Distribution and origin of authigenic smectite clays in Cape Roberts Project Core 3, Victoria Land Basin, Antarctica

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Abstract Of some 800 m of lower Oligocene marine sediments cored continuously from the seafloor in the Victoria Land Basin of Antarctica at Cape Roberts Site CRP-3, the lower 500 m exhibit authigenic smectite clay coats on shallow-water sandstone grains. A scanning electron microscope/EDS study of 46 fracture sections confirms that the distribution of the clay coats through the unit is not uniform or evenly distributed, but rather varies with depth, original porosity, and the kinds and abundance of source materials. Our results suggest that smectite emplacement resulted from in-situ, low-temperature burial diagenesis rather than hydrothermal or fault-focused thermobaric fluids.

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Introduction

In the Cape Roberts Core 3 (CRP-3, Fig. 1) from the Victoria Land basin, diatoms and calcareous nannofossils are not present beneath 194 meters below sea floor (mbsf) in the 930-m deep hole. This was unexpected. The culprit was diagenesis signaled by authigenic clay coats first noted in thin sections made on site and later described via scanning electron microscope (SEM) images by Wise et al. (2001). As a result, it was not possible to obtain a solid date for the base of the marine sequence, which is estimated to be close to the Oligocene/Eocene boundary (~34 Ma, Naish et al., 2001). A second major consequence was that most clay-mineral assemblages below 194 mbsf cannot be used reliably for paleoenvironmental analysis.

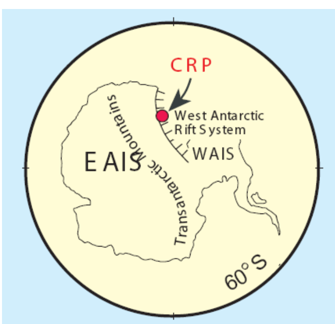

Figure 1. Location map of CRP-3 drill site.

Wise et al. (2001) suggested three hypotheses to explain the presence of the authigenic clay minerals in the bottom 500 m of the marine section: 1) Burial diagenesis; 2) Precipitation from hydrothermal fluids; and 3) Precipitation from regionally compactive thermobaric fluids (i.e., fault-focused fluids). Of these they favored the first possibility. In contrast, however, other authors have concluded that the occurrence of the authigenic smectite is more likely due to hydrothermal processes coupled with fluid movement along faults and fractures (Setti et al., 2004; Ehrmann et al., 2005).

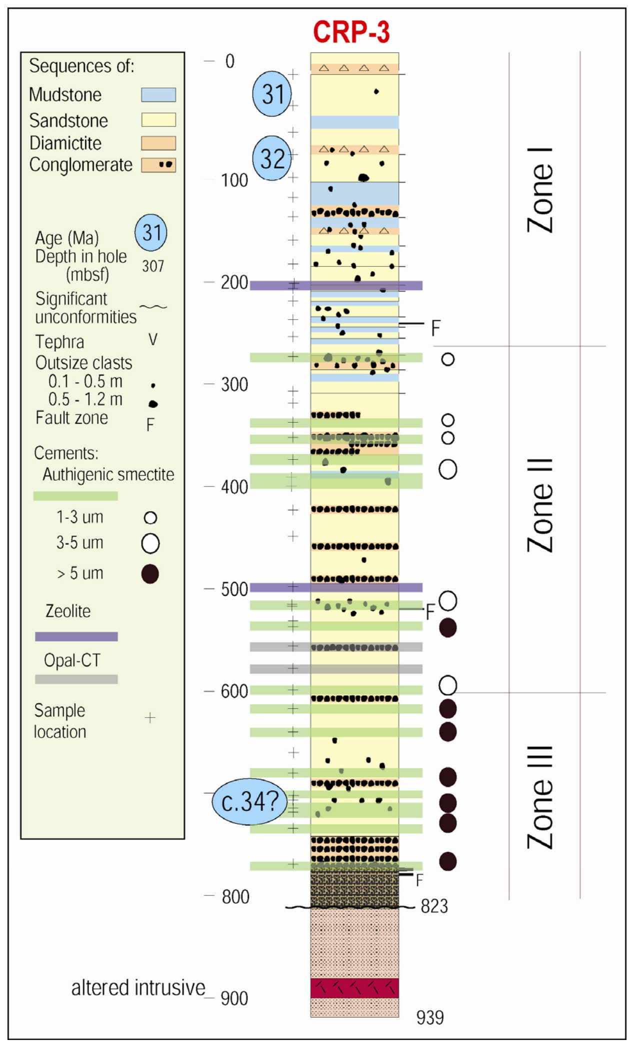

Figure 2. CRP-3 lithologic column, sample locations, and zones showing progressive authigenic-smectite development down core (green), zeolite (purple), and opal-CT (gray).

Methods

To gather further evidence on the distribution and origin of the authigenic clay and associated diagenetic minerals in CRP-3, we re-sampled the marine sequence at approximately 20-m intervals and examined 46 fracture samples from 22.40 to 902.26 mbsf in a Jeol 5900 SEM with attached EDS following standard procedures (see Plate 1 for details).

Results

The results, documented in over 500 SEM micrographs supplemented by examination of 70 thin sections, are summarized in Figure 2. Plate 2 gives our detailed observations as a data table.

The sequence can be subdivided into three zones according to clay content (Fig. 2) as follows:

Zone I (22.40 – 281.79 mbsf) clays are predominantly detrital in origin. The dominant lithologies of the sediments in this zone are mudstones, sandy mudstones, and diamictites.

Based on the criteria of Wilson and Pittman (1977), virtually all samples within Zone I contain detrital clays except at 205.11 mbsf where zeolites of the clinoptilolite/heulandite group are the only cementing agent in an otherwise clean, well-stratified sandstone (Fig. 3). The first recognizable authigenic clay occurs at 221.17 mbsf. Most clay at this depth is clearly detrital, but there are patches of authigenic clays displaying their characteristic morphology with thicknesses from basal (< 1μm) to 1 μm. These may have been transformed from pre-existing clay, rather than neoformed.

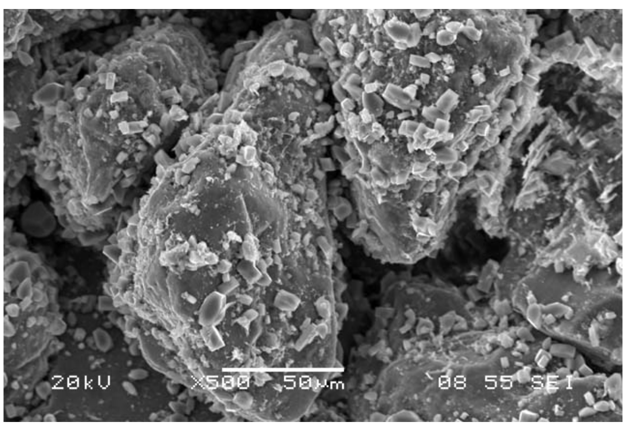

Figure 3. 205.11 mbsf: Electron micrograph showing extensive zeolite cement on quartz sand.

Zone II (281.79 – 621.79 mbsf) contains many intervals of authigenic clays 3-5 μm thick along with some intervals of detrital clays. Dominant lithologies of Zone II are well sorted, fine- to medium-grained sandstones with interlayered sandy mudstones.

The top of this zone at 281.79 mbsf is delineated by the first downcore occurrence of authigenic smectite *without* the presence of detrital clay. The absence of detrital clay strongly suggests that the authigenic clay formed without a detrital precursor. The smectite is not abundant, but instead occurs as patches on framework grains (Fig. 4). Even though the thickness of the smectite is only basal to 1 μm, the lack of preexisting clay argues for neoformation.

Of twenty-two Zone II samples, fourteen are cemented with authigenic smectite, five are bound by detrital clay, two at 560.23 mbsf and 584.48 mbsf are cemented with 2-3 μm opal-CT lepispheres (Fig. 5) and/or amorphous silica, and one is cemented with an unknown (zeolitic?) silica-rich material.

Zone III (621.79 – 781.27 mbsf) exhibits the thickest authigenic clays, *ca* 5-13 μm (Fig. 6). A few intervals also contain detrital clays. Excluding the authigenic clay, the lithologies of these sediments are clean, quartzose, fine- to medium-grained sandstones, some containing pebbly conglomerates. The main distinction between

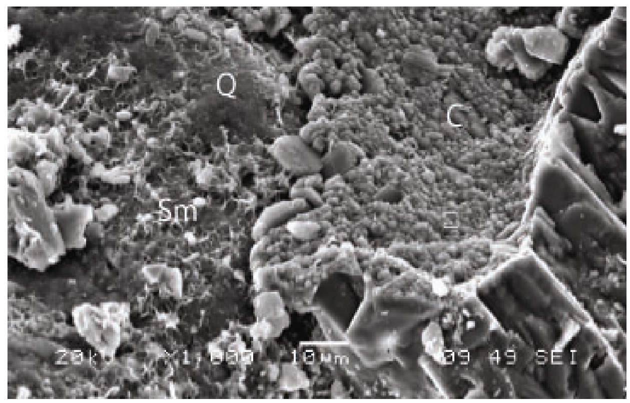

Figure 4. 281.79 mbsf: First downhole occurrence of patchy authigenic smectite (Sm), without detrital clays, on quartz sand (Q) along with calcite (C).

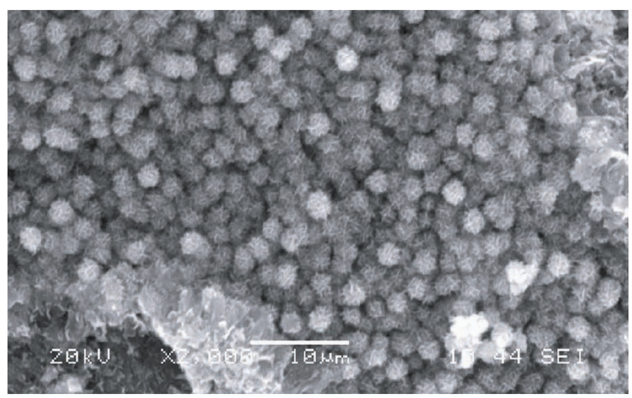

Figure 5. 560.23 mbsf: Opal-CT lepispheres *ca*. 3 microns in diameter are the only cement in this sample.

Zones II and III is the thickness of the authigenic-clay coats, which in the latter consistently exceeds 5 μm. Eight Zone III samples contain authigenic smectite and three detrital clay. Some important trends were observed with respect to the occurrence of authigenic smectite and the abundances of detrital minerals and volcanic lithic fragments.

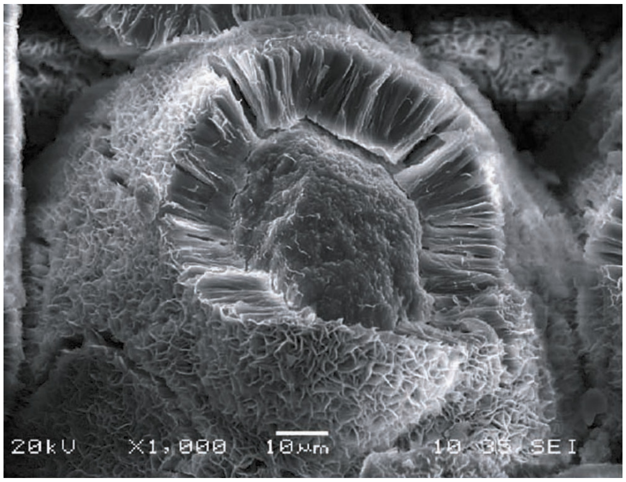

Figure 6. 773.76 mbsf: Authigenic smectite surrounding a quartz sand grain. The thickness and morphology indicate the clay is well-developed, which is typical for Zone III.

Based upon data from Smellie (2001, Tab. 1), where detrital minerals are few to absent clay coats are thinnest (e.g. 518.33 mbsf). As the percentage of these detrital minerals increases significantly downcore, however, clay coats thicken (~10 µm). The abundance of basaltic lithic grains changes in a pattern similar to that of the detrital minerals, with the greatest amounts below 600 mbsf (Smellie, 2001). Hence, detrital minerals and basaltic grains may have provided a substantial source of cations and/or silica necessary for smectite authigenesis.

Discussion

Our SEM investigation of samples from CRP-3 clearly illustrates the occurrence and distribution of authigenic smectite within the core, the apparent trends of which are generally similar to those identified by Ehrmann et al. (2005) via x-ray diffraction.

There is a considerable divergence of opinion in the literature, however, as to the mechanism responsible for the formation of the authigenic smectite and how high it extends in the core. Ehrmann et al. (2005) and Setti et al. (2004) argue that hydrothermal activity was the dominant mechanism for forming the authigenic smectite, whereas Wise et al. (2001) and the present study support *low-temperature burial diagenesis*. Setti et al. (2004, tab. 1b) also report authigenic smectite high in the core at 154.45 mbsf, but our SEM observations in that vicinity show no such evidence. The shallowest occurrence of authigenic smectite without the presence of detrital clay (i.e., clearly *neoformed* smectite) noted in the present study is at 281.79 mbsf, hence the authigenic smectite reported by Setti et al. may have been *transformed* from existing detrital clay.

In order for authigenic smectite to form, certain conditions must be met. These include: 1) a source of silica, 2) a source of cations such as Al, Fe and Mg, 3) appropriate temperature/pressure conditions, 4) time for the dissolution-diffusion-precipitation reaction to proceed, and 5) accommodation space along with fluid flow to replenish cations; i.e., pore volume and permeability.

Burial diagenesis is the least complicated and most likely of the models proposed to date to explain the presence of our authigenic smectite. To argue the case for burial diagenesis, the silica and cation sources must be present *in situ*. Some of the sources of silica possibly include volcanic material from the Ferrar Supergroup or siliceous microfossils such as diatoms, which are no longer present within CRP-3 below about 208 mbsf apparently due to diagenesis.

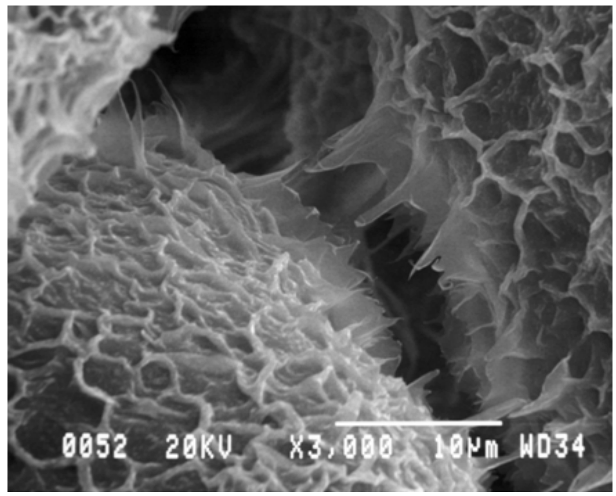

Figure 7. In contrast to Figure 6, this Zone II sample at 518.33 mbsf shows a poorly-developed clay coat.

We further suggest that the conditions necessary for burial diagenesis had been achieved at least below 281.79 mbsf. Therefore, with time, temperature, pressure, and precursor material permitting, the only limiting factor that could prevent the precipitation of authigenic smectite was pore volume and permeability. As discussed in detail by Wise et al. (2001, pg. 289), our results further demonstrate the spatial associations between abundant authigenic smectite, formerly clean sandstones, and high permeabilities. Low permeabilities below 600 mbsf (Fig. 8) are likely attributable to the well-developed clay coats and extensive carbonate cementation. There is also a spatial association between the amount of detrital minerals and basaltic lithic grains, and authigenic smectite development, suggesting appropriate precursor detrital materials were necessary for *in situ* burial diagenesis.

Maximum temperatures within CRP-3 could not have been more than about 60-80^{o} C, otherwise smectite would have begun to convert to illite (Bjørlykke and Aagaard, 1992). However, Velde (1995) states that trioctahedral smectite (akin to the authigenic smectite in this study) can begin to convert to a mixed-layer smectite/chlorite (S/C) phase near 50° C. Mixed layer S/C is not present according to the data of Ehrmann et al. (2005). Also, organic-walled dinoflagellates observed at the bottom of the section have retained their natural color, meaning they had not entered the oil-generating window of 75° C (Wise et al., 2001). Further supporting evidence for low temperatures comes from the lack of albitization, which occurs at 80-95° C (Velde, 1995). There was ample time for authigenesis to proceed from 30 Ma until terminated by Neogene glacial erosion at either 15 or 2.5 Ma as indicated by the hatch-marked pattern in Figure 9.

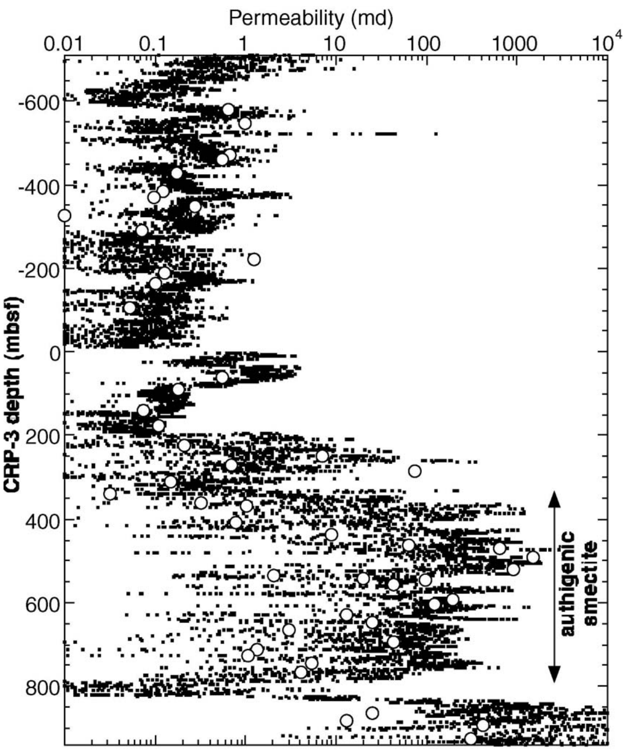

Figure 8. Permeability profile for CRP-3 (0-800 mbsf) (from Wise et al., 2001, fig. 7); circles represent discrete sample measurements.

Considering the amount of time the sediments resided at depth, it appears that elevated temperatures did not play a major role in the authigenesis of the CRP-3 smectites, and other conditions, such as available precursor material, porosity, and permeability, were the more important factors in authigenic smectite formation.

Conclusions

1. The requirements for authigenic smectite emplacement were met below 281.79 mbsf wherever sandstones had sufficient primary porosity and permeability.
2. There is an apparent correlation between well-developed authigenic smectite and the abundances of mineral detritus (i.e. K-feldspar, pyroxene, and plagioclase) and basaltic lithic fragments that could easily explain the cation source.
3. There was also an ample time window (from 13-28 Ma) in which to precipitate smectite even at the relatively low temperatures that apparently prevailed in the basin, hence the necessary time/temperature/pressure conditions could be fulfilled, which argues favorably for low-temperature, in-situ burial diagenesis.

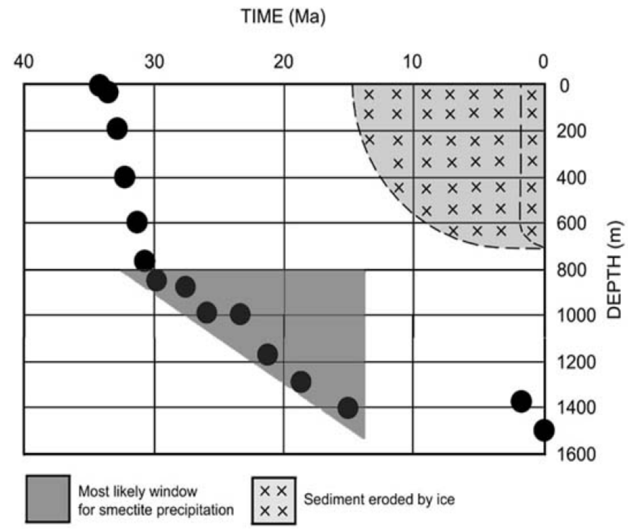

Figure 9. Time-depth diagram showing likely window for smectite authigenesis (solid) prior to major glacial erosion (hachured) (from Wise et al., 2001, fig. 9).

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