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Varations in Smectite Content and Crystallinity in Sediments from CRP-3, Victoria Land Basin, Antarctica

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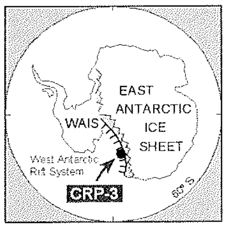

Abstract - The Cenozoic sediments of the CRP-3 drill core from the continental shelf of McMurdo Sound in Ross Sea, Pacific sector of the Southern Ocean, have been investigated for their clay mineral assemblages, especially for the smectite abundances, concentrations and crystallinities. The assemblages of CRP-3 are very different from those of the CRP-1 and CRP-2/2A drill cores. Thus, an almost monomineralic assemblage characterizes the sequence below 330 mbsf. This assemblage is made of well-crystallized smectite with probably authigenic origin between 800 mbsf and 625 mbsf. From 625 mbsf to 330 mbsf the assemblage consists of moderately crystallized smectite that, at least in part, seems to be of detrital origin and thus indicates weathering under a relatively warm and wet climate. In the interval 330-145 mbsf, smectite concentrations fluctuate between 50% and 100% and probably document alternating phases of chemical weathering under a warm and wet climate and physical weathering under a relatively cool and dry climate. Above 145 mbsf the smectite decreases dramatically to concentrations of about 20% and becomes poorly crystalline. In contrast, illite and chlorite become more abundant. Such an assemblage is typical for early Oligocene and younger sediments in McMurdo Sound and reflects physical weathering conditions under a cool climate on a glaciated Antarctic continent. Correlations of the changes in the clay mineral spectrum of CRP-3 with other cores from McMurdo Sound and from other parts of the Southern Ocean has to remain speculative at this stage, because of the poor age control.

INTRODUCTION

CRP-3 was drilled from October to December 1999 on the continental shelf of McMurdo Sound in Ross Sea, Pacific sector of the Southern Ocean, during the third - and final - campaign of the international Cape Roberts Project (Cape Roberts Science Team, 2000). One of the main objectives of the Cape Roberts Project was to reconstruct in detail the Cenozoic Antarctic climatic and glacial history. Whereas it is generally accepted that the onset of East Antarctic continental glaciation occurred in earliest Oligocene time (*e.g.* Hambrey et al., 1991; Wise et al., 1991; Ehrmann & Mackensen, 1992; Salamy & Zachos, 1999), very little is known on the climate and the Antarctic ice coverage and volume during the time preceding this major event.

The previous drill cores CRP-1 and CRP-2/2A of the Cape Roberts Project had recovered Quaternary to early Miocene and Quaternary to early Oligocene sediments, respectively (Cape Roberts Science Team, 1998, 1999). A target of CRP-3, therefore, was to penetrate into early Oligocene, Eocene and older sediments in order to better date and reconstruct the transition from an initially ice-free Antarctic continent to a continent almost completely covered by ice (Cape Roberts Science Team, 2000).

CRP-3 reached a final depth of 939.40 mbsf (metres below sea floor). The initial biostratigraphic investigations of the lowermost sediments of the core could not provide a precise and unequivocal age control. They suggest that the sediments above 823 mbsf are early Oligocene in age. Only the lowermost part of this interval may possibly consist of deposits of late Eocene age. The sediments below 823 mbsf are light-reddish brown medium-grained sandstones of the mid-Devonian Beacon Supergroup (Cape Roberts Science Team, 2000).

The Cenozoic sediments are mostly glacially influenced marine deposits. Between 823 mbsf and 330 mbsf sandstones and conglomerates prevail. No general agreement exists on the mode of deposition of these sediments. They are either a product of glaciofluvial discharge into shallow coastal waters or the result of possibly glacially scoured gravity flows. The sediments above 330 mbsf are quite similar to those recovered with the CRP-2/2A core. They consist mainly of diamictites and proximal to distal glaciomarine sediments that are arranged in cycles indicating phases of glacier advances and retreats (Cape Roberts Science Team, 2000).

This paper presents preliminary results of clay mineral investigations carried out on the Cenozoic sediments from CRP-3. It concentrates on the downcore distribution of smectite abundances, percentages and crystallinities. It thus complements the investigations of clay minerals in sediments of core CRP-1 (Ehrmann, 1998a) and core CRP-2/2A (Ehrmann, 2000). The main objectives are to reconstruct the source areas for the sediments and the paleoclimatic conditions on the Antarctic continent during deposition of the CRP-3 sediments.

Former studies of sediment cores from the Antarctic continental margin and the Southern Ocean have demonstrated the value of clay minerals in deciphering sediment provenance (*e.g.* Ehrmann et al., 1992; Petschick et al., 1996; Ehrmann, 1998a, 1998b). Because the composition of the clay mineral assemblages is also strongly controlled by weathering processes, *i.e.* physical *versus* chemical weathering processes, the clay mineral types and proportions of individual clay minerals can be used to reconstruct the paleoclimate and glacial history of Antarctica. Thus, the onset of East Antarctic continental glaciation in the earliest Oligocene is accompanied by a major change from smectite-dominated to illite-dominated clay mineral assemblages (Ehrmann & Mackensen, 1992; Ehrmann et al., 1992; Ehrmann, 1998b).

METHODS

Ninety five samples taken in almost constant intervals from the upper 800 m of Cenozoic sediments of the CRP-3 core were analyzed by the X-ray diffraction (XRD) method for their clay mineral composition. Bulk-samples of *c.* 5-10 cm^3 size were crushed, then oxidized and disaggregated by means of a 5% H_2O_2 solution. After washing the samples through a 63 µm sieve, the clay fraction was isolated from the silt fraction in settling tubes. The clay fraction was dried and weighted. Clay percentages were calculated. Forty milligram of clay were dispersed in an ultrasonic bath and mixed with 1 ml of an internal standard consisting of a 1% MoS_2 suspension. The samples were mounted as texturally oriented aggregates by rapidly filtering the suspension through a membrane filter of 0.15 µm pore width. The filter cakes were dried at 60°C and mounted on aluminium tiles. They were exposed to ethylene-glycol vapor at a temperature of 60°C for about 18 hrs before the XRD analyses.

X-ray analyses were conducted using an automated powder diffractometer Philips PW 1700 with CoKα radiation (40 kV, 40 mA). The samples were X-rayed in the range 2-40° 2θ with a speed of 0.02° 2θ per second. The diffractograms were evaluated on an Apple Macintosh Personal Computer using the "MacDiff" software (Petschick, freeware).

Peak areas were calculated for MoS_2 at 6.15 Å and for smectite at 17 Å, after graphical removal of the chlorite 14 Å peak. Other clay minerals were identified by their basal reflections at 10 and 5 Å (illite), 14.2, 7, 4.72 and 3.54 Å (chlorite), 7 and 3.57 Å (kaolinite). The relative percentage of smectite was semiquantitatively determined using empirically estimated weighting factors (Biscaye, 1964, 1965; Brindley & Brown, 1980). In order to also determine distribution patterns of smectite not influenced by dilution with other clay minerals, the smectite peak areas were set in relation to the peak area of the MoS_2 standard at 6.15 Å (Ehrmann et al., 1992).

The crystallinity, a measure of the lattice ordering and crystallite size, is expressed as the integral breadth (Δ° 2θ) of the smectite 17 Å peak (cf. Ehrmann, 2000). High values indicate poor crystallinities, low values indicate good crystallinities. The crystallinity values were grouped into the categories well crystalline (<1.5 Δ° 2θ), moderately crystalline (1.5-2.0 Δ° 2θ) and poorly crystalline (>2.0 Δ° 2θ) (cf. Diekmann et al., 1996).

The ages given in this paper refer to the time scale of Berggren et al. (1995) and were computed by linearly interpolating between magnetostratigraphic and biostratigraphic datum levels.

All raw data are available via the internet (data bank of the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany; www.pangaea.de).

RESULTS

The clay content of the CRP-3 sediments ranges between 0% and 56% (Fig. 1). The downcore distribution curve reflects mainly the lithological log of the core. Some minor discrepancies occur, however, because the visual core description was based mainly on medium and maximum grain sizes. The deeper part of the cored Cenozoic sequence, from 800 mbsf to *c.* 330 mbsf, is characterized by relatively low clay concentrations and only minor fluctuations in the clay content. Within this interval the clay concentration range relative constantly around 5% from 800 to 625 mbsf. From 625 mbsf to 330 mbsf the concentrations are even smaller and do not exceed 5%, except within two small segments around 550 mbsf and 410 mbsf, where they reach 7-9%. The low clay concentrations match well with the sandstones and conglomerates described from the lower part of the Cenozoic sediments. The clay concentrations are higher and more strongly fluctuating above 330 mbsf. They reflect the more variable lithology of the sediments, which comprise mainly diamictites, sandstones, siltstones and mudstones.

The Cenozoic sediments between 800 mbsf and 625 mbsf have relatively high smectite/standard ratios that fluctuate mainly between 15 and 20 (Figures 1 and 2). Low ratios of around 10 occur between 625 mbsf and 555 mbsf. Two samples in the interval

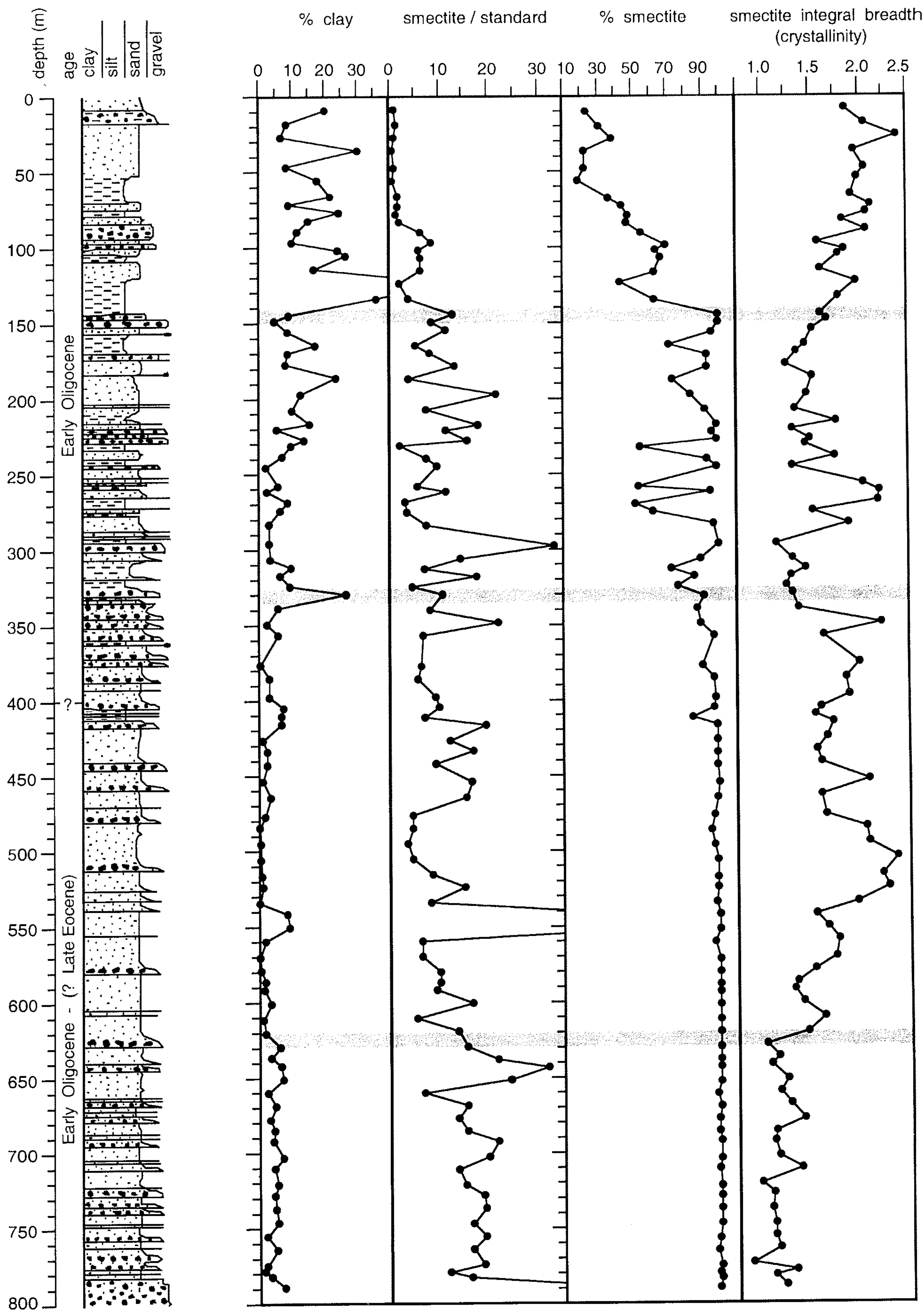

Fig. 1 - Lithological log of the drill core CRP-3 (Cape Roberts Science Team, 2000), clay content (%), smectite/standard ratio, smectite content (%) and smectite crystallinity (Δ° 2θ) in sediments of CRP-3.

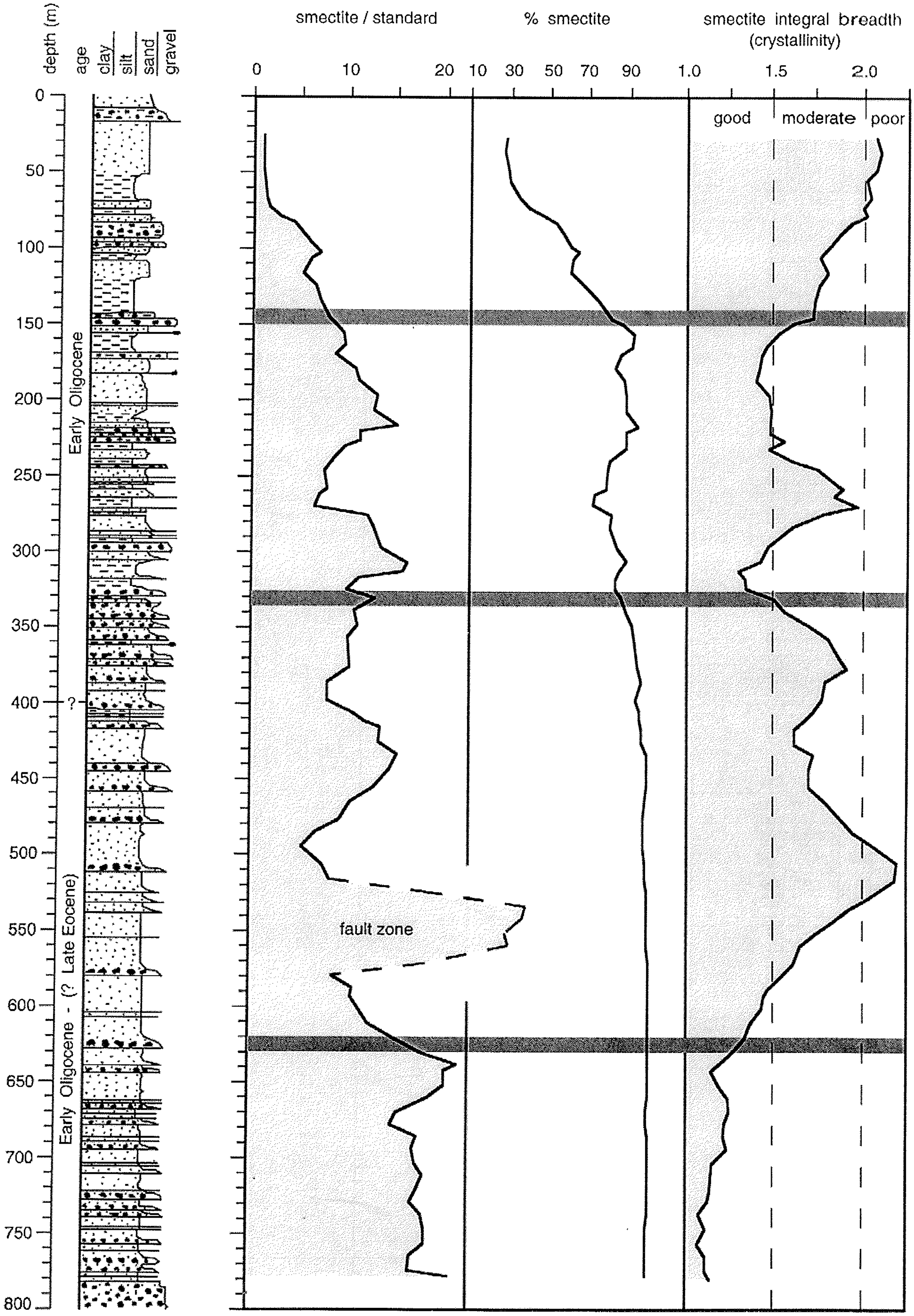

Fig. 2 - Main trend in the smectite/standard ratios, smectite percentages (%) and smectite crystallinities (Δ° 2θ) throughout the CRP-3 core, expressed as the 5-point running average. The dashed interval around 550 mbsf probably is caused by alteration of the clays due to a fault zone.

555 mbsf to 540 mbsf have maximum smectite/standard ratios of *c.* 55. Above, the smectite/standard ratios exhibit a cyclic pattern. Maxima with values of 15-20 occur at around 430 mbsf, 300 mbsf and 200 mbsf. Minima with smectite/standard ratios of about 5 occur at around 500 mbsf, 380 mbsf and 250 mbsf. A distinct trend of decreasing smectite/standard ratios is obvious at 200-85 mbsf. Above 85 mbsf, very low and constant ratios of <2 were measured.

The curve of smectite percentages can be subdivided into three major parts (Fig. 1). From 800 mbsf to *c.* 330 mbsf the clay mineral assemblages consists almost exclusively of smectite, with concentrations >95% below 400 mbsf, and a slight decreasing trend to concentrations of *c.* 90% at 330 mbsf. Between 330 mbsf and 145 mbsf the smectite concentrations highly fluctuate between 50% and 100%. The uppermost 145 m of the core are characterized by smectite concentrations decreasing from 100% to 20%.

The smectite crystallinity has a wide range and generally fluctuates between 1.0 and 2.5 $\Delta° 2\theta$ (Figs. 1 and 2). The smectites in the lowermost part of the investigated interval have best crystallinities with integral breadths values of around 1.1 $\Delta° 2\theta$. In the middle part of the core, two relatively distinct maxima in integral breadth values occur at around 510 mbsf and 250 mbsf, and one relatively indistinct maximum at around 380 mbsf. The uppermost *c.* 145 m of the core again are characterized by high values, *i.e.* by moderate to poor crystallinities.

DISCUSSION

The interpretation of smectite in marine sediments can be discussed controversially, because smectite may be either of detrital or of authigenic origin. Authigenic smectites derive mainly from volcanism, hydrothermal activity, hydrogenous activity or diagenetic processes (*e.g.* Chamley, 1989). The submarine alteration of volcanic glass and volcanic rock fragments is one of the most important processes. Authigenic smectites played only a minor role in the sediments of drill cores CRP-1 and CRP-2/2A (Ehrmann, 1998a, 2000; Setti et al., 1998, 2000).

Detrital smectites are provided from the adjacent continents. Therefore, they are useful tools for reconstructing the sediment source, the type of weathering and the paleoclimate. Smectites on the continents generally form by hydrolysis under humid and relatively warm climatic conditions, in environments characterized by very slow movement of water (Chamley, 1989). In Antarctica such conditions are thought to have prevailed before the onset of continental glaciation, in Eocene and older times (Robert & Maillot, 1990; Ehrmann & Mackensen, 1992; Ehrmann et al., 1992; Ehrmann, 2000). Evidence of smectite formation under a polar climate has been reported from a few soils and tills in Antarctica (Campbell & Claridge, 1987; Chamley, 1989). In general, smectite formation in the recent Antarctic environment is only a subordinate process. However, high smectite concentrations have been reported from glaciomarine sediments in areas with basalts in the hinterland (Ehrmann et al., 1992; Ehrmann, 1998a, 1998b), showing that basalts can provide considerable amounts of smectite under a polar climate.

The investigations of the sedimentary facies and the mineralogy of the bulk sediment, as well as of the composition of the gravel and sand fractions of the sediments have shown that the source area for the terrigenous components of the CRP-3 sediments has to be sought in the Transantarctic Mountains (Cape Roberts Science Team, 2000; Neumann & Ehrmann, this volume; Sandroni & Talarico, this volume; Smellie, this volume). The hinterland consists of a crystalline basement of late Precambrian and early Paleozoic granitic and metamorphic rocks. The basement rocks are overlain by quartzose sedimentary rocks of the Devonian to Triassic Beacon Supergroup. Both basement and sedimentary strata are intruded by sills and dykes of the Jurassic Ferrar Dolerite.

THE CLAY MINERAL RECORD 800-625 mbsf

The most striking feature in the smectite distribution pattern (Fig. 1) is the almost monomineralic composition of the clay fraction in the Cenozoic sediments below *c.* 625 mbsf. In this interval smectite comprises almost 100% of the clay minerals. Chlorite occurs only in traces and illite is totally absent in most of the samples. The clay concentration in the sediments is relatively small in this interval and ranges around 5%. The fluctuating smectite/standard ratios indicate a variable abundance of smectite in the clay fraction even if the smectite is the only clay mineral present. Thus, non-clay minerals, mainly quartz and some minor feldspar, are obviously present in the clay fraction (<2µm) and dilute the smectite. The smectite/standard ratios in this part of the core range from 15 to 20 (Fig. 2). They are distinctly higher than above, and they are also distinctly higher than in any other drill core in McMurdo Sound. The smectites have good crystallinities with an average integral breadth of 1.1 $\Delta° 2\theta$. The crystallinity therewith is much better than that recorded in nearby drill cores CRP-1 (Ehrmann, 1998a), CRP-2/2A (Ehrmann, 2000), CIROS-1 and MSSTS-1 (Ehrmann, 1997, 1998b), and it is better than in the sediments above 625 mbsf in CRP-3. Thus, the sediment interval between 800 mbsf and 625 mbsf has an unique clay mineral signature (Fig. 3).

The monomineralic clay assemblage is hard to explain in terms of weathering a mixed source in the

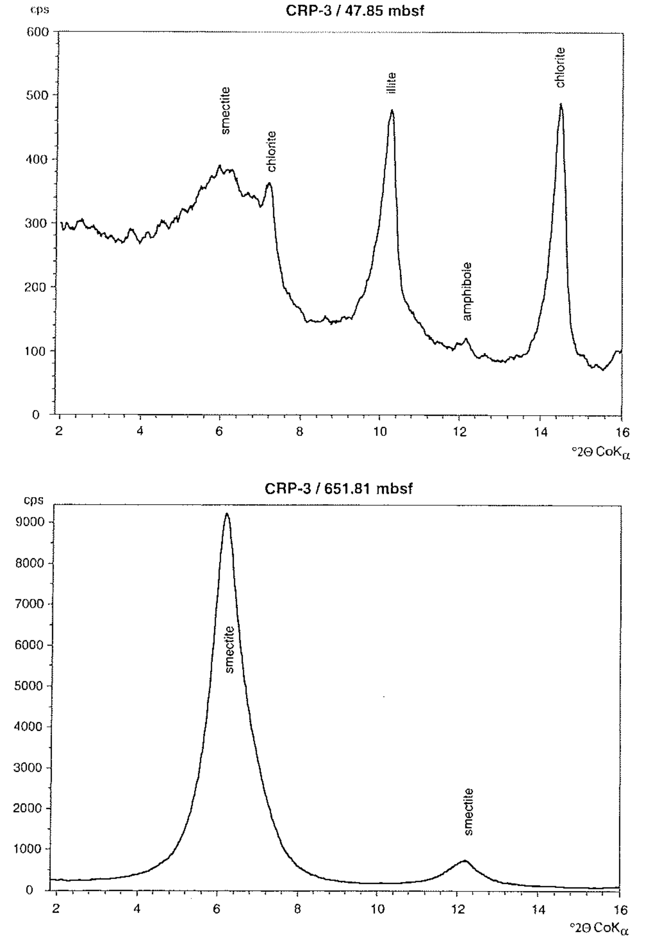

Fig. 3 - Typical diffractograms (glycolated samples) of two different clay mineral assemblages in sediments of the drill core CRP-3. Note the different scale on the axis of ordinates. Above: Clay mineral assemblage of a sample from 47.85 mbsf, consisting mainly of illite, chlorite and poorly crystalline smectite. Below: Monomineralic clay assemblage of a sample from 651.81 mbsf consisting of well crystalline smectite.

Transantarctic Mountains under a polar climate. The dolerites would possibly provide smectite also under these conditions. The sedimentary strata and the crystalline basement rocks, in contrast, would provide mainly illite and chlorite, which then would dilute the smectite. Consequently, samples of recent glacial debris taken from the Taylor Glacier and the Mackay Glacier in the hinterland of Cape Roberts do not contain any smectite. By chemical weathering under a humid and relatively warm climate, however, the source rocks in the Transantarctic Mountains would provide abundant smectite. One could argue that the high smectite concentrations below 625 mbsf in the CRP-3 core document such a time and indicate climatic conditions that were wetter and warmer than today, *i.e.* conditions that were typical for Eocene and older time.

Another possible explanation for the dominance of well crystalline smectite below 625 mbsf could be that the sediment source included abundant volcanic rocks that were not any more available at later times. XRD analyses of the bulk sediment revealed that the main components of the sediments at 800-625 mbsf are quartz, feldspar and pyroxene. Therefore a source in the upper Beacon Supergroup (Victoria Group) and the volcanic rocks of the Ferrar Supergroup including the basaltic Kirkpatrick Formation was assumed. Above 625 mbsf, however, a volcanic source is not very likely (Neumann & Ehrmann, this volume). This interpretation of a shift in the source is in accordance with the findings made during initial core characterization (Cape Roberts Science Team, 2000) and with the investigations of the sand fraction of the sediments (Smellie, this volume). A change in the smectite composition at 625 mbsf is indicated by their crystallinity, with well crystallized smectites below and moderately crystallized smectites above. This change could be due to different source rocks.

A third cause for the dominance of smectite below 625 mbsf could be seen in diagenetic processes. It was observed that pyroxene grains in the sand fraction may be replaced by smectite and that abundant phyllosilicate cement is present in the deepest part of the Cenozoic sequence (Cape Roberts Science Team, 2000). The chemistry of the smectites between 800 mbsf and 625 mbsf indicates an Al-poor, but Mg- and Fe-rich composition. The smectites were identified as intermediate members of the beidellite-saponite series, and an authigenic origin due to an alteration of pyroxenes and iron oxyhydroxide or due to an alteration of previous detrital smectite was assumed (Setti et al., this volume). Saponite commonly occurs in veins and voids of basic to ultrabasic rocks that are rich in Mg. Their formation probably included hydrothermal processes. Saponites may also form by alteration of other clay minerals (Heim, 1990). An alteration of volcanic rock fragments derived from erosion of the Kirkpatrick basalts seems a likely explanation for the occurrence of well crystalline smectites below 625 mbsf.

THE CLAY MINERAL RECORD 625-330 mbsf

The clay mineral assemblage between 625 mbsf and 330 mbsf is very similar to that below 625 mbsf. Also in this interval, the assemblage is monomineralic and consists of almost 100% smectite. Chlorite is present only in minor amounts. Illite occurs as traces in a few samples. The clay content of <5% is even lower than in the deeper part of the core. The smectite/standard ratios fluctuate between 5 and 15. The main difference to the interval 800-625 mbsf is the only moderate to poor crystallinity of the smectite. Values of the integral breadth fluctuate between 1.3 and 2.4 $\Delta° 2\theta$, with an average of 1.7 $\Delta° 2\theta$. Neither the fluctuations in smectite/standard nor the fluctuations in the crystallinity can be linked to lithological changes. In general, however, high smectite/standard ratios are roughly accompanied by relatively good crystallinities (Fig. 1 and 2).

The chemistry of the smectite is very variable in this part of the core (Setti et al., this volume). Some smectites are Al-rich, some are Mg-rich and some are Fe-rich. Thus, around 435 mbsf, the smectites have a saponite-beidellite composition, like in the interval 800-625 mbsf. In contrast, Fe-Al beidellites occur around 341 mbsf, 406 mbsf, and 522 mbsf. Beidellites generally form under acid leaching conditions in podzolised soils or podzols under forests in cool to cold temperate climates similar to that of Patagonia. In many of these soils the weathering process resulted in the transformation of micas to beidellite (Brown & Tedrow, 1964; Gjems, 1970; Churchman, 1980). Fe-Al beidellites also were the main smectite type in the sediments of the drill cores CRP-1 and CRP-2/2A (Setti et al., 1998, 2000). The compositional and morphological features clearly indicated a detrital origin of the smectites in those cores, and also for CRP-3 a detrital origin can be assumed (Setti et al., this volume).

The fluctuating crystallinities possibly mirror the variable chemistry of the smectites, with intervals of detrital Fe-Al beidellite being characterized by poor crystallinities (Fig. 1). Unfortunately, not enough samples were analysed hitherto for their chemical composition to allow further and more detailed correlations.

According to the mineralogy of the bulk sediment and the sand fraction, the source area for the sediments of this interval was also located in the Transantarctic Mountains. From *c.* 620 mbsf to *c.* 420 mbsf the sandstone-dominated Taylor Group of the Beacon Supergroup acted as the main source, before the erosion in the valleys reached the level of the basement rocks (Cape Roberts Science Team, 2000; Neumann & Ehrmann, this volume; Smellie, this volume). Thus, volcanics played a subordinate role as source rocks. This could be the reason for the reduced occurrence of authigenic smectites in the corresponding sediments.

The almost monomineralic clay assemblages in the interval 625-330 mbsf differs from that in the interval 800-625 mbsf by the presence of poorer crystalline detrital smectites. To explain detrital clay mineral assembalges with almost 100% smectite requires a much wetter and warmer climate than today, as already discussed above.

Within the interval 625-330 mbsf, two "exotic" samples at 551.7 mbsf and 542.7 mbsf have smectite/standard ratios of 52-57 (Fig. 1). These anomalous values may be attributed to a fault zone at *c.* 540 m (Cape Roberts Science Team, 2000). The fault zone is hydraulic active as can be seen mainly from the temperature profile in the logging data (Bücker et al., this volume). Along the fault, diagenetic processes may be especially pronounced resulting in the high smectite/standard ratios and in the slightly enhanced clay percentages (Fig. 1).

THE CLAY MINERAL RECORD 330-145 mbsf

The characteristic feature in the clay mineral data of the interval 330-145 mbsf are smectite percentages varying between 50 and almost 100% (Fig. 1). The chemical character of the smectites is similar as in the interval 625-330 mbsf. Both detrital and authigenic smectites are present. Therefore, this interval may document a changing influence of authigenic smectite formation versus detrital input. Alternatively, it may document fluctuations in the climate, with alternating intervals of intense smectite formation by chemical weathering under a warm and wet climate, and reduced smectite formation under a cooler climate favoring physical weathering with formation of illite and chlorite. Indication for a cooler climate above 330 mbsf comes also from the sedimentary facies changing from sandstones and conglomerates below this level to diamictites and proximal to distal glaciomarine sediments above (Cape Roberts Science Team, 2000).

On Maud Rise and on Kerguelen Ridge in the Southern Ocean clay mineral assemblages with smectite concentrations exceeding 90% characterize sediments older than 38 Ma (Tab. 1). In 38 Ma to 34 Ma old sediments, smectite concentrations decrease somewhat and fluctuate between 60% and 100% (Ehrmann, 1991; Ehrmann & Mackensen, 1992). Also in the supposed upper Eocene sediments of CIROS-1, strongly fluctuating smectite concentrations of up to >80% are documented (Ehrmann, 1998b). In contrast, the Oligocene and younger clay mineral assemblages at all these sites are characterized by abundant illite and chlorite.

Tab. 1 - Summary of trends in the development of clay mineral assemblages in Eocene/Oligocene sediments from Maud Rise and Kerguelen Plateau, Southern Ocean (after data by Ehrmann & Mackensen, 1992).

<33 Ma	mixed clay mineral assemblage 20-40% smectite, 60-80% illite and chlorite
33.9-33.1 Ma	dramatic shift in clay mineralogy decrease in smectite concentrations from 80% to 20% increase in illite concentrations shift correlates with increase of $\delta^{18}O$ by >1‰
38-34 Ma	slightly decreasing smectite concentrations smectite contents fluctuating between 60% and 80% increase in chlorite concentrations
>38 Ma	monomineralic clay mineral assemblage 100% smectite

One thus could speculate that the sediments below 330 mbsf in CRP-3 are older than 38 Ma and that the sediment interval 330-145 mbsf represents the time 38 to 34 Ma. However, this is not in accordance with the preliminary chronology for the CRP-3 core (Cape Roberts Science Team, 2000). According to the magnetostratigraphic data the top of Chron 13n may be situated at about 335 mbsf. This datum is 33.06 Ma. The base of Chron 13n with an age of 33.55 Ma is at 625 mbsf (Florindo et al., this volume).

THE CLAY MINERAL RECORD 145-0 mbsf

The clay mineral assemblage in the uppermost interval of CRP-3 is characterized by smectite concentrations decreasing from 100% to about 20%. Above *c.* 60 mbsf the concentrations seem to constantly range around 20% (Fig. 1). The assemblages show the typical pattern that was observed in sediments of the drill cores CRP-1 and CRP-2/2A, with abundant illite and chlorite present, but only minor amounts of poorly crystalline smectite (Fig. 3). Such an assemblage is typical for physical weathering of a source like the Transantarctic Mountains under a cool and dry climate.

The chemistry of the smectites is similar to those of CRP-1 and CRP-2/2A. The smectites are dioctahedral and consist mainly of Fe-rich beidellites of detrital origin (Setti et al., this volume). The interval 145-0 mbsf is also stamped by the highest clay percentages of the core, which however strongly fluctuate between 7% and >30%.

The decrease in the smectite percentages is accompanied by a deterioration of the smectite crystallinities from integral breadth values of *c.* 1.6 to 2.4 $\Delta° 2\theta$ (Figures 1 and 2). Above *c.* 85 mbsf the crystallinity values reach a relatively constant level of >2 $\Delta° 2\theta$ and therewith the highest level of the core, except for the interval 540-480 mbsf. Crystallinities of 2-2.4 $\Delta° 2\theta$ were also recorded from other drill sites in McMurdo Sound. They are characteristic for the lower Miocene to Quaternary sediments of the core CRP-1 (Ehrmann, 1998a), for the lower Oligocene to Miocene sediments above 470 mbsf at CRP-2/2A (Ehrmann, 2000), for the lower Oligocene to Miocene sediments above 425 mbsf at CIROS-1 and for the upper Oligocene to Pliocene sediments at MSSTS-1 (Ehrmann, 1998b). These values, therefore, seem to be typical for weathering processes in a glacial regime that controlled smectite formation since earliest Oligocene time.

The smectite/standard ratios also decreased in the uppermost interval of CRP-3 and reach the lowest recorded values of the Cenozoic sedimentary sequence. Above *c.* 85 mbsf the smectite/standard ratios are constantly <2 (Figures 1 and 2). Such low values are also characteristic for the Miocene to Quaternary sediments of CRP-1, the lower Oligocene to Miocene sediments of CRP-2/2A and CIROS-1 and the upper Oligocene to Miocene sediments of MSSTS-1 (Ehrmann, 1998a, 1998b, 2000).

This discussion shows that the clay mineral signature of the upper *c.* 85 m of core CRP-3 is typical for lower Oligocene and younger sediments in McMurdo Sound. Also in other parts of the Southern Ocean a change from smectite-dominated to illite-dominated assemblages was observed. The shift in the clay mineralogy coincides with a dramatic shift in the stable istope record, which marks a major step in the long-term transition from an ice-free to a glaciated Antarctic continent. The shift in the isotope signal was caused by both cooling and ice-sheet growth, and it is well dated on Maud Rise and Kerguelen Plateau to 33.9-33.1 Ma (Tab. 1; *e.g.* Ehrmann & Mackensen, 1992; Mackensen & Ehrmann, 1992; Salamy & Zachos, 1999).

From the clay mineral record alone, one could speculate that the level of 85 mbsf in CRP-3 has an age of 33.1 Ma and that this levels corresponds to a depth of *c.* 470 mbsf in CRP-2/2A and to a depth of *c.* 425 mbsf in CIROS-1. However, according to the initial core characterization, there is no overlap between the cores CRP-3 and CRP-2/2A. Preliminary biostratigraphical investigations furthermore indicate an age of *c.* 31 Ma at 48 mbsf and an age of *c.* 32.5 Ma at 114 mbsf (Cape Roberts Science Team, 2000). In addition, the shift in clay mineral assemblages and in isotopes occurs within Chron 13n. The interval 145-80 mbsf, however, is characterized by reverse polarity.

CONCLUSIONS

The preliminary investigations of the clay mineral assemblages in the Cenozoic sediments of the drill core CRP-3 in McMurdo Sound document the transition from a warm climate in late Eocene time to a cool climate in early Oligocene time, even if the dating and the correlation with other sedimentary sequences from the Antarctic continental margin is still a problem at the moment.

Different from previous cores in McMurdo Sound, CRP-3 below 330 mbsf cored sediments with a monomineralic clay assemblage consisting of almost 100% smectite. Between 800 mbsf and 625 mbsf the smectites are characterized by the best crystallinities and highest smectite/standard ratios of all sediments recovered by the Cape Roberts Project and by cores CIROS-1 and MSSTS-1 in McMurdo Sound. This assemblage can be explained best by an authigenic origin of the smectite, as also shown by the investigations of Setti et al. (this volume). The smectite formation probably was favored by the weathering of the basaltic Kirkpatrick Formation in the Transantarctic Mountains.

The monomineralic clay assemblage between 625 mbsf and 330 mbsf still consists of smectites, but the smectites are only moderately to poorly crystalline in this interval and the smectite/standard ratios are lower. The chemical composition of the smectites argues for both authigenic and detrital components (Setti et al., this volume). This assemblage may be interpreted as a result of weathering a mixed source in the Transantarctic Mountains under a relatively warm and wet climate.

The climate obviously changed during deposition of the sediments between 330 mbsf and 145 mbsf. The corresponding clay mineral assemblage is characterized by smectite concentrations fluctuating between 50% and 100% and probably indicates alternating phases of physical weathering and chemical weathering, respectively. The conditions probably shifted several times between a relatively cool and dry climate and a warm and wet climate.

The clays of the upper some 145 m of CRP-3, finally, document a further cooling period, which led to an intensification of physical weathering on the Antarctic continent. The smectite concentrations decrease to about 20%. In contrast, illite and chlorite become more abundant. The smectite crystallinity deteriorates distinctly and is only poor in this interval. Such an assemblage is typical for early Oligocene and younger sediments in McMurdo Sound and was previously documented from drill cores CRP-1, CRP-2, CIROS-1 and MSSTS-1. It reflects physical weathering conditions under a cool climate on a glaciated Antarctic continent.

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