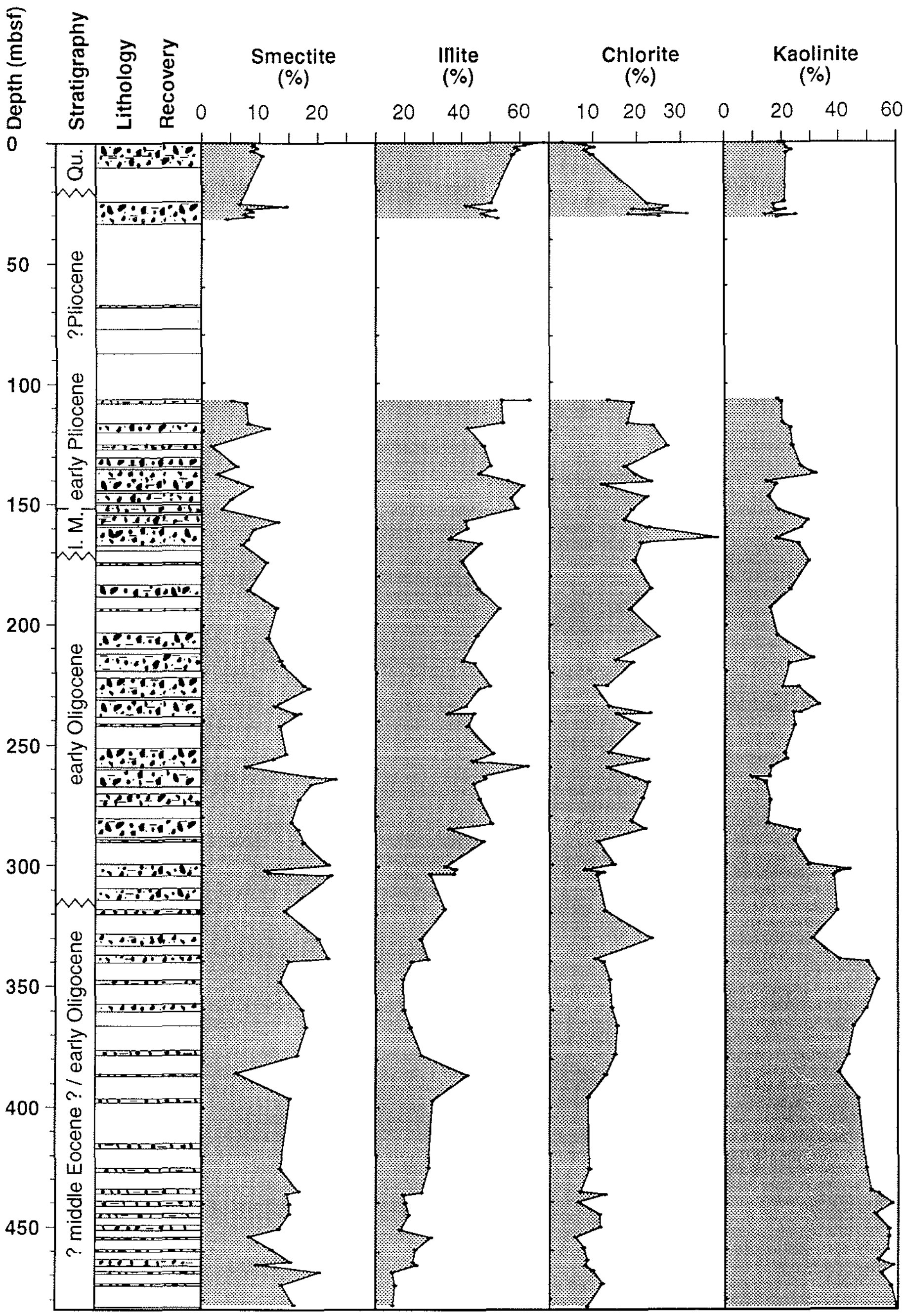

Fig. 2. Clay mineral assemblages at ODP Site 739 on the continental shelf of Prydz Bay, southernmost Indian Ocean (data from Hambrey et al., 1991). Site 742 shows the same general concentration patterns. For legend see Fig. 7.

of kaolinite in lower Oligocene sediments (Fig. 2). Most of the kaolinite was interpreted as a recycled product, derived from the erosion of old kaolinite-bearing sedimentary rocks or soils (Hambrey et al., 1991). The source of the kaolinite might be sought in equivalent rocks to the Permian Amery Formation, which comprises sandstones with a kaolinitic matrix (Trail and McLeod, 1969). Such rocks are probably also filling the Lambert Graben beneath the Lambert Glacier and the Amery Ice Shelf.

The facies of the lower Oligocene sediments illustrates that the grounding line of the ice shelf complex was close to Site 739 during that time interval and glaciation was stronger than today (Hambrey et al., 1991). Sedimentological, paleontological and isotopic data indicate that a continental East Antarctic ice sheet had developed in the earliest Oligocene (e.g. Ehrmann and Mackensen, 1992). The high kaolinite content can be directly linked to this development. The earliest glaciers that reached the sea probably eroded large quantities of soil and loose weathering products derived from both basement rocks and sedimentary strata and transported this material into Prydz Bay. Later, when the ice sheet was fully established and all the unconsolidated detritus had been removed from the continent, the glaciers began to erode unweathered rocks. Therefore, only minor amounts of kaolinite were provided. In contrast, illite and chlorite increased in concentration.

Illite and chlorite probably were provided by the hinterland of Prydz Bay, where large quantities of appropriate source rocks occur. This area is composed mainly of migmatites and gneisses and smaller areas of quartzites and schists (Trail and McLeod, 1969; Craddock, 1982; Ravich and Fedorov, 1982). The origin of the smectite is less clear. It is possible that the smectite was recycled from unknown preglacial sediments and soils. Thus, Bardin et al. (1979) and Bardin (1982) found soils and tills in the Prince Charles Mountains containing largely illite and chlorite, but also some smectite and vermiculite. Smectite also might be transported by currents into Prydz Bay.

The setting of Prydz Bay is very similar to the Ross Sea shelf on the other side of East Antarctica (Fig. 1). Ross Sea sediments were sampled by the CIROS-1 drilling operation in McMurdo Sound (Table 1; Barrett, 1989). The core recovered a lower Oligocene to lower Miocene glacial sequence. The upper Oligocene to lower Miocene clay mineral assemblages consist of illite and chlorite representative for physical weathering. In the lower Oligocene sediments, in contrast, large amounts of smectite are present. Around 60% of the clay fraction is composed of beidellite, a Fe-rich smectite, which today forms in soils of forests or scrublands under a cool to cold temperate climate. A similar climate was therefore postulated for the early Oligocene, with the Ferrar Dolerite as a source for the smectite (Claridge and Campbell, 1989). In analogy to the lower Oligocene kaolinite maximum in Prydz Bay, however, one also could conclude that the smectite was derived from loose weathering products and ancient soils, which were transported by glaciers into the sea, and that the smectite thus represents the first phase of glacial scour.

At numerous sites on the Antarctic continental shelf, lodgement tills of the last glacial period were recovered by shallow coring (e.g. Domack et al., 1980; Anderson et al., 1983). Because lodgement tills are deposited from grounded ice, their clay mineral composition directly reflects the composition of the source area. For example, in the Crary Trough, a more than 1200 m deep depression on the southeastern Weddell Sea shelf (Fig. 1), the <2 µm-fraction of the lodgement till contains relatively high amounts of kaolinite and quartz, and low amounts of illite, talc, amphibole and feldspar. This composition indicates that sedimentary rocks are a significant component of the source area. The corresponding source is found in the northern Transantarctic Mountains, where Paleozoic sedimentary sequences of the Beacon Supergroup crop out (Stephenson, 1966; Weber, 1982) and are commonly rich in kaolinite (Piper and Brisco, 1975). The clay mineral composition of the lodgement till is relatively constant with depth (Fig. 3; Melles, 1987; Fütterer and Melles, 1990). Thus, the source area, and therewith the ice flow lines, did not change significantly during the time span recorded. A comparable homogeneity of lodgement tills was detected on the Ross Sea continental shelf (Anderson et al., 1980).

In surface sediments overlying the lodgement till of Crary Trough, the kaolinite and quartz content of the <2 µm-fraction shows distinct maxima in two regions at the shelf edge, in the southeastern Crary Trough and, less clear, off Berkner Island (Fig. 4). An opposite trend is shown by talc, amphibole, feldspar and illite (Fig. 5). These distribution patterns indicate different source areas, different transport paths and/or different transport media.

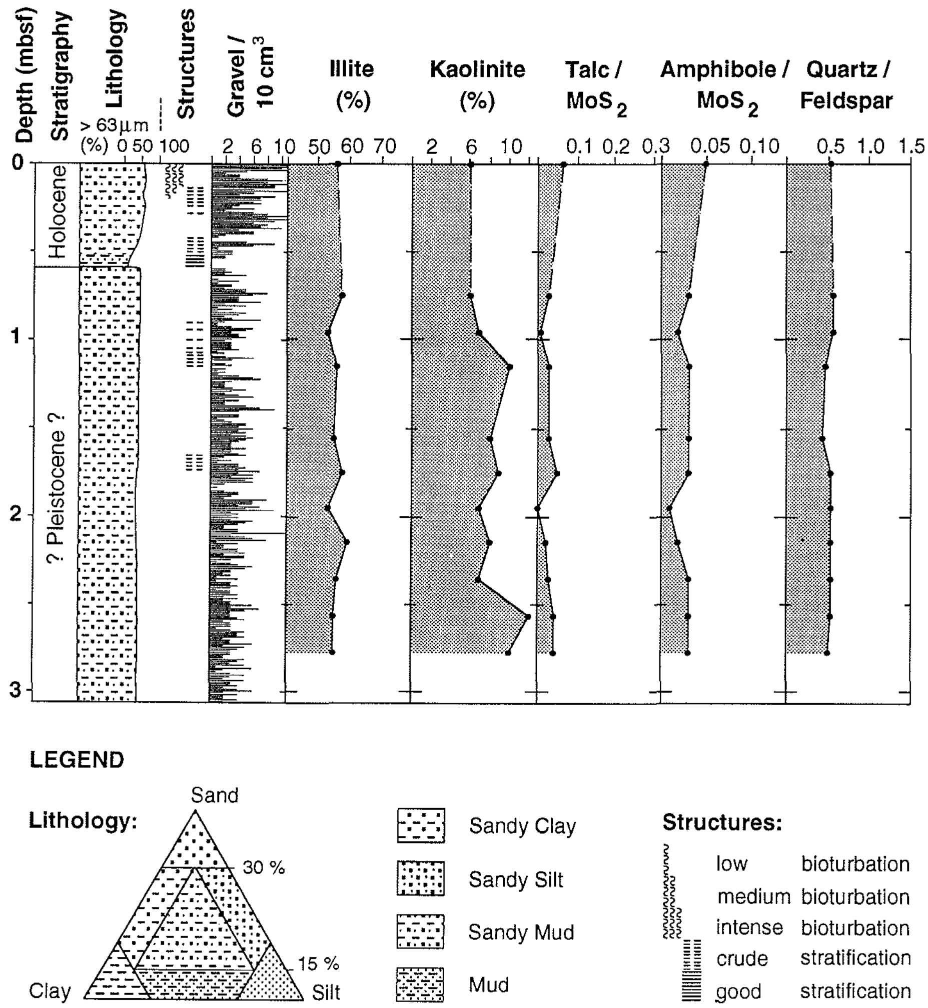

Fig. 3. Clay mineral assemblages at Site PS1400 in the Crary Trough, southern Weddell Sea. The location of the core is shown in Figs. 4 and 5.

High contents of kaolinite and quartz probably document the accumulation of physical weathering products of sedimentary rocks. In the southeastern Crary Trough, mountain glaciers, such as the Schweitzer and Lerchenfeld Glacier, flow into the Filchner Ice Shelf or directly into the sea and deliver significant amounts of sedimentary rock debris from the northern Transantarctic Mountains (Fig. 4). This hypothesis is confirmed by the composition of ice-rafted pebbles (Oskierski, 1988). The high kaolinite and quartz contents off Berkner Island, which however is documented by one sample only, may also document a glacial supply of sedimentary rocks.

The kaolinite and quartz maxima at the shelf edge (Fig. 4) were interpreted as a result of transport and redistribution of fine material from the southern Crary Trough by the northward flowing Ice Shelf Water (Melles, 1991). The high concentrations of illite (Fig. 5), talc, amphibole and feldspar document the flow of the Eastern Shelf Water as part of the Antarctic Coastal Current. These minerals indicate a source in the surrounding of the eastern Weddell Sea, where magmatic and especially metamorphic rocks of the crystalline basement occur (Juckes, 1972; Wolmarans and Kent, 1982; Oskierski, 1988). The physical wheathering products of this source area may be trans-

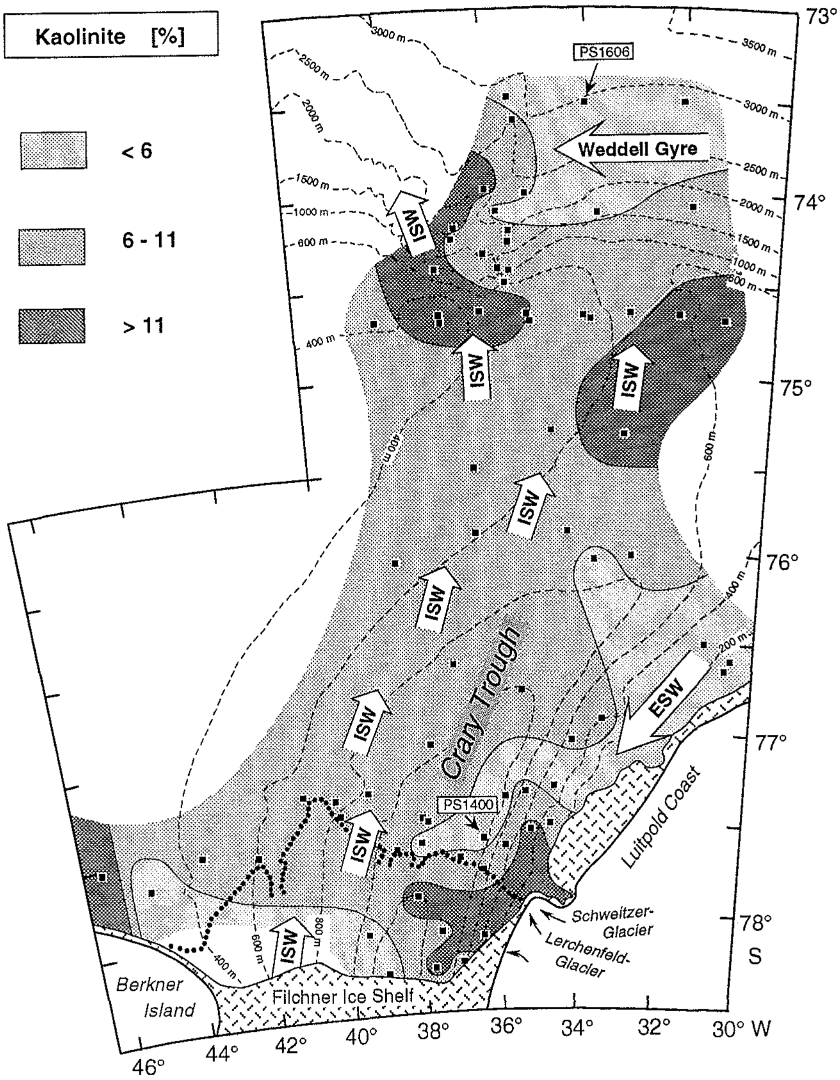

Fig. 4. Kaolinite distribution in surface sediments at the continental margin of the southeastern Weddell Sea. The principal circulation of the Ice Shelf Water (*ISW*), the Eastern Shelf Water (*ESW*) and the *Weddell Gyre* is indicated, as well as the locations of cores *PS1400* and *PS1606* presented in Figs. 3 and 8. The map is based on 72 undisturbed samples taken during several *Polarstern* expeditions of the Alfred Wegener Institute.

ported by icebergs or ocean currents, which move westward with the Antarctic Coastal Current.

Another example for almost exclusively glacially transported fine material in surface sediments comes from the continental shelf in the eastern Weddell Sea. Off Kapp Norvegia, maximum smectite concentrations of $>30\%$ are found (Fig. 6). The smectite content decreases significantly towards the shelf areas in the northeast and southwest. An especially distinct decrease occurs towards the continental slope and the Weddell Sea Basin in the northwest, where smectite accounts for $<15\%$ of the clay minerals. In our opinion, this pattern can be explained only by an input of smectite from the Antarctic continent. There, the smectite probably is eroded and transported by ice. It is released into the sea by melting icebergs or by basal melting beneath ice shelves. Off Kapp Norvegia the continental ice flows directly into the sea and causes the maximum in smectite content.

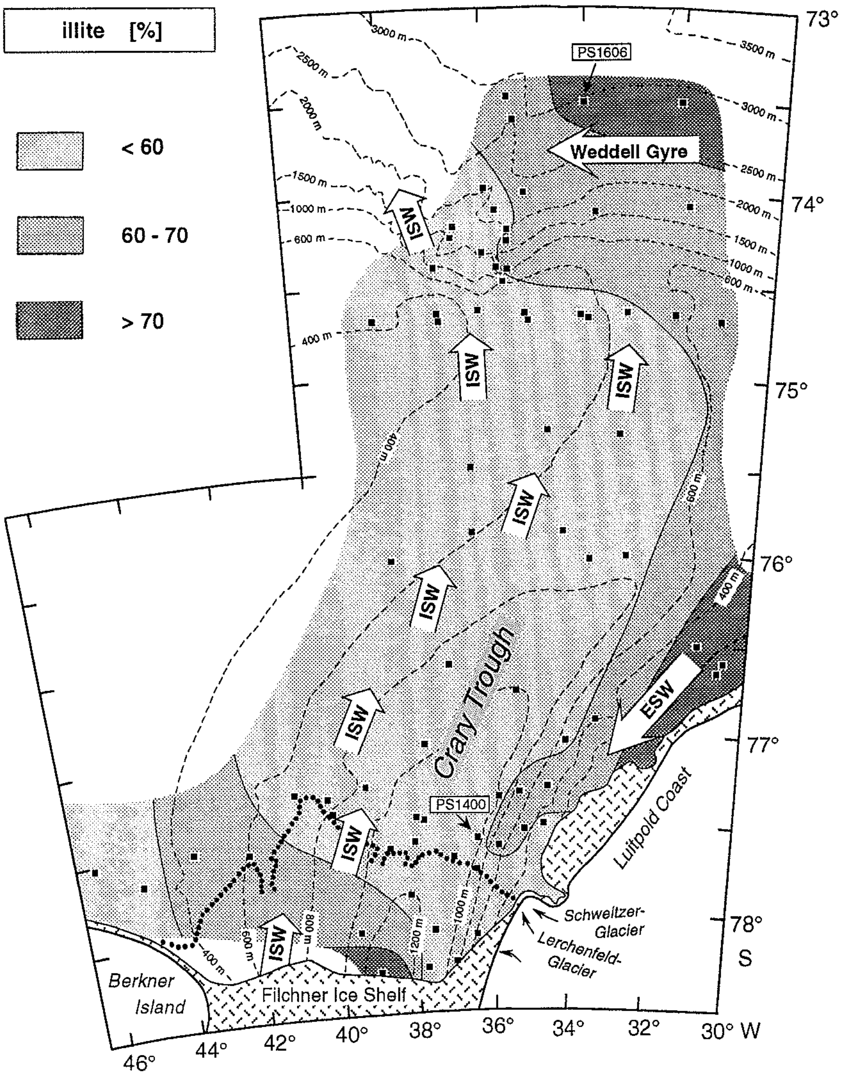

Fig. 5. Illite distribution in surface sediments at the continental margin of the southeastern Weddell Sea. The principal circulation of the Ice Shelf Water (*ISW*), the Eastern Shelf Water (*ESW*) and the *Weddell Gyre* is indicated, as well as the locations of cores *PS1400* and *PS1606* presented in Figs. 3 and 8. The map is based on 72 undisturbed samples taken during several *Polarstern* expeditions of the Alfred Wegener Institute.

Further southwest and northeast, beneath and in front of the ice shelves, sediment redistribution and dilution caused by marine processes may result in lower smectite concentrations. Probably the source rocks for the smectite are mainly weathered Mesozoic basalts and minor sedimentary rocks of the Beacon Supergroup. Both occur at Nunataks in the catchment area of the ice streams, which enter the Weddell Sea around Kapp Norvegia (Juckes, 1968; Olaussen, 1985; Peters, 1989). Additionally, the occurrence of appropriate source rocks beneath the continental ice can be deduced from the petrographic composition of ice-rafted pebbles on the Weddell Sea shelf (Oskierski, 1988).

Examples from the Antarctic continental slope

To date, Site 693 drilled at a midslope bench in the eastern Weddell Sea off Kapp Norvegia (Table 1; Fig. 1) gives the best and longest geologi-

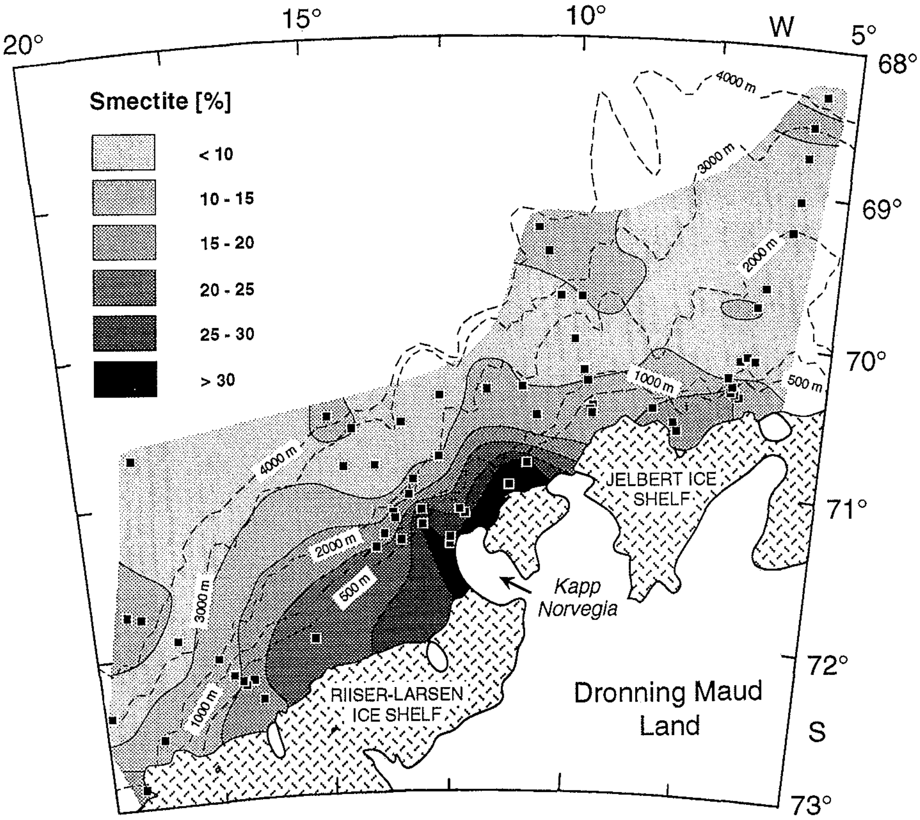

Fig. 6. Smectite distribution in surface sediments at the continental margin off Kapp Norvegia, eastern Weddell Sea. The map is based on 67 undisturbed samples taken during several *Polarstern* expeditions of the Alfred Wegener Institute.

cal record of an Antarctic continental slope setting. Drilling at Site 693 recovered sediments of Aptian–Albian to recent age (Fig. 7). The sequence is interrupted by a hiatus spanning Albian to early Oligocene time. The Cretaceous sediments are dominated by mudstones, the lower Oligocene to lower Pliocene sediments by mud with varying amounts of diatoms. The younger sediments consist of mud relatively poor in microfossils (Barker et al., 1988).

Clay mineral assemblages at Site 693 were investigated in order to detect their response to the Antarctic cryospheric evolution in a proximal setting and to study sedimentary processes at a glacially influenced continental slope (Grobe et al., 1990b; Robert and Maillot, 1990). The Cretaceous assemblage at Site 693 is characterized by 85–100% smectite, whereas the early Oligocene to early Miocene interval is dominated by 75–90% illite. The illite is accompanied by 0–20% smectite, 0–20% chlorite and traces of kaolinite. From late Miocene to recent times, illite is still dominant, but less than previously, while the smectite content increases slightly (Fig. 7).

The dominance of smectite in the Cretaceous sediments reflects a warm climate with chemical weathering in Antarctica. Robert and Maillot (1990) assumed seasonally alternating wet and arid conditions with smectite formation in a poorly drained environment. After the Albian–early Oligocene hiatus, totally different conditions are documented by the clay mineral assemblages (Fig. 7). The dominance of illite and the low content of smectite demonstrate the paucity of chemical weathering onshore, but increased physical weathering of schists, graywackes and intrusive rocks under cold conditions. The simultaneous increase in smectite and kaolinite content above the early/late Miocene hiatus (Fig. 7) may be interpreted as the result of enhanced erosion of ancient sediments,

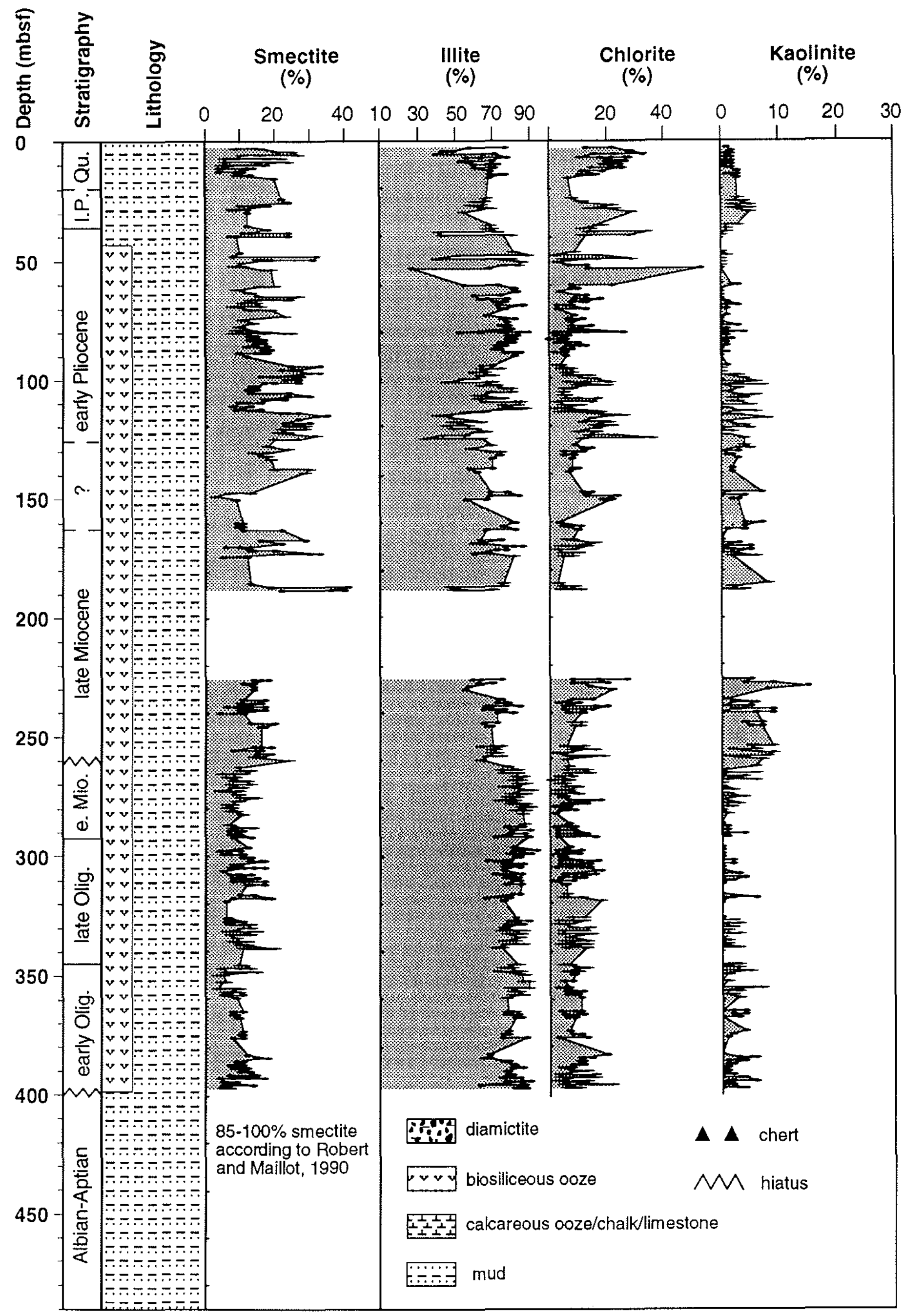

Fig. 7. Clay mineral assemblages at ODP Site 693 at the continental slope off Kapp Norvegia, eastern Weddell Sea (data in part from Grobe et al., 1990b; stratigraphy from Gersonde et al., 1990).

which probably was caused by an increased ice flow. The relatively strong fluctuations in the smectite and illite concentrations are explained by fluctuations in the climatic conditions and associated circulation (Robert and Maillot, 1990).

In contrast, Grobe et al. (1990b) discussed the Cenozoic changes in the clay mineral assemblages at Site 693 mainly as a result of selective transport and deposition. In their opinion, the effect of ocean currents and the ratio of ice rafting to current transport controls the clay mineral distribution at the Antarctic continental margin. Smectite as the usually smallest clay mineral remains longer in suspension and is therefore transported further than other clay minerals. Smectite thus may serve as an indicator for a sedimentary environment dominated by current-derived detritus (Grobe et al., 1990b).

In late Quaternary sediments of the continental slope off Kapp Norvegia smectite concentrations correlate inversely with the gravel content of the sediments and reveal maxima during glacial stages. While the gravel content of glaciomarine sediments normally is a direct indicator for ice-rafting, the smectite contents in this case can be used as an indicator for mainly hydrodynamic and gravitational sediment transport. During glacial maxima these transport processes dominated, whereas iceberg transport was reduced due to an almost permanent sea-ice cover and a reduced mass budget of the Antarctic ice sheet. In contrast to smectite, illite maxima occur during interglacial stages and may be the result of intensified iceberg transport (Grobe, 1986; Grobe et al., 1990a,b; Grobe and Mackensen, in press).

The low smectite content in the surface sediments on the lower continental slope off Kapp Norvegia (Fig. 6) is compensated by illite concentrations generally exceeding 70%. High illite concentrations were also found on the continental margin further east of Kapp Norvegia (Elverhøi and Roaldset, 1983) and at the lower continental slope adjacent to the Crary Trough (Fig. 5; Melles, 1991). The source area for the illite has to be sought on the East Antarctic craton. From there, the illite is transported southward along the continental margin probably by water or icebergs circulating clockwise with the Weddell Gyre.

Late Quaternary changes of the Weddell Sea circulation pattern are documented, for example, in a sediment core from Site PS1606 at the lower continental slope adjacent to the Crary Trough (Figs. 4 and 8). In spite of the limited stratigraphic information, it is obvious that the supply of clay-sized material by the Weddell Gyre, characterized by high contents of illite, talc, amphibole and feldspar, was repeatedly interrupted. In these times, the sediment was delivered from the south, either by gravitational or hydrographic transport. Which one of these processes was active, cannot be concluded from the clay mineral record alone. However, in combination with other sediment parameters such as structures and textures, several coarse-grained gravitational deposits could be identified (Fig. 8; Melles, 1991).

Examples from the deep sea off Antarctica

Deep-sea basins are the final sink for terrigenous material delivered from the continental margins by suspension, ice rafting, gravity flows etc. As examples for a deep-sea environment, the composite Sites 745 and 746 in the Australian–Antarctic Basin of the Indian Ocean and Site 694 in the Weddell Basin of the Atlantic Ocean are chosen (Table 1; Fig. 1). Both locations have approximately the same water depth and the same distance to the Antarctic continent.

The upper Miocene to recent sediments at Sites 745 and 746 are typically distal glaciomarine, mixed terrigenous and biosiliceous in composition, with two cyclically alternating facies. One facies is characterized by a relatively high biosiliceous production, low concentration of fine material and a high concentration of smectite. It represents conditions similar to that of the present-day. The other facies is more glacially influenced and is characterized by a large amount of terrigenous material and a higher amount of detrital clay minerals (Ehrmann and Grobe, 1991; Ehrmann et al., 1991).

The upper Miocene to recent clay mineral assemblage in the Australian–Antarctic Basin consists of 10–50% smectite, 50–80% illite, 5–30% chlorite and 0–20% kaolinite (Fig. 9). All clay minerals illustrate only minor significant long-term changes, but strong short-term changes caused by the cyclic sedimentation. The dominance of illite and chlorite over smectite and kaolinite is a result of physical weathering of mainly igneous rocks on the nearby East Antarctic craton. The consistency of the clay mineral assemblages since the late Miocene implies relatively stable weathering conditions on the continent with no major phases of warmer climate, which could allow chemical weathering. The clay minerals may have been derived directly as a result of drifting icebergs. They might also have been

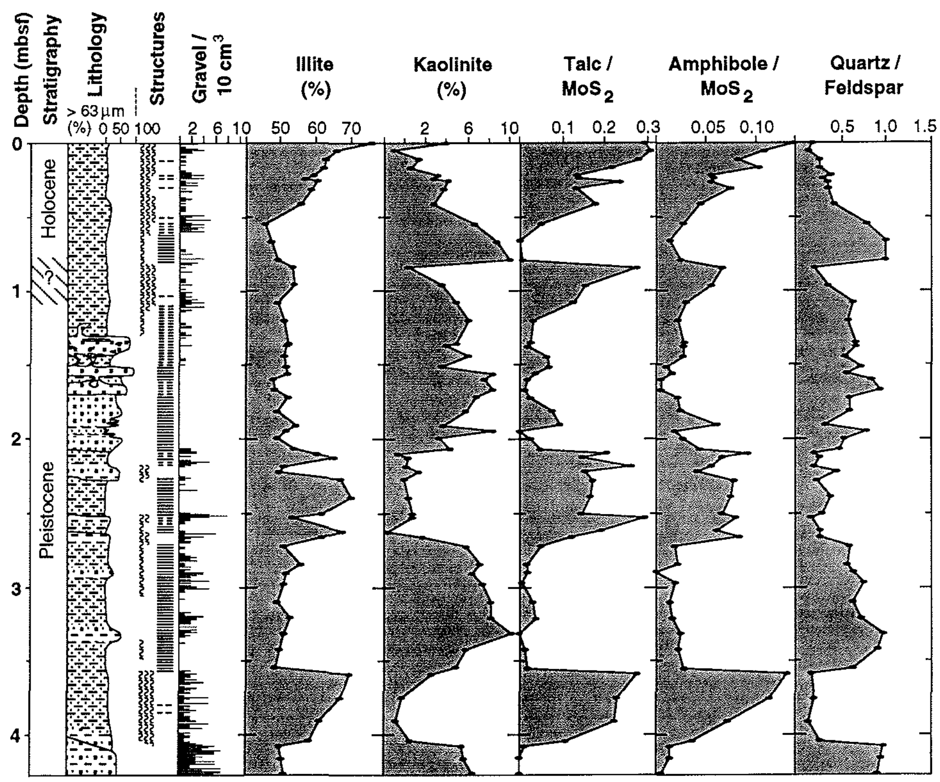

Fig. 8. Clay mineral assemblages at Site PS1606 at the lower continental slope of the southern Weddell Sea (data from Melles, 1991). The location of the core is shown in Figs. 4 and 5. For legend see Fig. 3.

transported down the continental slope by gravitational processes, or might have been brought in by currents. Thus, the cyclically changing concentrations of the individual clay minerals are not thought to represent fluctuations in the intensity of glaciation. Rather they are due to complex interactions of different transport mechanisms, which of course in turn may be controlled by climate and glacial processes (Ehrmann and Grobe, 1991; Ehrmann et al., 1991).

A different picture arises from the Weddell Basin. The middle Miocene to lower Pliocene sediments recovered at Site 694 in the Weddell Basin (Table 1) are dominated by mud and mudstones typical for a detrital environment (Barker et al., 1988). In the lower Middle Miocene sediments, 40–45% illite and 25–45% chlorite dominate the clay mineral assemblages. From the upper Middle Miocene to the lower Upper Miocene the contents of illite (25–55%), chlorite (15–35%) and smectite (10–55%) are strongly fluctuating. Upcore the smectite content increases to 25–70%, the chlorite content decreases to 0–20%, while the illite concentration remains constant at about 25–50% (Robert and Maillot, 1990).

This clay mineral assemblage implies—by comparison with the assemblages at Site 693 and at Sites 745 and 746—a West Antarctic source for at least parts of the assemblage. Thus, the enhanced smectite content since the late Miocene was interpreted as evidence for erosion of ancient sedimentary rocks at the Antarctic margin. The maximum smectite contents in sediments of late Early Pliocene age was thought to be indicative for increased current activity (Robert and Maillot, 1990). This period, however, was also characterized by expanding glaciers and ice shelves after the pronounced early Pliocene deglaciation (Hodell and Kennett, 1986; Pickard et al., 1988). The re-advancing glaciers and ice shelves could incorporate large amounts of debris, which during the deglaciation had been deposited in the coastal

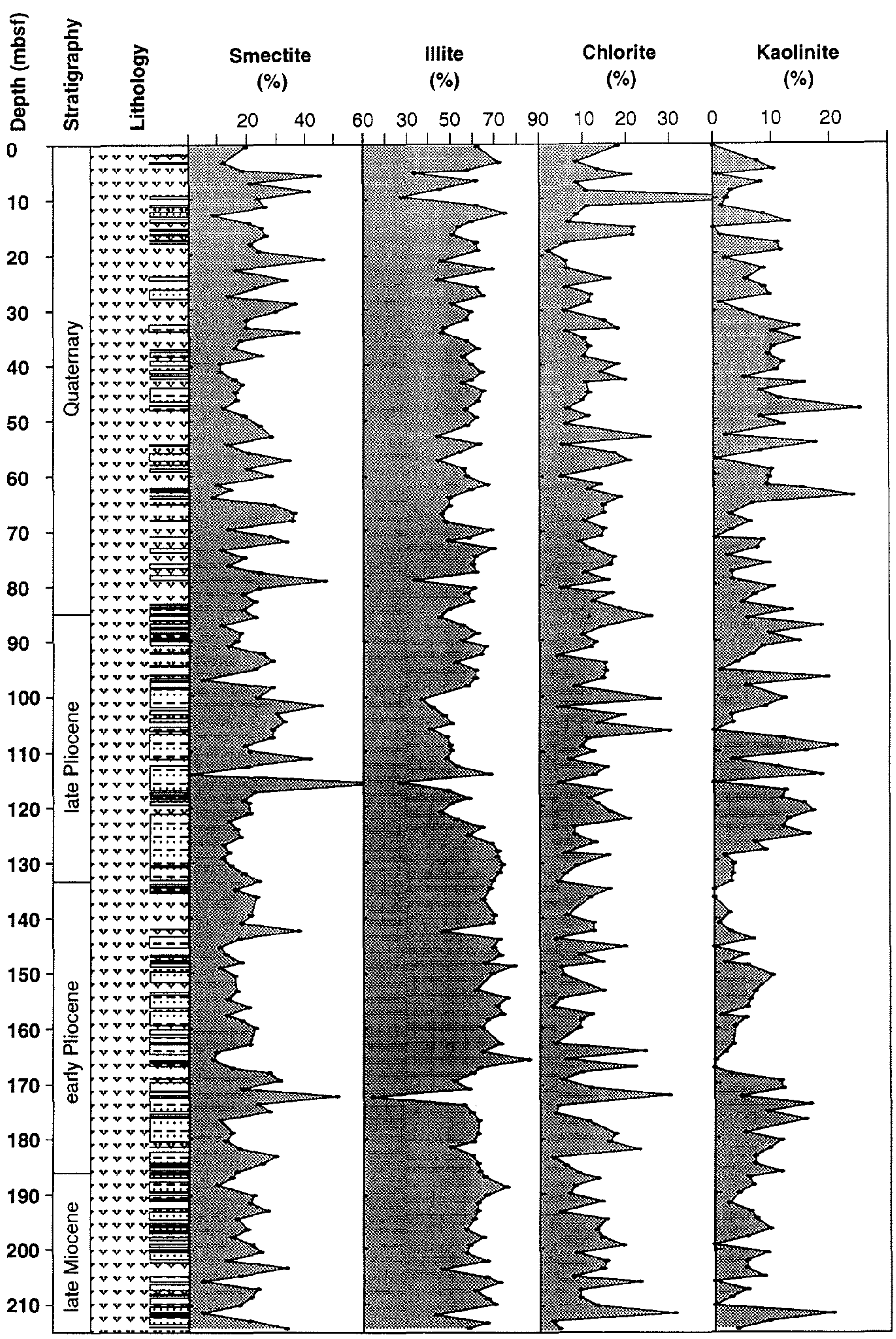

Fig. 9. Clay mineral assemblages at ODP Site 745 in the Australian–Antarctic Basin (data from Ehrmann et al., 1991). For legend see Fig. 7.

areas and on the continental shelf. Icebergs and ocean currents could transport this material to distal regions and possibly could cause the maximum in smectite content.

Only a few studies on the clay sedimentology of Quaternary deep-sea sediments from the Antarctic Ocean exist to date. In sediments from the continental slope and abyssal plain of the western Weddell Sea, Pudsey et al. (1988) distinguished turbidites from hemipelagic muds, which may have similar textures and structures, by higher chlorite contents. This is an example how clay minerals could be significant in identifying gravitational sediment transport over distances of several hundred kilometers. An example for long-distance hydrographic transport and for the significance of clay minerals for paleoceanographic interpretations was presented by Chamley (1975). In sediments of the last glacial stage from the Vema Channel (southwestern Atlantic Ocean) he found high chlorite contents, which he could trace back to Antarctica. The chlorite probably was transported to this distal setting by the Antarctic Bottom Water.

Examples from submarine elevations in high latitudes

Examples for submarine elevations come from Maud Rise in the southern Atlantic Ocean (Figs. 10 and 11) and from Kerguelen Plateau in the southern Indian Ocean (Fig. 12). Both structures are separated from the Antarctic continent by deep-water pathways preventing them from sediment inputs by slumpings or turbidites. The sediments at Sites 689 and 690 on Maud Rise and at Sites 738 and 744 on Kerguelen Plateau (Table 1) are highly pelagic in character. The Cretaceous to Miocene sediments are dominated by nannofossil oozes, chalks and limestones, the latest Miocene to recent sediments consist mainly of diatom oozes (Barker et al., 1988; Barron et al., 1989). Clay mineral assemblages were investigated in order to reconstruct the paleoceanography of the Antarctic Ocean and to reconstruct the Cenozoic paleoclimatic and glacial history of Antarctica (Robert and Maillot, 1990; Ehrmann, 1991; Ehrmann and Mackensen, 1992).

Sites 689, 690, 738 and 744 show essentially the same patterns in the clay mineral assemblages (Figs. 10–12). The clay fractions of the Cretaceous, Paleocene and Eocene sediments are dominated by smectite with concentrations generally exceeding 90%. In the upper Eocene to lowermost Oligocene sediments, the smectite content decreases from about 90 to 70%. A distinct and sudden fall to minimum values of 10–20% occurs in lowermost Oligocene sediments. Relatively low smectite concentrations dominate the remainder of the Oligocene sequence. In Miocene to recent sediments of both Maud Rise and Kerguelen Plateau values fluctuate around 40%. Illite shows a strong negative correlation with smectite. Chlorite and kaolinite appear at Kerguelen Plateau Sites 738 and 744 and at Maud Rise Site 689 in significant amounts since the late Eocene (Figs. 10 and 12). In contrast, at Maud Rise Site 690 they also had a maximum from late Early Paleocene to early Eocene times (Fig. 11; cf. Robert and Maillot, 1990).

The distinct dominance of smectite over illite and chlorite in Cretaceous to late Eocene sediments implies relative stable conditions with chemical weathering under humid conditions in Antarctica. Physical weathering processes played a limited role only. The late Early Paleocene to early Eocene kaolinite maximum at Site 690 may indicate that the climate was appropriate for kaolinite formation in parts of Antarctica (Robert and Maillot, 1990). However, because of the strong correlation with chlorite, it also could be caused by the erosion of a kaolinite- and chlorite-bearing source. The lack of kaolinite at the nearby Site 689 suggests a transport of the kaolinite by a deep ocean current which did not reach the shallower Site 689 (Robert and Maillot, 1990). The lack of kaolinite on Kerguelen Plateau could be due to a different composition of the source area. In late Eocene time, the chlorite and kaolinite contents increased at Maud Rise Site 689 and on Kerguelen Plateau, with the kaolinite probably being recycled from old sedimentary rocks. This implies slightly enhanced physical weathering, possibly as a result of the expansion of glacierized areas in the inner part of East Antarctica. First signs of ice rafting were found on Kerguelen Plateau and Maud Rise in middle Eocene sediments and indicate that some

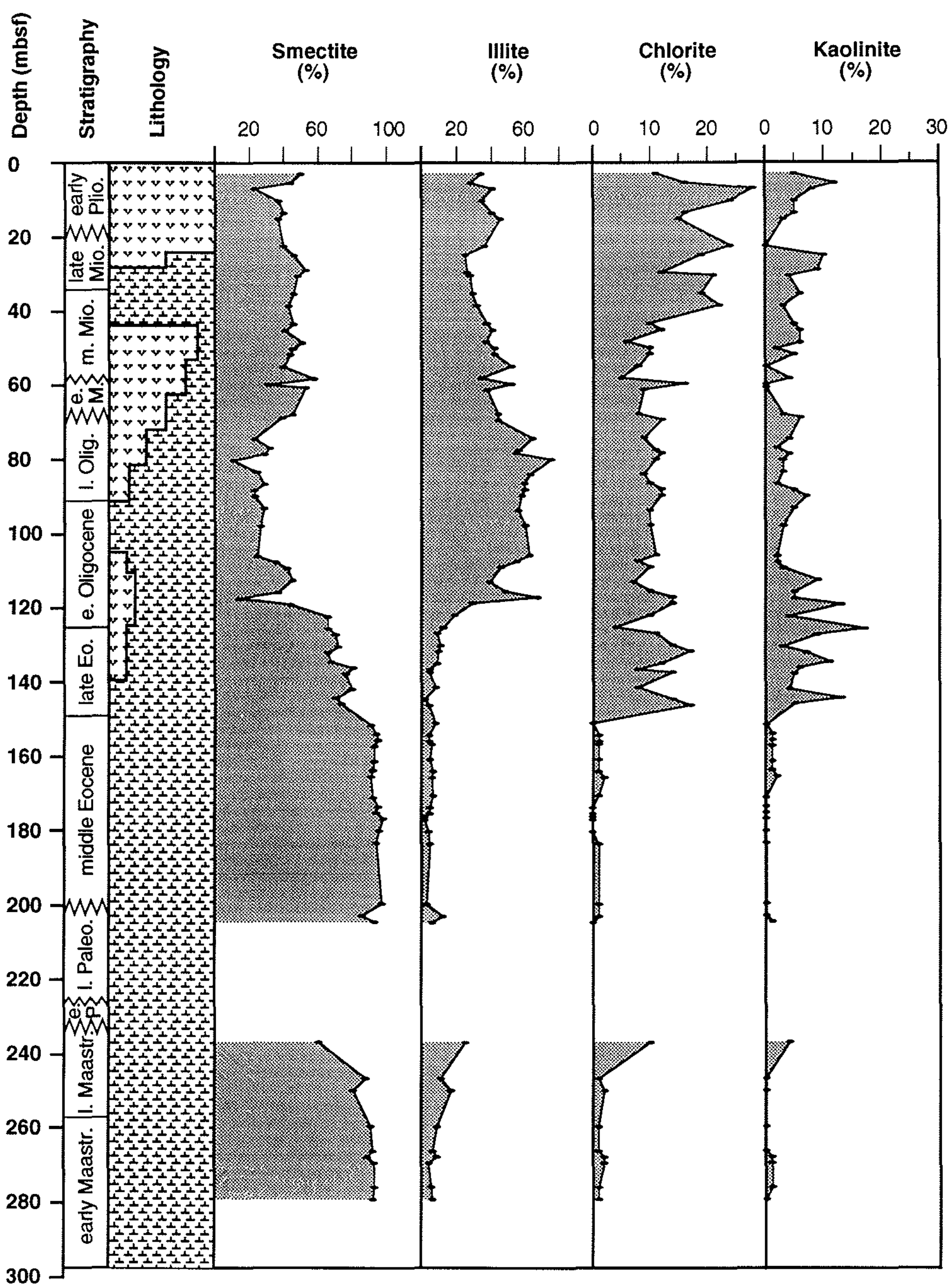

Fig. 10. Clay mineral assemblages at ODP Site 689 on Maud Rise in the southern Atlantic Ocean. For legend see Fig. 7.

glaciers had reached the coast by that time (Ehrmann and Mackensen, 1992).

According to the clay mineral assemblages, a cooler climate established in the earliest Oligocene time, between 36.3 and 35.9 Ma. It resulted in the cease of chemical weathering and the start of intense physical weathering. Thus, the smectite content decreased dramatically, whereas the illite concentrations increased in the same amount (Figs. 10–12). This event has been interpreted as the onset of continental glaciation in East Antarctica, which is supported by numerous other sediment

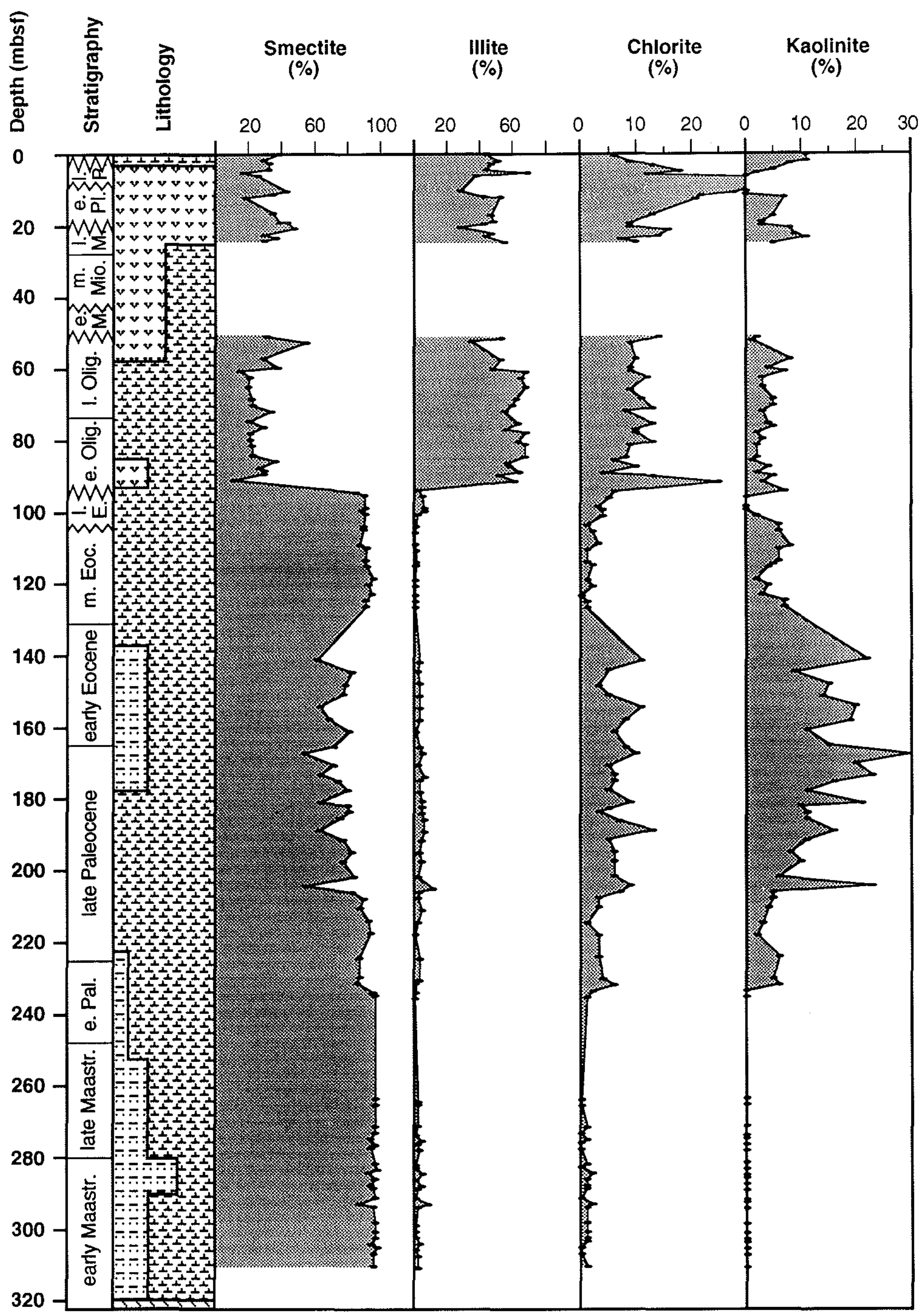

Fig. 11. Clay mineral assemblages at ODP Site 690 on Maud Rise in the southern Atlantic Ocean. Note the higher kaolinite content in late Paleocene to early Eocene sediments compared to Site 689 (Fig. 10). For legend see Fig. 7.

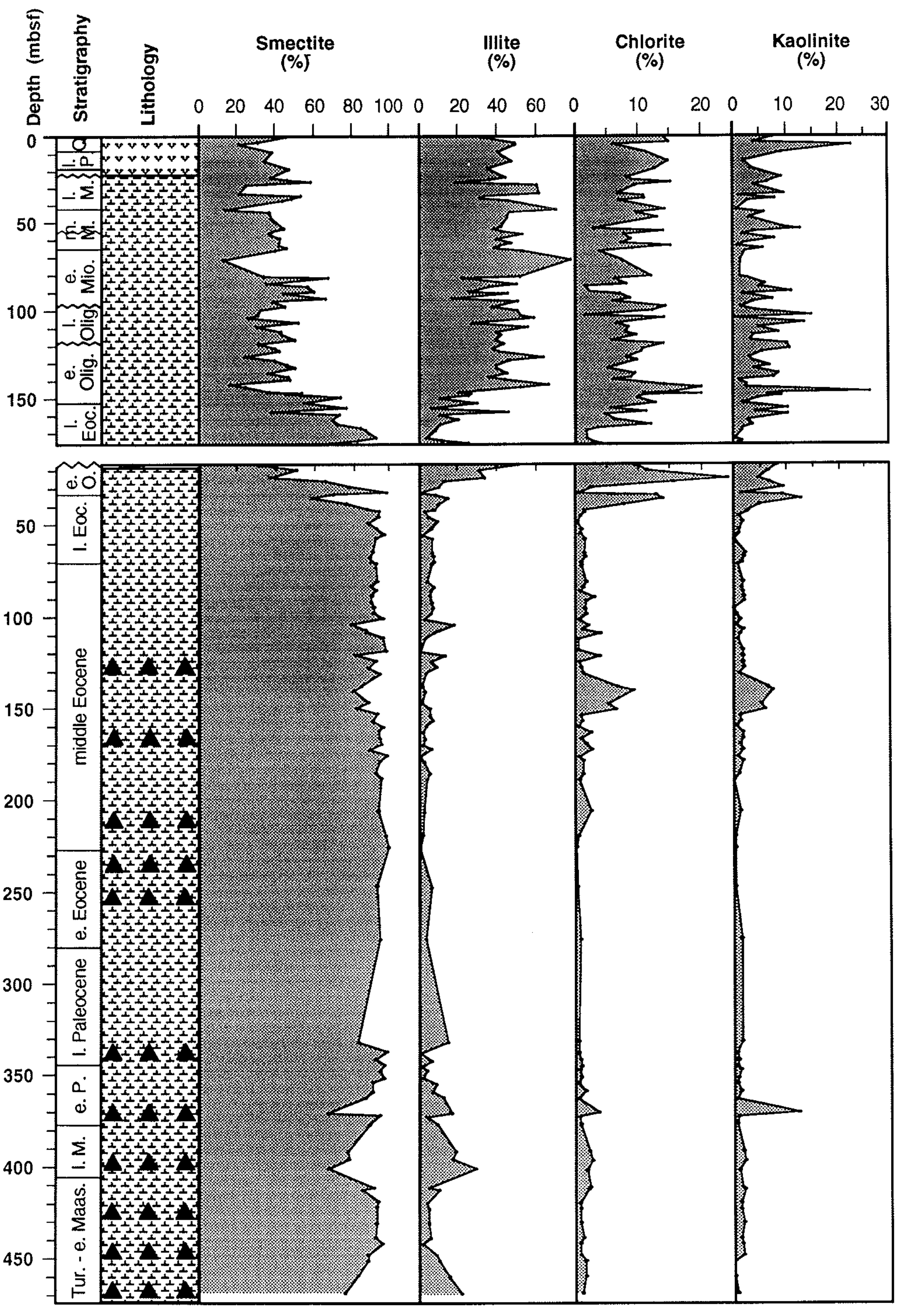

Fig. 12. Clay mineral assemblages at Site 744 (above) and Site 738 (below) on the southern tip of Kerguelen Plateau in the southern Indian Ocean. The data are from Ehrmann (1991). For legend see Fig. 7.

parameters and the stable oxygen isotope record (Ehrmann and Mackensen, 1992).

In Oligocene to recent sediments, the clay minerals chlorite, illite, and kaolinite do not reveal changes in their concentrations patterns as distinctive as those close to the Eocene/Oligocene boundary indicating that the main shift in the weathering regime had happened at that time. However, this does not necessarily imply that also the main paleoclimatic shift had occurred at that time. Once the Antarctic continent was covered by ice and dominated by physical weathering processes, the clay mineral composition of the sediments would not have changed significantly in response to a further cooling event. The total amount of detrital clay minerals, however, may mirror such a climatic change. Following the early Oligocene minimum in smectite content, the concentrations rose suddenly, but did not reach their former values (Figs. 10–12). They indicate somewhat warmer conditions than in the early Oligocene, but colder conditions than in Eocene, Paleocene and Cretaceous times. A climatic optimum in the early Miocene is documented by maximum Neogene smectite concentrations on Kerguelen Plateau (Ehrmann, 1991), but only slightly indicated on Maud Rise due to hiatuses.

The smectite concentrations on Maud Rise and on the southern Kerguelen Plateau reveal a strong negative correlation with the oxygen isotope curves for planktonic and benthic foraminifers (Ehrmann, 1991; Ehrmann and Mackensen, 1992). Thus, smectite concentrations show a decrease in the middle Eocene, a marked drop shortly after the Eocene/Oligocene boundary, an increase after the early Oligocene minimum, relatively constant values until the early Miocene, a maximum in the early Miocene, and a decreasing trend in younger sediments. The correlation between the oxygen isotope curves and the smectite content is striking in Paleocene to early Miocene sediments, but less convincing in younger sediments. The weaker correlation in more recent time is probably due to oceanographic changes. The opening of the Drake Passage as a deep-water pathway probably initiated the development of an intensified circumpolar Antarctic current and thus created a more complicated circulation pattern around Antarctica, which also may have influenced the clay mineral distribution.

Discussion of the significance of clay minerals

Late Mesozoic and Cenozoic sediments

The examples presented in this paper give some idea about the significance of clay minerals in different settings for reconstructing paleoenvironment, glacial history and sedimentary processes. A basic problem which strongly affects the value of clay minerals, but which has not been discussed so far, is the diagenetic alteration of the sediments. This may concern all drill sites penetrating deep below the seafloor into old sediments. Diagenesis may prohibit the disaggregation of the sediments during sample preparation and also may complicate a reliable qualitative and especially a quantitative study of clay mineral assemblages. Diagenesis further may act by transforming clay minerals and thus disturbing or destroying their original paleoenvironmental implications.

Some diagenesis obviously took place at the investigated sites as indicated by the occurrence of chert and clinoptilolite in Eocene and older sediments. However, we did not detect evidence that diagenesis affected the clay mineral assemblages. In contrast, at Site 737 near Kerguelen Island, the sediments and clay mineral assemblages were highly altered, probably due to an enhanced heat flow; therefore the clay minerals of this site could not be interpreted in terms of paleoenvironment and paleoclimate.

In late Mesozoic and Cenozoic sediments, the significance of clay mineral assemblages for reconstructing paleoenvironmental conditions strongly varies with the geological and morphological position of the sites under investigation. Close to the continent, on the Antarctic continental shelves, the glacial signals are very strong. However, the sedimentary record often is incomplete, because advancing glaciers and ice shelves may remove parts of the sedimentary sequences and may cause major reworking. In addition, in this part of Antarctica, the paleoclimatic signal may be less pronounced than the signal caused by sedimentary processes and therefore may be obliterated. Thus, the proximal settings are especially suitable for reconstructing sedimentary processes and for identifying source areas and changes in the transport regime.

At the Antarctic continental slope, sediment redistribution by slumping, turbidity currents, conturites and bottom currents may play an important role and may control the clay mineral distribution. However, in the case of Site 693 at Kapp Norvegia, it has been shown that, although the sediment redistribution may mask the paleoclimatic signal, it does not destroy it entirely. Both signals are in a delicate balance and each of them may dominate at certain times or at certain localities. In contrast to deposits both on the glacial continental shelf and in the deep sea, the sediments on the continental slope may contain calcareous foraminifera suitable for sediment dating and for stable isotope studies.

The deep-sea basins represent distal settings and are large sinks for all terrigenous detritus delivered from the continents. The clay minerals may have experienced a wide variety of different transport media and processes before they are deposited in these basins. Therefore, they are important tools for deciphering and reconstructing sedimentary processes, which in turn may allow to draw conclusions on the paleoclimate. The direct paleoclimatic significance of clay minerals increases with distance to the continents, which is clearly shown by Quaternary sediments of the South Atlantic Ocean (R. Petschik, pers. commun., 1991).

A totally different picture arises from submarine elevations, such as the Kerguelen Plateau and Maud Rise, which cannot be reached by slumps and turbidites. Detrital components are provided by suspension, wind or ice. The amount of clay minerals at those locations is normally very low (< 5% of bulk sediment), but they store a wealth of paleoclimatic information. The presence of calcareous microfossils provides the possibility for exact biostratigraphic age determinations and for direct comparisons with the information gained from the oxygen isotope record. In the case of Maud Rise, even detailed paleoceanographic information could be deduced from the clay mineral assemblages (Robert and Maillot, 1990).

The different examples presented in the previous chapters have emphasized the value of clay mineral data for reconstructing paleoclimate through time. Especially the Cretaceous to Oligocene record reflects pronounced changes in the weathering regime on the Antarctic continent due to paleoclimatic changes. Thus the transition from a warm and humid climate with chemical weathering to a cold and arid climate with physical weathering is documented at all sites that recovered sediments of the respective age. In the earliest Oligocene, a continental East Antarctic glaciation established, and since then intense physical weathering, mainly glacial scour, prevailed on the Antarctic continent. Since that time the climatic variations were not strong enough to force a major change in the weathering regime, which could be detected easily in the clay mineral assemblages of the marine sediments. At most locations the climatic signals were therefore obliterated by hydrodynamic processes.

Quaternary sediments

In Quaternary sediments of the Antarctic Ocean, the amount of non-layered minerals is much higher than in lower latitude clay fractions. Therefore the quantification of non-layered minerals may provide important informations. Although hydrolysis was not an effective process in Antarctica during the Quaternary, some smectite and kaolinite was transported from the continent to the sea. These two minerals were reworked from ancient rocks by physical processes. Hence, the mineral distribution in the clay fraction in the first instance depends on the nature of the source rocks.

On the Antarctic continental shelf, the terrigenous detritus supplied by the ice may be deposited as lodgement till beneath the grounded ice. The clay mineral assemblage of such a sediment directly reflects the composition of the source rocks. The ice-rafted debris also may accumulate in the glaciomarine environment through rainout from ice shelves or through melting of sediment-laden icebergs. In this case, the clay mineral assemblages may be affected by marine processes, which could cause an enrichment or dilution of individual minerals. Additionally, previously deposited sediments can be redistributed by glacial, marine or gravitational processes. Thus, the mineral composition of the clay fraction of Quaternary sediments depends both on the source material and on the various transport processes. The determination of the clay mineral distribution, therefore, can be an important tool for the reconstruction of source areas of the fine material as well as for the reconstruction of sedimentary processes. Because both in turn depend on the climatic situation, Quaternary clay mineral records of the Antarctic Ocean provide indirect information concerning the climatic history of the southern high latitudes.

Most of the examples presented have illustrated that often sedimentary processes can be identified by the clay composition only if combined with other sedimentological parameters such as sediment structure, texture or physical properties. Investigations of the clay mineral composition are most promising in those areas, where changes in source regions with distinct petrographic differences are expected, and where distances from the source region are low.

Conclusions

The value and shortcomings of clay mineral assemblages off Antarctica for reconstructing late Mesozoic to present-day paleoenvironmental conditions have been discussed and reviewed, based on several selected examples coming from different geological and morphological settings. Some of the examples are presented in this study for the first time (Table 1). The conclusions can be summarized as follows:

(1) Our proposed method of sample preparation and XRD-measurements with an internal MoS_2 standard proved to be successful in allowing us to detect changes in the concentration of individual clay minerals, independent from dilution effects by other minerals or amorphous components. Additionally, the method allows semi-quantitative interpretations of the distribution of non-layered minerals and mineral groups in the $< 2\ \mu m$ fraction.

(2) Direct paleoclimatic information can be obtained from clay mineral assemblages of Cretaceous to Oligocene sediments. During this period, the transition from chemical weathering to physical wheathering occurred on the Antarctic continent and is documented by a change from smectite-dominated to illite- and chlorite-dominated clay mineral assemblages.

(3) The best records of the weathering regime can be obtained from submarine elevations. There, the sediments are not influenced by sediment redistribution such as sediment gravity transport, which is common on continental slopes and in deep-sea basins. Generally, the stratigraphic record is more complete on submarine elevations than on continental shelves and slopes, where it is affected by hiatuses. Furthermore, good stratigraphic control normally allows exact dating of the discovered changes in paleoenvironment.

(4) Since early Oligocene time, when a continental East Antarctic glaciation had established, mainly physical weathering occurred and the primary clay mineral assemblages were dominated by detrital clay minerals. Variations in the clay mineral records are predominantly due to different sediment sources as a result of different glacial, hydrographic or gravitational transport processes. Therefore, clay minerals are an important tool for defining and interpreting sedimentary processes.

(5) The clay minerals may be affected by a variety of sedimentary processes, from which generally the dominating process is controlling the assemblage. The sedimentary processes depend on environmental conditions, such as the continental ice volume, the sea-ice coverage or the oceanographic circulation, which are directly linked to climatic variations. Therefore, the clay mineral assemblages in Quaternary sediments provide no direct but indirect paleoclimatic information.

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