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The worm gut; a natural clay mineral factory and a possible cause of diagenetic grain coats in sandstones

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Abstract

Using a series of experiments, we show that the formation of clay minerals can occur biologically via the processes of sediment ingestion and excretion by worms. Specimens of lugworm, *Arenicola marina*, were fed a mixture of coarse grained quartz sand and unweathered, finely crushed Icelandic basalt in experimental tanks that simulated an intertidal, shallow-marine, sedimentary environment. Faecal casts as well as the starting material and samples from a control tank, collected and separated into < 2 μm fractions, were analysed using X-ray diffraction and Fourier Transform Infrared spectroscopy. The faecal samples were found to have lost plagioclase feldspar due to dissolution and to contain new clay minerals (kaolinite, illite and a 14 Å clay) not present in the original or control samples. The experiments show that macrobiotic ingestion processes induce rapid clay growth. These clays coat sand grains and may be the precursors to porosity-preserving chlorite coats found in sandstones.

Keywords: Clay mineral; Faecal cast; Lugworm; FT-IR; Weathering

1. Introduction

Animals use and rely on sediment in a variety of ways: as dwellings and habitats, for protection, and also as direct food sources. Nearly all infaunal macrobiota ingest sediment, either directly to gain nutrition from the organic coatings or else because their mouth parts are incapable of differentiating organic from inorganic particles. Worms have lived on Earth since the late Precambrian and are some of the most prolific and important organisms alive today. Initially the formation of clay minerals was considered to be an inorganic process although recent work has addressed the effect of microorganisms on these processes. There has been negligible focus on the effect of higher organisms on weathering. Here we report on an investigation of the effects of mineral digestion by marine worms and show that clay minerals are rapidly produced in the guts of the common lugworm (*Arenicola marina*).

2. Methods

The effects of sediment ingestion on mineral assemblages were tested using an experimental protocol with controls, experiments and blanks, utilising X-ray diffraction (XRD) and Fourier Transform Infrared spectroscopy (FT-IR). We have already shown that digestion affects sand fabrics since excreted sand grains tend to have a newly formed layer of clay adhering to

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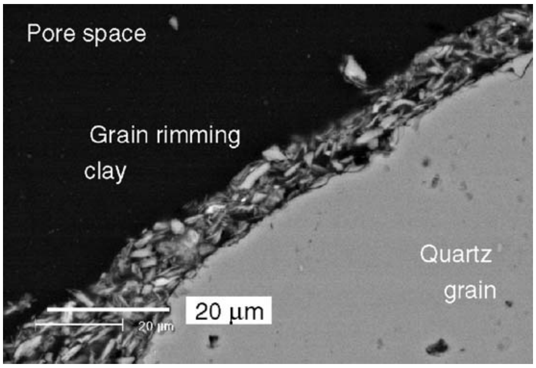

Fig. 1. SEM image of a polished section of an experimental cast sample. The once clean quartz grain has acquired a clay rim due to digestive processes (Needham et al., 2005).

their surfaces (Fig. 1 and Needham et al., 2005). The question now is whether this process affects mineralogy. The specimens of *A. marina* lived in, and ingested, unweathered clay mineral-free basalt interlayered with pure modern aolian quartz sand in oxygenated sea water tanks, over a ten week period (see Needham et al., 2004 for experimental methods). Samples of the original basalt and control tank samples were collected for analysis. Faecal cast samples were also collected from the sediment surface of the experiment tank. No specific worm food was added to the tanks; the worms survived on organic matter on the aeolian sand grains and micro-fauna in the seawater.

Original, control and cast samples prepared for XRD analysis were washed and separated into a < 2 μm fraction by centrifugation. The clay suspensions were air dried on glass slides to produce oriented mounts for XRD analysis. These samples were subsequently glycolated to assess if smectite minerals were present. The suspensions were also frozen and freeze-dried. Clay powders were weighed and mixed in defined quantities (~0.2 mg sample to ~200 mg of KBr) and ground with KBr to produce pressed pellets for FT-IR spectroscopy. Original, control tank and worm cast samples were all treated in exactly the same way prior to analysis to facilitate comparison. All XRD and FT-IR traces are entirely equivalent; no quartz was introduced to the < 2 μm fraction cast samples from the aeolian sand since this: (1) was singularly coarse grained sand and (2) no quartz was found in the original basalt–quartz mixture (see later).

3. Results

The original basalt fed to the worms was dominated by plagioclase, olivine and pyroxene. XRD traces of the < 2 μm fraction of the basalt show no clay minerals of any sort in the initial basalt (i.e. no sericitic alteration observed, Fig. 2a). XRD results showed significant changes in the worm faecal casts when compared to both the original material fed to the worms and material from control tanks (no worms, Fig. 2a). Original minerals

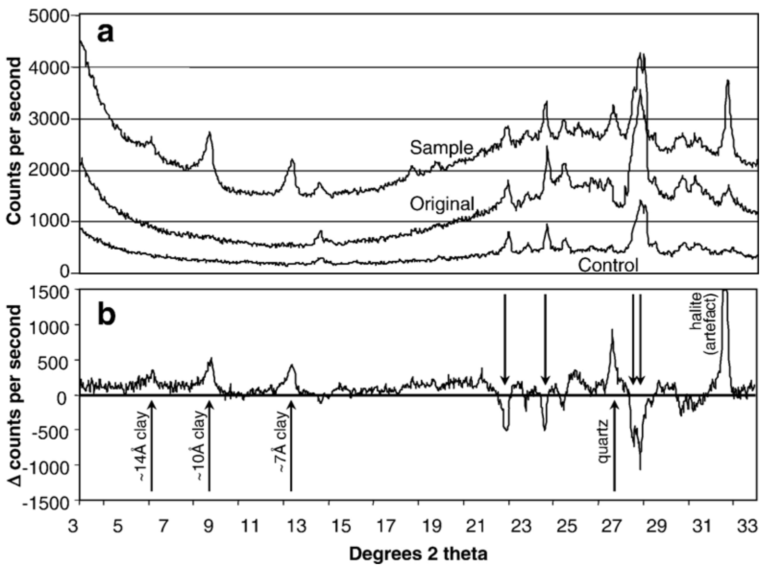

Fig. 2. XRD traces (a) <2 μm fraction samples from the original basalt–sand mixture, a control tank sample and a faecal cast sample from *A. marina* (lugworm). (b) The control tank sample XRD trace has here been digitally subtracted from the faecal cast trace to highlight small-scale changes. There are multiple positive peaks (up-arrows) relating to clay mineral and quartz growth. Dissolution (down-arrows) of parent plagioclase, pyroxene and olivine is recorded as negative peaks.

dissolved and new clay minerals, or 'bio-clays', precipitated. An original material XRD trace was digitally subtracted from faecal cast traces in order to highlight small-scale changes. The subtracted XRD traces reveal net mineral growth as positive peaks and yet there are also negative peaks that represent net mineral dissolution (Fig. 2b). Note that the control tank sample has no discernable clay mineral XRD peaks (Fig. 2) suggesting that there is no alteration of the basalt in the absence of worms above the detection limit of XRD.

Plagioclase dissolution is represented by XRD negative peaks in the 27–28° 2θ region (Fig. 2b) although negative peaks also represent dissolution of pyroxene and olivine. Significant changes occur in the 2–20° 2θ region (Fig. 2) of the subtracted XRD trace where new clay mineral 'positive' peaks appear. Clay minerals, not present in the < 2 µm fraction in either the original or control material, must be the product of worm digestive processes. The most significant XRD peaks represent clay mineral basal spacings of ~7, ~10 and ~14 Å. These basal spacings could represent a combination of chlorite, muscovite (illite), smectite and kaolinite, as well as a variety of mixed-layer clay minerals. In the cast sample there is also a pronounced XRD peak at 26.6° 2θ which probably represents growth of quartz in the < 2 µm fraction. Even in the < 2 µm fraction, precise clay mineral identification and quantification are not easy using XRD and the peak at ~14 Å proved particularly hard to interpret although it is likely to be either vermiculite or chlorite.

FT-IR, more sensitive than XRD to the small quantities of clay minerals produced in the experiments, proved ideal for mineral identification and quantification and so helped to define the bio-clays. A control FT-IR trace was digitally subtracted from faecal cast FT-IR traces to highlight mineral dissolution and precipitation. The subtracted IR spectra (Fig. 3) showed the development of numerous, new mineral bands in the worm casts; many of them representing clay minerals. In this case, the spectra were recorded as percentage transmittance so that relative mineral growth is represented by 'negative' bands and mineral dissolution as 'positive' bands. The IR spectra show the development of new bands not present in the original and control at 3695 and 3622 cm^{-1} typical of kaolinite. Comparison to standards of known concentration revealed that there was up to about 1% neoformed kaolinite in the basalt worm cast. The band at 3622 cm^{-1} has a broad shoulder suggesting the occurrence of illite (also corroborated by bands at 911, 828, 531, and 472 cm^{-1}; Fig. 3), in accordance with the 10 Å peak shown by XRD (Fig. 2). The bands at 800, 780, 400 and 376 cm^{-1} (Fig. 3) are compatible with the growth of quartz, thus corroborating the XRD data (Fig. 2). Since quartz was not found in the original basalt < 2 µm fraction, it must also result from worm digestive processes. The FT-IR traces also support the XRD data

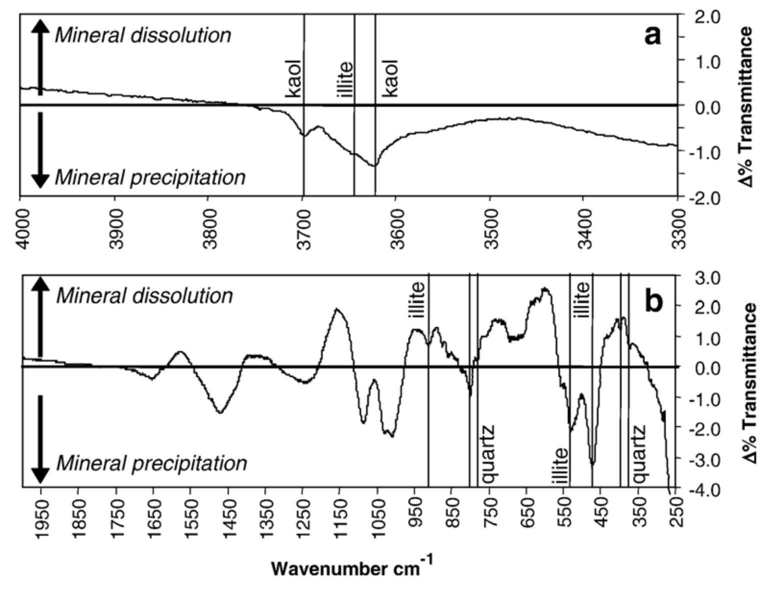

Fig. 3. FT-IR spectra of a lugworm faecal cast with a spectrum from the original material subtracted from a faecal cast spectrum. Mineral growth is recorded as negative bands and dissolution as positive bands. (a) In the 3000–4000 cm^{-1} region (O–H stretching) bands at 3695 and 3622 cm^{-1} are due to kaolinite. There is a broad shoulder on the band at 3622 cm^{-1} indicating that illite is present. (b) Spectra in the 250–1200 cm^{-1} region show mineral growth at 877, 531, 472 (illite) and 800, 780 cm^{-1} (quartz). The positive bands are due to plagioclase dissolution.

with the relative removal of plagioclase feldspar and pyroxene.

4. Discussion

Using XRD and FT-IR on the < 2 μm fraction we have shown that new bio-clay minerals precipitate as a result of sediment ingestion and excretion by annelid worms. The 10 Å XRD peak has been confirmed as illite and the 7 Å peak has been confirmed as kaolinite by FT-IR. The remaining XRD peak at 14 Å is plausibly due to vermiculite although it could also be chlorite. Basalt weathering is normally considered to occur on a timescale of tens to many thousands of years so that alteration in a matter of weeks is much faster than has been reported previously.

Since the neoformed clay minerals produced are similar to the natural, expected weathering products of a basaltic parent material, it seems likely that the worms catalyse an intrinsic chemical weathering reaction due to a combination of low gut pH and a reducing environment, mechanical grinding movements, as well as the presence of enzymes and bacteria in the guts of higher organisms.

Comparison of our results to those of experiments on the rate of inorganic basalt alteration (Gislasson and Oelkers, 2003) can be made using a number of assumptions; reaction over ten weeks, at low temperature (~7 °C), in mildly acidic conditions (pH ~5) for material with a surface area of ~2000 cm^2/g. The rate of transformation in the guts of worms is at least 100 times faster than in abiotic conditions. However, this is a very cautious estimate since we have here compared the experimental rate of abiotic *dissolution* to the rate of biogenic mineral *precipitation*. Moreover, the sediment has not spent ten weeks permanently in the guts of worms; the actual time spent inside the worm's guts is likely to be much less than ten weeks. Clay minerals have been reported to form due to bacterial processes (e.g. Konhauser and Urrutia, 1999) although the rate of macrobiotically induced processes reported here seems to be faster than microbiologically induced processes that would be on-going in the control tank.

Chlorite and illite coats on sand grains probably do not form directly during deposition but can be the result of burial diagenetic transformation of precursor clay mineral rims (Aagaard et al., 2000). When worms eat sand-clay grade mixtures, previously clean sand grains acquire a rim of clay (Fig. 1). It is possible that chlorite and illite precursor minerals develop in the guts of worms, form rims to sand grains and then get transformed into chlorite or illite coats during burial diagenesis. Chlorite grain coats can maintain sandstone porosity and permeability to abnormally great depths by inhibiting growth of quartz cement whereas illite grain coats block pore throats and encourage quartz grain pressure solution (Worden and Morad, 2003). Animal–sediment interactions may thus have profound effects upon consequent sandstone reservoir quality.

5. Conclusions

1) Sediment ingestion and excretion processes represent a newly discovered way in which clay minerals form in sandstones.
2) The production of clays during ingestion by worms is at least two orders of magnitude faster than inorganic reactions.
3) Biogenic clay rims may transform into reservoir quality-influencing clay coats during burial diagenesis.

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