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Rockmagnetic Characterization of the Setana and Chiraigawa Formations in SW Hokkaido (Soebetsu River, Kuromatsunai)

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ABSTRACT

Rockmagnetic investigations were conducted on sediments constituting the upper part of the Setana Formation and the Chiraigawa Formation, of Plio-Pleistocene age, exposed along the Soebetsu River in the vicinity of Kuromatsunai town, Hokkaido. Average mass-specific low-field magnetic susceptibility (χ) had the lowest value (15.2×10^{-8} m^3kg^{-1}) at one site in the Kuromatsunai Formation, but higher values represented by wide ranges of $(26.1–132.2) \times 10^{-8}$ m^3kg^{-1} and $(135.6–870.1) \times 10^{-8}$ m^3kg^{-1} characterized the Chiraigawa and Setana Formations, respectively. Magnetomineralogical analyses by isothermal remanence (IRM) acquisition, Curie temperature determinations, and electron microscopy aided with energy dispersive X-ray analysis suggest the presence of several types of magnetic minerals: (i) one of a soft coercivity phase, probably a Ti-poor magnetite, with a Curie temperature of ca. 535–555°C, occurring throughout the section; (ii) one of intermediate coercivity, relatively rich in Ti (ca. 10% by weight), with a Curie temperature of ca. 460–475°C, restricted to two relatively thin layers of the Chiraigawa Formation, each several tens of cm thick; and (iii) a hard-coercivity hematite-like and/or a very-hard-coercivity goethite-like phase contributing up to 0.5–5% of the saturation IRM acquired at 2.5 T. Combined use of susceptibility and several ratios or differences derived from IRM acquisition data, bi-plots of IRM vs. χ, and magnetomineralogical inferences were used to discriminate rockmagnetic zones within the Soebetsu River Section. Similar rockmagnetic analyses have proven to be effecive for mapping as well as for lithostratigraphical correlations of geological sections. Combined use of these rockmagnetic zones with other environment/climate proxy data may prove effective in paleoenvironmental reconstruction.

Keywords: Magnetic susceptibility, Rock magnetism, Curie temperature, Setana Formation, Hokkaido

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INTRODUCTION

The Kuromatsunai district in SW Hokkaido, especially the Setana Formation (SF), has been the object of renewed geobiological studies because of a rich fossil record (molluscs, foraminifera, calcareous nannofossils known for decades [1–3] and diverse species of bryozoans discovered recently [4–5]) well preserved in marine sediments deposited during varying (e.g., subarctic to cool-temperate [1]) paleoclimatic conditions during Early to Late Pleistocene times [2, 3]. The Soebetsu River in the vicinity of Kuromatsunai town has good exposure of a section ca. 8 m thick, comprising the topmost part of the Kuromatsunai Formation (KF), > 6 m of highly fossiliferous sandy sediments (mud content 7–13%, except in the topmost and bottom parts [3]) of SF, and ca. 1.8 m thick relatively fine but less fossiliferous sediments, possibly deposited in a lacustrine environment, of the Chiraigawa Formation (CF). The SF portion in the Soebetsu River section is known as the Soebetsu Member, and its age has been bracketed to 1.0–0.6 Ma (upper Setana Formation) primarily on the basis of nannofossils [3].

Studies of remanent magnetization recorded by rocks and natural sediments occurring near the Earth's surface, rocks recovered from marine sections, or sea-floor magnetic anomalies over the entire globe have revealed that the Earth's magnetic field (EMF) remained in essentially a normal polarity state (except for several very short-duration reversal events, or excursions) from 0.78 Ma to the present, a period termed the Brunhes Normal Polarity Epoch [6]. During the preceding 2.58–0.78 Ma period, the Matuyama Reverse Polarity Epoch, the EMF was predominantly in the reverse state, except for several short periods such as the Jaramillo Event (1.07–0.99 Ma) and Olduvai Event (1.95–1.77) characterized by normal polarity. In view of the 1.0–0.6 Ma age [3] assigned to the upper Setana Formation, we expected the Soebetsu Member sediments to contain a reverse-polarity remanence in the lower part followed by normal polarity in the upper part, whereas the Chiraigawa Formation, supposedly dating after ca. 0.6 Ma, should contain essentially normal polarity.

The present study was initiated with two objectives: (i) measurement of fundamental rockmagnetic parameters, such as magnetic susceptibility and isothermal remanence, with the purpose of discriminating rockmagnetic zones that could be used for effective regional mapping, lithostratigraphic correlation, and possibly paleoenvironmental/climate interpretation; and (ii) determination of the magnetic

Fig. 1 Geological divisions of the area in and around Kuromatsunai, adapted from [3]. The star indicates the location of the Soebetsu outcrop that exposes the upper part of the Setana Formation and the Chiraigawa Formation. The Setana Formation consists mainly of fine sandstone, with abundant molluscan fossils, nannofossils, and fossil bryozoans.

mineralogy and magnetic parameters that could be used to judge the stability of remanence in samples to be used for magnetostratigraphic study aimed at magnetic polarity determination and thereby dating. This paper gives a brief overview of the rockmagnetic investigations, whereas the magnetic polarity stratigraphy and aspects of the magnetic fabric, currently being studied, will be presented elsewhere in the near future.

SAMPLING AND MEASUREMENT DETAILS

Sampling performed along the Soebetsu River involved the collection of oriented samples (st0–8, sc1 –12) for determining directional and/or scalar properties (magnetic polarity and magnetic fabric), and non-oriented samples (s1–55) at discrete intervals for determination of scalar quantities (refer to lithologic column in Fig. 4 for sampling levels). From each non-oriented sample, collected in a polyethylene bag, three specimens were obtained using nonmagnetic cubic plastic boxes, each 7 cc in volume. Magnetic susceptibility and its frequency dependence and IRM magnitudes were measured on both oriented and non-oriented specimens in 7-cc boxes and recalculated to a mass-specific basis. Thermomagnetic analyses (high-field remanence or magnetic susceptibility vs. temperature) were made on small subsamples from a few levels. Measurements were made at Hokkaido University (Bartington MS2 system), JAMSTEC (2G Squid magnetometer or Natsuhara Spinner SSM89 magnetometer, and a 2G Pulse magnetizer), Kochi Core Center (AGICO KLY susceptibility bridge and a Natsuhara NMB-2000 thermomagnetic balance) and University of Tübingen (scanning electron microscope aided with an energy-dispersive X-ray system).

RESULTS OF MEASUREMENTS AND THEIR INTERPRETATION

Low-field magnetic susceptibility and frequency-dependent susceptibility

Average mass-specific low-field magnetic susceptibility (χ) at the base of the section, represented by black and green laminated silty clay attributed to KF, yielded (6.8–19.5) x 10^{-8} m^3kg^{-1} with an average of 15.2 x 10^{-8} m^3kg^{-1}. For the CF sites, predominated by mudstone, χ showed an intermediate range (26.9–132.2) x 10^{-8} m^3kg^{-1} with a mean of 72.0 x 10^{-8} m^3kg^{-1}. For the Setana Formation sites, the susceptibility range was (135.6–870.1) x 10^{-8} m^3kg^{-1} with an average of 72.0 x 10^{-8} m^3kg^{-1}. Hence, the three groups of sediments can be easily discriminated by measuring the magnetic susceptibility. Frequency-dependent susceptibility, defined as $\chi_{FD\%} = 100 \text{ x } (\chi_{LF} - \chi_{HF}) / \chi_{LF}$, where LF and HF represented 0.465 kHz and 4.65 kHz, respectively, was < 1.3% for the samples from the Setana Formation. These values indicate the absence of a significant amount of superparamagnetic or extra-fine magnetic grains in the Soebetsu Member sediments.

Isothermal remanent magnetization (IRM) characteristics

IRM acquisition and demagnetization experiments allowed discrimination of two groups of specimens throughout the section according to the values of the median acquisition field (MAF) and the median destructive field (MDF). The first group, represented by site st0 (the base of the section), all sites from SF, and most sites from CF (e.g., sc1–6 and sc8–9) yielded an MAF of 30–40 mT and MDF of 140–160 mT. The second group, represented by several sites (e.g., sc7 and sc11) from CF yielded an MAF of 80 mT and MDF of 440–480 mT. These data clearly suggest the predominance of a soft-coercivity mineral (s) throughout the section, with the exception of two thin layers that include sc7 and sc11, respectively, within the CF, where an intermediate-coercivity magnetic mineral occurs (Fig. 2). Unmixing of IRM by component analysis [7] helped to identify presence of two components in the first group and three components in the second group. Samples from sites st0, st4, and sc1 possess a soft

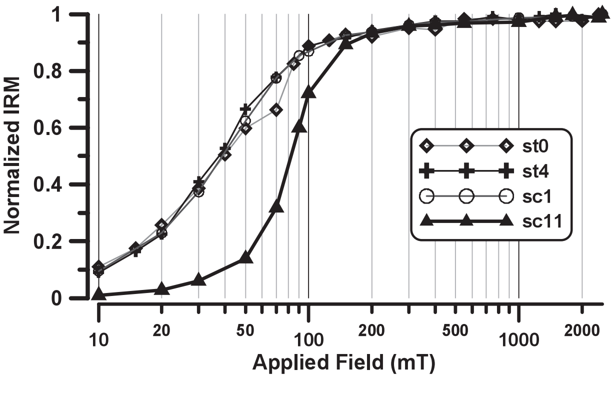

Fig. 2 Isothermal remanent magnetization (IRM) acquisition curves for four representative specimens (st0, the base of Setana Formation, probably the Kuromatsunai Formation; st4, Setana Formation; and sc1 and sc11, Chiraigawa Formation). The fact that more than 90% of the IRM is acquired by 300 mT suggests a dominant contribution of soft-coercivity (magnetite-like) minerals. For explanation, see text.

component (A), characterized by a medium acquisition field ($B_{0.5}$) of 30–40 mT with a logarithmic dispersion parameter (DP) of 0.32–0.35, that contributes to 96–97% of the total IRM, while the rest can be attributed to a hard hematite-like component ($B_{0.5}$ = 630 mT, DP = 0.20). In contrast, sc11 can be modeled in terms of three components [7]: (i) a soft-coercivity component, similar to that in other sites along the section, contributing to 15% of the total IRM, (ii) an intermediate-coercivity component characterized by ($B_{0.5}$ = 90 mT, DP = 0.12) with an 81% contribution, and (iii) a hard hematite-like mineral and/or very hard goethite-like mineral, which collectively contribute to the remaining 4% of the saturation IRM ($IRM_{2.5T}$).

Thermomagnetic analyses

The thermal behavior of high-field remanence and susceptibility of selected specimens were measured by cycling small amounts between room temperature and 700°C, in either a vacuum or an argon atmosphere to control probable oxidation. Measured data and derived curves for determining Curie temperatures are shown in Figs. 3 and 4. From remanence vs. temperature curves, it is evident that a magnetic mineral with a Curie temperature of ca. 535°C, probably a Ti-poor magnetite, is the dominant contributor in the first group of samples. Susceptibility vs. temperature curves (Fig. 4) show evidence of two types of magnetic minerals that possess distinct Curie temperatures estimated as Tc1 (ca. 460–475°C) and Tc2 (ca. 555°C) using the points that mark the beginning of the linear segments in the inverse susceptibility vs. temperature data and that represent the Curie or Neel temperatures of transition from ferromagnetic to paramagnetic behavior. The differences in the heating and cooling curves indicate thermochemical transformations leading to the formation of magnetic minerals with varying thermal-transition temperatures (Curie/Neel or decomposition temperatures).

Combined analysis of IRM, Curie temperatures and mineral chemistry

Combined with differences in the thermal variation of saturation remanence as well as low-field susceptibility, Ti-poor magnetite, with a Curie temperature of ca. 535–555°C appears to be the dominant magnetic mineral in the first group. A second magnetic mineral, believed to correspond to the intermediate-coercivity phase seen in the IRM acquisition plots, yields a Curie temperature of 460–475°C; it occurs in the second group of specimens.

X-ray analysis of a single opaque grain ca. 80 μm in size from specimen s7–2 (a specimen in the second group) showed the following chemical composition (in wt %): Fe, 47.38; Ti, 9.29; Al, 1.96; Mg, 0.89; Si, 0.78; S, 0.22; and the rest as O, 39.49. We assume that this relatively Ti-rich magnetic phase corresponds to the intermediate coercivity phase and is responsible for the contrasting behavior of the specimens belonging to second group and confined to the thin layers in CF. Apart from the soft and intermediate components, hard to very hard coercivity

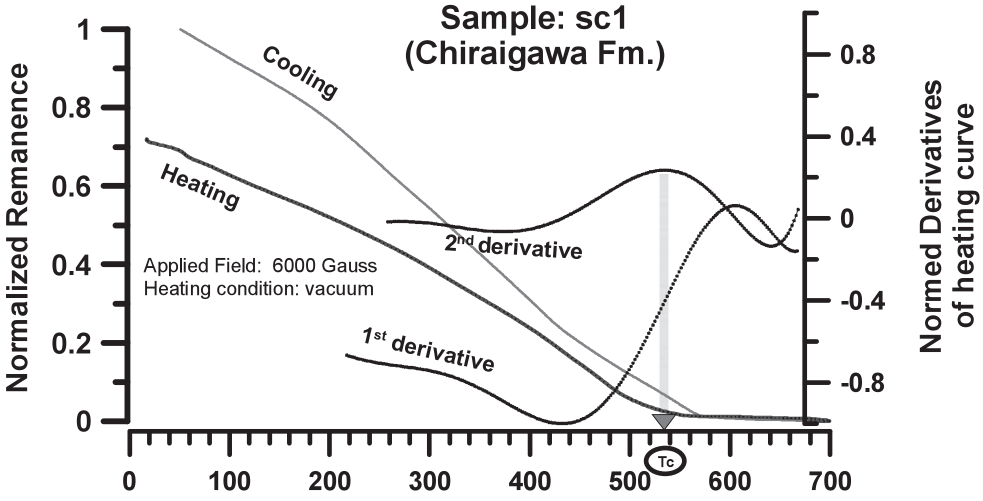

Fig. 3 Thermal variation in strong-field remanence (in a vacuum > 1 Pa) for a sample of the first group (see text). A Curie temperature of ca. 535°C was estimated as the temperature corresponding to maximum in the second derivative (i.e., the point of maximum curvature in the thermomagnetic curve during heating). A Ti-poor magnetite with this Curie temperature is probably the main magnetic mineral in most of the lithological column.

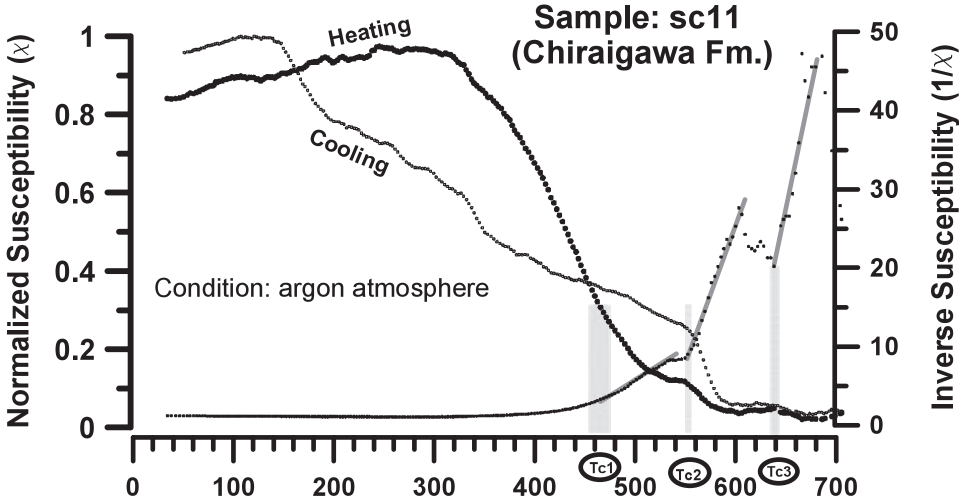

Fig. 4 Thermal variation of susceptibility (in an argon atmosphere) for the second group of samples (see text for details). At least two types of magnetic minerals that possess distinct Curie temperatures are evident. Temperatures (Tc1–3) corresponding to the beginning of the linear segments in the inverse susceptibility curve during heating are interpreted to correspond to Curie temperatures of the magnetic minerals present. Of them, Tc1 (ca. 460–475ºC) and Tc2 (ca. 555ºC) are inferred to be reliable estimates.

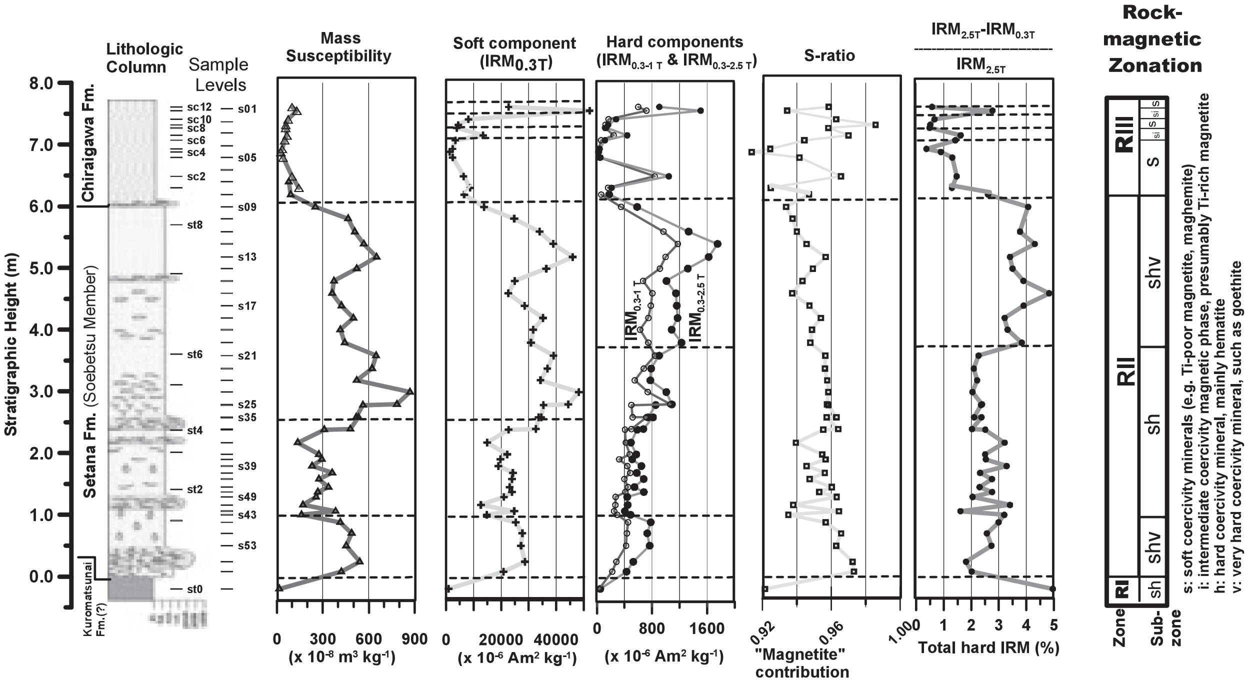

Fig. 5 Lithostratigraphic column along the upper Setana Soebetsu River Section in the vicinity of Kuromatsunai town, SW Hokkaido, with corresponding plots of rockmagnetic parameters. Rockmagnetic zonation deduced from these plots is shown at the far right.

phases (hematite and goethite) are responsible for several percent of the IRM magnitudes acquired above 0.3 T and persisting up to 2.5 T.

Rockmagnetic zonation

Several rockmagnetic parameters are plotted against the lithostratigraphic column in Fig. 5 in order to perform rockmagnetic zonation. Among these parameters, the soft component $IRM_{0.3T}$ actually includes also the so-called intermediate component present in samples from the two thin layers of CF. The S-ratio is the ratio of the soft component (remanence obtained after back-field demagnetization at –0.3T) to the total IRM contribution ($IRM_{2.5T}$). The hard components calculated as the differences IRM_{1T}–$IRM_{0.3T}$ and $IRM_{2.5T}$–IRM_{1T} roughly correspond to the contents of hematite-like and goethite-like phases, respectively. The total hard IRM is the sum of these two phases normalized to $IRM_{2.5T}$. Dotted lines separate intervals differing in the rockmagnetic parameters considered. Three zones (R1-RIII) can be discriminated by the susceptibility magnitudes, whereas the other parameters collectively discriminate the subzones marked with small-case letters (s, h, v, representing soft, hard, and very hard coercivity magnetic phases, respectively). The susceptibility vs. SIRM bi-plot shown in Fig. 6 allows rapid discrimination of some of the rockmagnetic zones and subzones. It is noteworthy that the rockmagnetic subzone RIIshv corresponding to the 3.5–6 m interval, which shows distinct enrichment in hard coercivity minerals, coincides with the cold time period inferred from isotopic variation of the benthic foraminifera *Cibicides refulgens* [8].

CONCLUDING REMARKS

Magnetic susceptibility, measured rapidly in situ or in the laboratory on samples collected at close intervals, effectively discriminates rock formations in the Kuromatsunai district. Although the susceptibility is determined by the total contribution of all mineral constituents (ferromagnetic, paramagnetic, and diamagnetic minerals) and also by the grain size of ferromagnetic minerals, in these magnetically strong sediments with input from volcanogenic sources, it is basically dictated by the concentration of Ti-poor magnetite. Further discrimination of lithostratigraphic intervals is possible by considering the susceptibility with saturation remanence (response of the total concentration of ferrimagnetic minerals), although measurement of saturation remanence requires collection of the sample, imparting an artificial remanence and measurement thereof. Detailed IRM investigations give a range of parameters that allow the discrimination of rockmagnetic zones based on subtle variations in magnetic mineral types, their concentrations, and so on. Our rockmagnetic investigations were effective in finding thin layers that could serve as regional key horizons, marked by a magnetic mineral with a relatively high amount of Ti and distinct coercivity, within the Chiraigawa Formation.

The Curie temperatures determined in this study are consistent with the range of 475–535°C reported from the eastern part of Toya Lake, situated about 60 km to the east, where the rock types are andesite lava, pumice tuff, and dark gray silt [9]. Similar values are evident from the thermomagnetic curves ob-

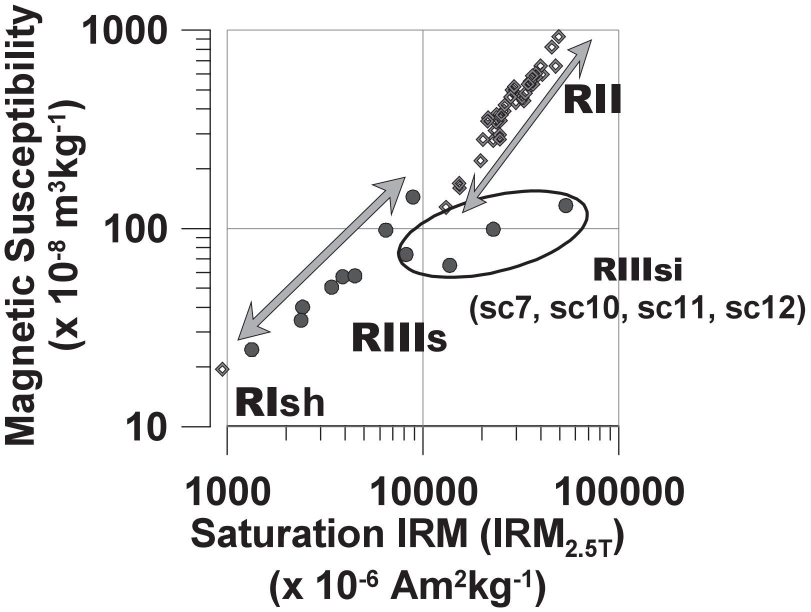

Fig. 6 Bi-logarithmic low-field magnetic susceptibility vs. saturation isothermal remanence (SIRM) plot and discrimination of rockmagnetic zones proposed on the basis of several parameters.

tained for pyroclastic deposits and lava from SW Hokkaido [10].

Minor variation in the proportions of different magnetic mineral phases (soft, hard, and very hard) reflected in the susceptibility and other rockmagnetic parameters observed in this study may be linked to many factors active during the period of deposition, such as variation in the supply of detrital magnetic minerals by rivers and winds, *in situ* formation of magnetic minerals by authigenic processes, degree of preservation or dissolution of magnetic grains, dilution effects (i.e. proportional reduction in the content of magnetic minerals owing to increase in the amount of biogenic carbonate and/or silica) all of which are intimately related to paleoenvironmental/climatic conditions [11].

Further interpretation will require consideration of these types of variation in the context of a detailed chronological framework as well as comparison with other paleoenvironmental/climatic proxy parameters.

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