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Distribution of Heavy Minerals in CRP-1

K. POLOZEK & W. EHRMANN

Institut für Geologische Wissenschaften und Geiseltalmuseum, Domstrasse 5, D-06108 Halle (Saale) - Germany

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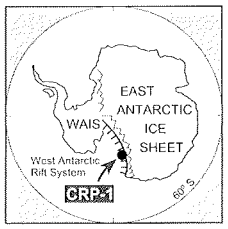
Abstract - Heavy minerals from the lower Miocene and Quaternary sediments of the CRP-1 drillcore have been investigated in order to characterise the mineralogical composition of the sediments and to reconstruct their source areas. The sediments are dominated by very high concentrations of pyroxenes. Hornblende, stable heavy minerals (zircon, garnet, epidote, titanite and apatite), opaque and altered minerals are quantitatively minor. The downcore distribution of the pyroxenes indicates 5 cycles. Each cycle starts with diamictites and proximal glacimarine sediments containing maximum concentrations of pyroxenes of up to 80% in the heavy mineral fraction, and grades into distal glacimarine sediments, with a lower pyroxene content. The heavy minerals indicate a mixed source for all CRP-1 sediments. The proximal sediments consist mainly of minerals derived from a crystalline basement and clastic sedimentary rocks, such as are widespread in the Transantarctic Mountains. However, they also contain a minor component derived from volcanic rocks. The distal sediments, in contrast, are dominated by a volcanic source, which was probably situated to the south of the drillsite, in the region of the present-day Ross Ice Shelf.



INTRODUCTION

Heavy minerals are good indicators for reconstructing the source area and dispersal of sediments (*e.g.* Boenigk, 1983; Pettijohn et al., 1987). Although very few studies on heavy minerals in sediments of the ocean surrounding Antarctica have been carried out, the distribution of individual heavy minerals and the associations of different heavy minerals can be used for reconstructing glacial history and ice-mass dynamics of Antarctica (Von der Borch & Oliver, 1968; Xianlan & Yunlong, 1990; Diekmann & Kuhn, in press; Ehrmann & Polozek, submitted). The aim of this paper therefore is to present the initial results of an investigation of the heavy mineral assemblages in sediments of the CRP-1 drillcore.

The core CRP-1 was drilled during the Cape Roberts Project in October 1997 in 153 m water depth off Cape Roberts in McMurdo Sound, Ross Sea (Fig. 1; Cape Roberts Science Team, 1998). The stratigraphy of the 147 m long CRP-1 core comprises lower Miocene and Quaternary sediments, which are separated from each other by a major hiatus at 43 mbsf (metres below sea floor; Cape Roberts Science Team, 1998). The lower Miocene interval was preliminarily dated to *c.* 22-17.5 Ma. Both the Miocene and the Quaternary intervals are of special interest, because they are unknown from the previous drilling investigations CIROS-1, CIROS-2 and MSSTS-1 in McMurdo Sound (Fig. 1; Barrett & Scientific Staff, 1985; Barrett, 1986, 1989). The sedimentary sequence in CRP-1 consists of alternating diamictite, sandstone, siltstone and claystone showing a distinct glacial influence involving several episodes of ice advance and retreat. However, it is believed that ice did not completely disappear from the coast of Antarctica during the period represented by the sediments in CRP-1 (Cape Roberts Science Team, 1998).

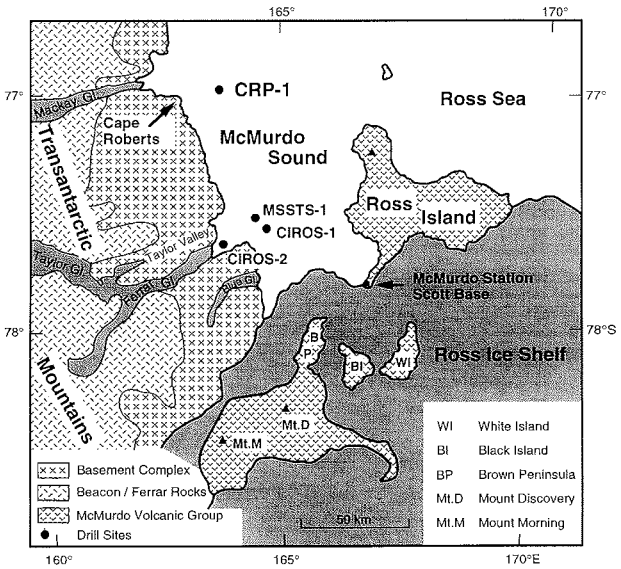


Fig. 1 - Location of the CRP-1 drillsite on the continental shelf of McMurdo Sound, Ross Sea. The positions of the drillsites CIROS-1, CIROS-2 and MSSTS-1 are also indicated. Bedrock geology is from Warren (1969).

METHODS

The heavy minerals were separated from the very fine sand fraction (63-125 μm) of 29 samples distributed evenly throughout the CRP-1 core. Sodium metatungstate solution

was used as a heavy liquid (density = 2.83 g/cm^3) for density separation in a centrifuge. After 20 minutes of centrifuging, the test tubes containing the heavy minerals at the bottom and the light minerals at the top were frozen in liquid nitrogen. The light and heavy mineral fractions were then thawed in turn, decanted into separate filters and dried. The heavy minerals were mounted with Meltmount (refractive index = 1.68), and then identified and counted under a polarising microscope. For each sample, at least 300 grains were counted along several traverses. The results are presented as grain percentages of the total heavy mineral fraction (Fig. 2). No chemical analyses have been carried out. All raw data are lodged in the data-bank of the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany (available *via* www.pangaea.de).

CHARACTERISTICS AND DISTRIBUTION OF HEAVY MINERALS

In total, 52 heavy mineral types including pyroxene and amphibole varieties were identified in the sediments of CRP-1. The mineral spectrum is dominated by pyroxenes. Completely altered and opaque minerals are also common. Amphiboles (varieties of hornblende) and stable minerals (epidote, zircon, garnet, titanite and apatite) are minor (Fig. 2). Other minerals like mica, topaz, tourmaline, palagonite, olivine, xenotime, calcite, siderite, rutile, pumpellyite, vesuvianite and haematite, also present in very minor amounts, show no significant changes in their downcore distribution patterns. They are therefore not discussed in this progress paper.

PYROXENES

The pyroxenes are generally prismatic and display a variety of pale to very pale colours (green-brown, yellow-green, nearly colourless), often with a weak pleochroism. Titanaugite shows typical brown-violet colours. Some grains have exsolution lamellae. Two groups of pyroxenes can be distinguished in the CRP-1 sediments based on cleavage characteritics. The first group exhibits a significant cleavage, sometimes along the direction of exsolution lamellae. In some cases, the cleavage is dark-coloured, because of the presence of fine opaque grains. The second group lacks a visible cleavage. There is no obvious correlation between cleavage characteristics and colour of the pyroxene minerals. The pyroxenes are variably altered, the alteration apparently developing along, and extending out from the cleavage and sometimes resulting in complete alteration of the original mineral. Cockscombs or ragged margins are also found occasionally on grains without visible cleavage.

Clinopyroxenes are most abundant, probably forming about 50-75% of the entire pyroxene population. The clino- and orthopyroxenes are distinguished only by their straight extinction and, where possible, by their optical character. However, based on these criteria no minute differentiation is possible. Therefore, pyroxenes are treated

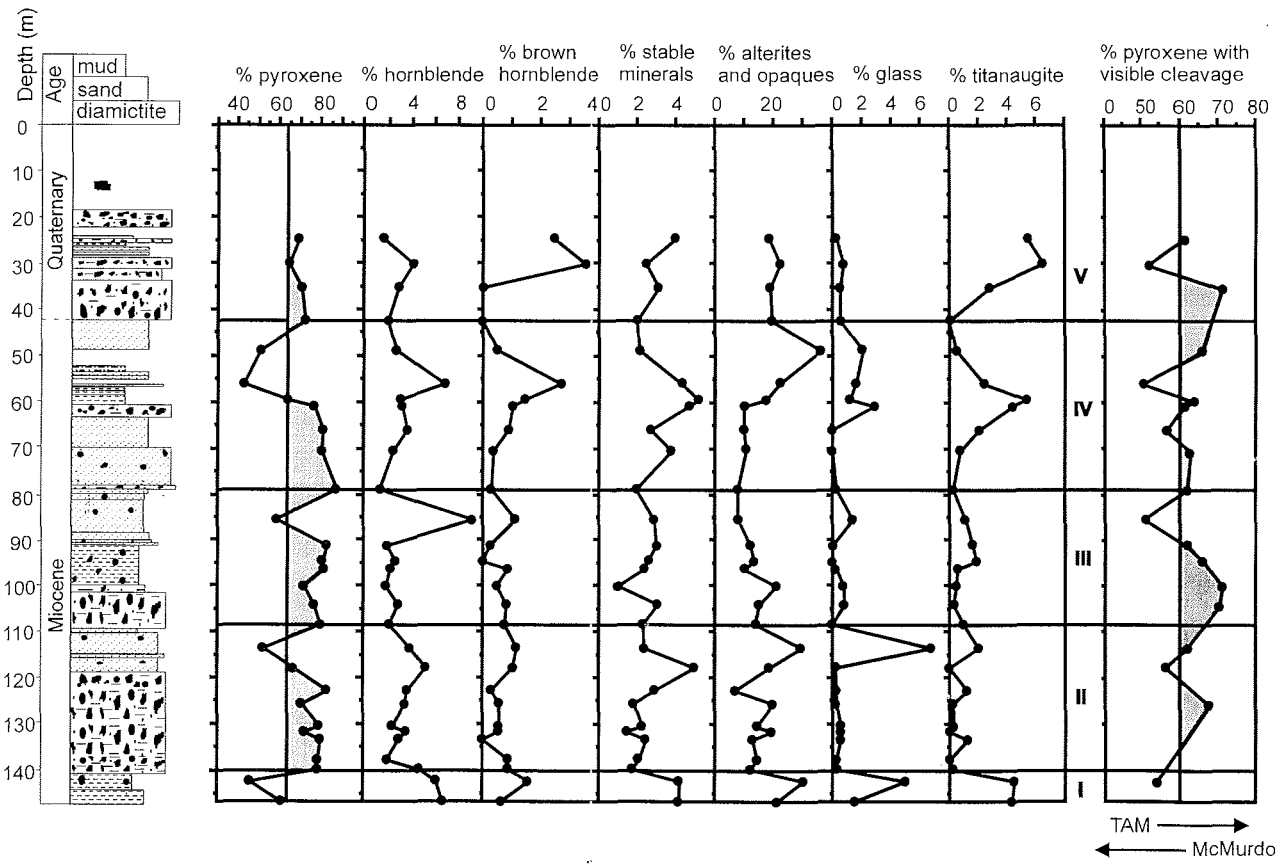


Fig. 2 - Percentage distribution of the main heavy mineral groups identified in the CRP-1 core. Five cycles can be observed (I - V). The column on the right-hand side indicates the percentage of pyroxenes with conspicuous cleavage which is indicative for a source in the Transantarctic Mountains (TAM), whereas pyroxenes with no cleavage indicate a likely volcanic source in the region of the present-day Ross Ice Shelf.

as one group in this paper. Titanaugite is the only pyroxene that is discussed separately.

CRP-1 sediments are characterized by very high concentrations of pyroxenes, reaching up to 80% of the heavy mineral population (Fig. 2). The distribution of pyroxenes exhibiting cleavage is also shown in figure 2 and has very similar patterns of maxima and minima which mirror those of the whole pyroxene population. The concentration of titanaugite shows three maxima, two of which correlate with maximum glass concentrations (Fig. 2). Abundances of titanaugite and glass correlate negatively with total pyroxene concentrations, and positively with pyroxenes without a visible cleavage.

ALTERED AND OPAQUE GRAINS

All brown to black minerals, which are so intensely altered that no assignment to a mineral group was possible, were combined within one group. Partially altered grains that still allowed identification of the original mineral were included in the relevant mineral group. Altered grains occur in concentrations of 5-30%, whereas opaque grains are generally less common (1-5%). Three maxima of altered and opaque minerals in the sedimentary succession correlate with minima of total pyroxene concentration.

HORNBLENDES

Amphiboles were subdivided according to their colour. The petrographical characteristics suggest that they are mainly varieties of hornblende. Colourless amphiboles (possibly tremolitic) occur only in trace amounts. Green hornblende shows pleochroism from green to brown, is only faintly cleaved and occurs in 1-5%. Brown hornblende shows pleochroism from brown to red, is also only faintly cleaved and reaches maximum concentrations of 4%. Colourless and green amphiboles were combined into a single group, but, because a different source is likely for brown hornblende (see later), it is presented separately (Fig. 2). In CRP-1 sediments, the abundance of brown hornblende correlates with that of the green and colourless hornblendes.

OTHER HEAVY MINERALS

Each of the minerals epidote, zircon, garnet, titanite and apatite only occurs in minor concentrations of 0-3%. The epidote group comprises epidote and clinozoisite, rarely piemontite and allanite. Epidote minerals occur as subrounded to rounded grains.

Zircon grains are also subrounded to rounded and range from colourless to pale yellow, red and grey-brown. Titanite grains are subrounded and colourless to light yellow. Garnet occurs as subrounded to angular, colourless or pink grains, some with opaque inclusions. The mainly colourless, but occasionally light grey apatite grains are subrounded to rounded.

Because epidote, zircon, garnet, titanite and apatite very likely have the same source area (Ehrmann & Polozek, submitted) and because of their very minor concentrations, they were combined into one group, the stable heavy minerals (Fig. 2). Abundances of the stable heavy minerals correlate with those of the amphiboles and are antithetic to pyroxene abundances.

STABILITY OF HEAVY MINERALS

The stability and the influence of weathering on heavy minerals have been discussed extensively (*e.g.*, Nickel, 1973; Morton, 1985; Pettijohn et al., 1987). Some heavy minerals are unstable during chemical weathering but stable during physical weathering, factors which will influence the types and proportions of the heavy minerals. For example, garnet is less stable to chemical weathering under acidic pH conditions, but more stable to transportation, whereas apatite is susceptible to alteration in an acidic environment, but is stable under other diagenetic conditions. Apatite grains also very quickly become rounded during transportation. Zircon is extremely stable against both chemical and physical weathering, generally retaining an euhedral shape and becoming rounded only after substantial recycling. Epidote is also stable to moderately stable under most conditions. By contrast, titanite quickly becomes rounded even after minor transport, although those crystals are relatively easily broken. Pyroxenes and amphiboles are affected by most kinds of weathering.

In the CRP-1 samples, garnet and apatite are subangular to well rounded, exhibiting no evidence of chemical weathering, such as etching. Zircons and epidote are subrounded to rounded because of transport. Pyroxenes show different features of alteration. However, these minerals show no systematic downcore change in the intensity of alteration features and are present in abundance in all the samples analysed. Therefore, it is likely that changes in the distribution patterns of heavy minerals in CRP-1 sediments are not controlled by weathering, and they probably reflect variations in input from the source area. This suggestion is supported by values for the chemical index of alteration (CIA), which are uniformly low in the CRP-1 core and interpreted to indicate only limited chemical weathering in a glacial environment during the early Miocene and Quaternary (Krissek & Kyle, this volume).

SOURCE AREAS FOR HEAVY MINERALS

The hinterland of CRP-1 consists of two lithologically contrasting areas that could both serve as sources for the CRP-1 sediments (Fig. 1; Warren, 1969). The geology of the southern and eastern parts of McMurdo Sound is characterised by Cenozoic alkali volcanic complexes. They include outcrops at Ross Island, White Island, Black Island, Brown Peninsula, Mt. Discovery and Mt. Morning (Fig. 1). In contrast, the Transantarctic Mountains west of McMurdo Sound consist of a widespread crystalline basement of upper Precambrian to lower Paleozoic granites and metamorphic rocks of the amphibolite facies overlain by sedimentary rocks, mainly non-marine sandstones,

quartzites and siltstones of the Devonian to Triassic Beacon Supergroup (Fig. 1). Both basement rocks and sedimentary strata are intruded by sills and dykes of the Jurassic Ferrar Dolerite. Scattered small occurrences of olivine basalt assigned to the McMurdo Volcanic Group and more altered Jurassic Kirkpatrick basalts comprise only a few percent of the exposed rocks within the Transantarctic Mountains.

The heavy mineral distribution in CRP-1 sediments is characterized by a very high concentration of pyroxenes. Pyroxenes without visible cleavage have previously been described from sediments of the CIROS-2 drillcore, where they dominate the pyroxene group (Ehrmann & Polozek, submitted). Because their distribution pattern in CIROS-2 correlates strongly with that of heavy minerals characteristic of a volcanic provenance, a source area in the McMurdo Volcanic Group is assumed for the corresponding pyroxenes in CRP-1 (Tab. 1). Also, Weiblen et al. (1981) described pyroxenes from the McMurdo Volcanic Group lacking cleavage or with cleavage only poorly developed. Titanaugite is an additional indicator for sediments derived from the McMurdo Volcanic Group (Fig. 2; Nathan & Schulte, 1968). A source area in the Transantarctic Mountains is assumed for other pyroxenes observed in CRP-1, which are characterized by a conspicuous cleavage. The volcanic rocks of the Ferrar Group probably provided these pyroxenes (Tab. I; Cape Roberts Science Team, 1998).

A Transantarctic Mountains source is also likely for epidote, zircon, garnet, titanite and apatite, because these minerals are not typical constituents of mafic volcanics (Tab. 1). Apatite, titanite and zircon are well-known accessory minerals of the Granite Harbour intrusive complex (Ghent & Henderson, 1968; Skinner & Ricker, 1968a; Smillie, 1992). Some zircons are red-coloured, due to long-term effects of radioactivity. The intensity of colour increases with radiation and geological age. Therefore, red zircons are probably derived from Precambrian rocks (Zimmerle, 1972), such as some of the basement rocks in the Transantarctic Mountains (Fig. 1).

The occurrence of subrounded to rounded grains of zircon, apatite and titanite is consistent with recycling of sedimentary rocks, in this case the Beacon Supergroup, although titanite is not described as a typical mineral of the Beacon Supergroup (Tab. 1; Laird & Bradshaw, 1982; Skinner & Ricker, 1968b). Garnet and epidote also occur occasionally as subrounded to rounded grains and may also have been recycled from the sedimentary rocks of the Beacon Supergroup (Laird & Bradshaw, 1982; Skinner & Ricker, 1968b; La Prade, 1982). Furthermore, they are known from metamorphic rocks such as the metasediments and orthogneisses of the Koettlitz Group in the Transantarctic Mountains (Riddolls & Hancox, 1968; Allibone, 1987).

The green and colourless amphiboles are generally rock-forming minerals of intermediate magmatic rocks and often metamorphic rocks. Green hornblendes were described from the Granite Harbour intrusive complex (Ghent & Henderson, 1968; Skinner & Ricker, 1968a; Smillie, 1992). Other sources of green hornblendes and colourless amphiboles (tremolitic amphiboles?) could be amphibolites of the Koettlitz Group. Brown hornblende (oxyhornblende and kaersutite) occurs in volcanic rocks and has been described from hornblende trachytes, hornblende basalts and trachyandesites of the McMurdo Volcanic Group (Cole & Ewart, 1968; Nathan & Schulte, 1968; Kyle, 1990; LeMasurier & Thomson, 1990).

It is difficult to interpret the provenance of the altered and opaque grains. Opaque minerals are constituents of all rocks in the hinterland of CRP-1. However, a high concentration of opaque minerals in general points to a volcanic source (Wimmenauer, 1985), and is possibly supported in this investigation by the crude covariation between abundances of altered and opaque grains, glass and titanaugite.

Tab. 1 - Main source rocks and provenance areas interpreted for heavy minerals in CRP-1 sediments.

Mineral		Source rocks	Provenance
pyroxene	without visible cleavage	McMurdo Volcanic Group	RIS
pyroxene	with cleavage	Ferrar Group	TAM
titanaugite		McMurdo Volcanic Group	RIS
alterites		omnipresent McMurdo Volcanic Group	RIS
opaques		omnipresent McMurdo Volcanic Group	RIS
hornblende	brown	McMurdo Volcanic Group	RIS
hornblende	green colourless	Koettlitz-Group Granite Harbour intrusive complex	TAM
apatite		Beacon Supergroup Ferrar Group Granite Harbour intrusive complex	TAM
zircon	colourless	Beacon Supergroup crystalline basement	TAM
	pink metamikt	Precambrian basement ?	TAM
titanite		Granite Harbour intrusive complex	TAM
garnet	subangular	Koettlitz Group Granite Harbour intrusive complex	TAM
	rounded	Beacon Supergroup	TAM
epidote	angular rounded	Koettlitz Group Beacon Supergroup	TAM TAM

Note: TAM = Transantarctic Mountains, RIS = region of the present-day Ross Ice Shelf.

DISCUSSION

Pyroxenes dominate the heavy mineral assemblages in CRP-1 sediments. Both the downcore distribution of total pyroxenes and of pyroxenes with conspicuous cleavage indicate 5 cycles in the CRP-1 drillcore (Fig. 2). Each cycle starts with diamictites and proximal glacimarine sediments, and grades into distal glacimarine sediments. The proximal sediments are characterized by high total pyroxene concentrations and a high proportion of pyroxenes with distinct cleavage. The distal glacimarine sediments contain less pyroxenes, but more stable minerals and hornblendes. Within the pyroxene group, there is a shift to those characterized by no visible cleavage (Fig. 2). The distribution of stable minerals and hornblendes show a trend which is broadly antithetic to that of the pyroxenes. However, these minerals typically occur in much smaller quantities compared with the pyroxenes and the relationship is probably a result of dilution by the pyroxenes.

The cycles described show a crude correspondence to sequence stratigraphy (Cape Roberts Science Team, 1998). Sequence boundaries are reported at *c.*142, 115, 108, 92, 79, 63, 55, 43 and 31 mbsf. The sequence boundaries at 142, 108, 79 and 43 mbsf are also clearly visible in the heavy mineral record (Fig. 2) and are reproduced by the concentration curve of pyroxenes. The sequence boundaries at 115, 92, 63, 55 and 31 mbsf, in contrast, are not visible in the pyroxene concentration curve. However, they are, in part, slightly indicated in the percentage curve of pyroxenes with conspicuous cleavage. The poor documentation of some of the sequence boundaries in the heavy mineral record is possibly due to an insufficient sample density.

At the beginning of a cycle, the ice advanced as a grounded ice mass, as a floating ice mass or as a high number of icebergs. The diamictites and proximal glacimarine sediments were deposited close to the ice. The high concentration of pyroxenes with visible cleavage points to a main source of the ice in the Transantarctic Mountains. Then the ice retreated, and distal glacimarine sediments, such as mud or silt, were deposited. The concentration of pyroxenes derived from the Transantarctic Mountains decreased, and the influence of pyroxenes derived from the McMurdo Volcanic Group increased. Parallel to this trend, we find increases in the abundance of titanaugite and glass, which both are typical for a volcanic source. Thus, the change in the heavy mineral assemblages indicates an increased importance for input from a volcanic source probably in and around the present-day Ross Ice Shelf. However, the heavy mineral assemblages of all samples seem to be a mixture of sediment components derived from the Transantarctic Mountains in the west and from the McMurdo Volcanic Group in the south (Fig. 2; Tab. 1). A mixed sediment source for the CRP-1 sediments is also concluded from the mineralogical composition of the bulk sediment (Ehrmann, this volume).

Our results suggest a scenario in which, at the beginning of each cycle, the ice came from the west, from the Transantarctic Mountains. When these ice masses retreated to a landward position, the influence of southerly ice increased. Icebergs calving in the region of the present-day Ross Ice Shelf drifted to the north and deposited components derived from the McMurdo Volcanic Group. The next ice advance from the Transantarctic Mountains would again bring basement-derived and Beacon-derived components, and also would rework those components derived from the McMurdo Volcanic Group and deposited earlier on the shelf.

A further possible explanation for the mixed nature of the heavy minerals would be that at no time a grounded ice mass advanced across the shelf, but that icebergs coming from different directions drifted across the drillsite and were responsible for the glacimarine sediments of CRP-1. At the beginning of each cycle, icebergs calving from mountain glaciers in the west dominated over icebergs coming from the south. At the end of each cycle, in contrast, icebergs coming from the south were more frequent. Current transport, theoretically, also could provide parts of the heavy mineral assemblages. This kind of transport could be assumed for heavy minerals coming from the south, and could also be responsible for the missing correlation with coarse-grained volcanic debris (Smellie, this volume), which rather was transported by ice or released as airfalls deposit.

CONCLUSIONS

The present study has demonstrated the significance of heavy mineral assemblages for reconstructing source areas and transport paths for Antarctic ice through time. Although interpretation of the abundances of individual heavy minerals may be equivocal, interpretations of associations of different heavy minerals are a valuable tool for reconstructing the glacial history of the McMurdo Sound area.

The heavy mineral spectrum in the lower Miocene and Quaternary sediments of the CRP-1 core indicates a mixed sediment source. Pyroxenes dominate the heavy mineral assemblages and were derived mainly from the Transantarctic Mountains. However, some distinctive pyroxenes indicate a persistent influence of a volcanic source, which was probably in the McMurdo Volcanic Group situated in the region of the present-day Ross Ice Shelf.

The variations of heavy minerals, especially where pyroxene percentages are concerned, together with changes in lithofacies, indicate a cyclic sedimentation pattern. Each cycle starts with proximal sediments with high pyroxene concentrations, mainly pyroxenes indicative of a source mainly in the Transantarctic Mountains. These sediments grade into distal glacimarine sediments that are characterised by lower pyroxene concentrations and by a dominance of volcanic-derived pyroxene grains. The main source for these sediments is probably the McMurdo Volcanic Group situated to the south of the CRP-1 drillsite.

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