The positive correlation between the average geomagnetic activity and the area of the filaments will be discussed elsewhere[10] where we suggest that it arises for two reasons. First, large filaments may produce more extensive disturbances in the solar wind which have a higher probability of intercepting the Earth. Second, the particle and magnetic flux densities within these disturbances may be greater. Whatever the details of the correlation, it is clear that some disappearing filaments signal the occurrence of geomagnetic disturbances. Therefore, as suggested by Joselyn and McIntosh[8], they should be incorporated into techniques that are used for the prediction of geomagnetic storms.

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Apparent correlation of palaeomagnetic intensity and climatic records in deep-sea sediments

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Most reports of a correlation between Pleistocene climate and geomagnetic field intensity rely strongly on the assumption that sediment natural remanent magnetic (NRM) intensity provides a record of geomagnetic field strength and is not sensitive to local changes in properties of the sediment. Critical assessment of relevant data presented here and elsewhere[1,2] from deep-sea sediment cores shows that a pronounced dependence of NRM intensity on sediment composition can occur which implies that this assumption is unlikely to be generally valid. As sediment composition often reflects varying depositional conditions induced by climatic change, the significance of correlations proposed between Pleistocene palaeomagnetism and climatic indicators in deep-sea sediments may be less dramatic than sometimes supposed.

A fundamental relationship between geomagnetic field behaviour and climate change has been suggested, largely on the basis of an apparent correlation in geomagnetic and climatic indices over time scales ranging from historical observatory records of geomagnetic intensity and air temperature[3] to the Pleistocene record of palaeomagnetic and palaeoclimatic data in deep-sea sediments[4,5]. Periods of low (high) geomagnetic intensity have been proposed to correspond to high (low) air temperature or warm (cold) climate. Suggestions for the underlying mechanism have included magnetic field interaction with the atmosphere thereby influencing climate[6], the distribution of ice affecting core motions and the geomagnetic field[7], or that there is some common causative agent, for example, variation in the eccentricity of Earth's orbit modulating both climate and the geomagnetic field[8–10]. A hypothetical magnetic trigger has even been entertained to explain climate change on Mars[11]. In view of the lack of consensus on a viable causal mechanism and the complexity of the two systems involved, it seems worthwhile to examine the nature of the reported empirical correlations to ascertain which lines of inquiry are likely to be productive or if they have so little observational basis that they will probably result in unproductive speculation. In this regard, Sternberg and Damon[12] found no statistically significant global relationship between geomagnetic intensity and climate over the period covered by direct observatory records.

Correlations between geomagnetism and climate over geological timescales are by necessity based on indirect records such as those obtained in continuously deposited deep-sea sediments. Deep-sea core RC11-120 from the southern Indian Ocean (lat. 48°31′S, long. 79°52′E) has one of the most complete and detailed records of climate change available for the past 250,000 yr[13] and proved suitable for magnetic study. The down-core variation of oxygen isotope composition (^{18}O) of planktonic forminifera, carbonate content ($CaCO_3$), magnetic susceptibility (k) and the intensity of stable NRM and its inclination direction are compared in Fig. 1. The ^{18}O variation is interpreted to reflect changes primarily in global ice volume and provides a climatic record which can be correlated worldwide[13,14]. The remanent inclinations are generally consistent with expected values for a normal polarity dipole field and show little indication of anomalous field behaviour except possibly for a long-term trend which is not considered here. The striking feature in all these data, however, is the close visual correlation of the ^{18}O, $CaCO_3$, k and NRM curves. The significance of these correlations bears directly on the question of geomagnetic–climatic relationships.

Although carbonate deposition is a complicated process with many controlling factors, a close association between carbonate content and climate has been recognized in many Pleistocene deep-sea pelagic sediments from early stages of research[15,16]. In core RC11-120, the high inverse correlation between ^{18}O and $CaCO_3$ ($r = -0.79$) indicates that high carbonate contents closely correspond to intervals of low global ice volumes. The same climatic interpretation of carbonate contents can be made

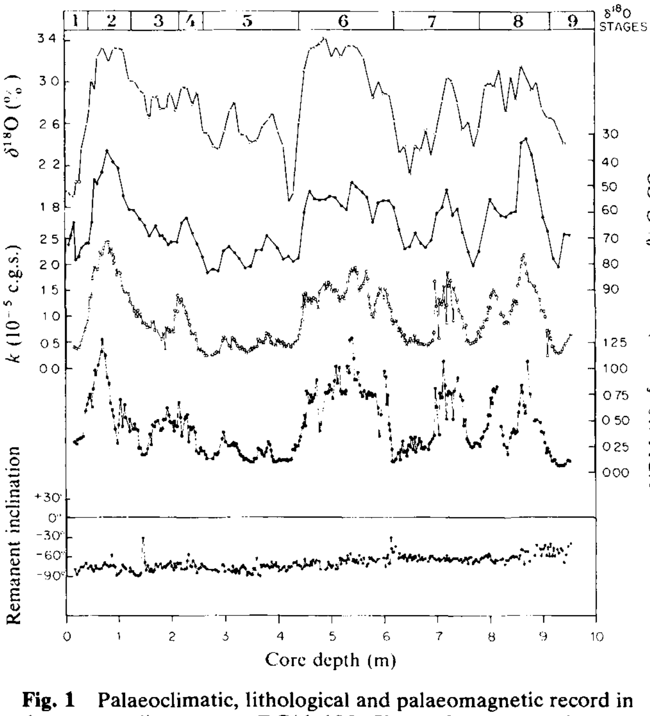

Fig. 1 Palaeoclimatic, lithological and palaeomagnetic record in deep-sea sediment core RC11-120. Shown from top to bottom are down-core logs of: *a*, oxygen isotope composition of planktonic foraminifera ($\delta^{18}O$)[13]; *b*, calcium carbonate content (% of $CaCO_3$, with scale inverted); *c*, magnetic susceptibility (k); *d*, intensity of NRM; *e*, the inclination direction of NRM. The intensity and direction of NRM are after alternating field demagnetization at 100 Oe to remove unstable magnetization component. The $\delta^{18}O$ values are interpreted to reflect primarily global ice volume and the record is subdivided into the stages shown at the top, odd (even) numbered corresponding to interglacial (glacial) intervals; the age of the stage 1/2 boundary is approximately at 9.4 kyr, stage 5/6 boundary at 127 kyr and the stage 7/8 boundary at 251 kyr[13].

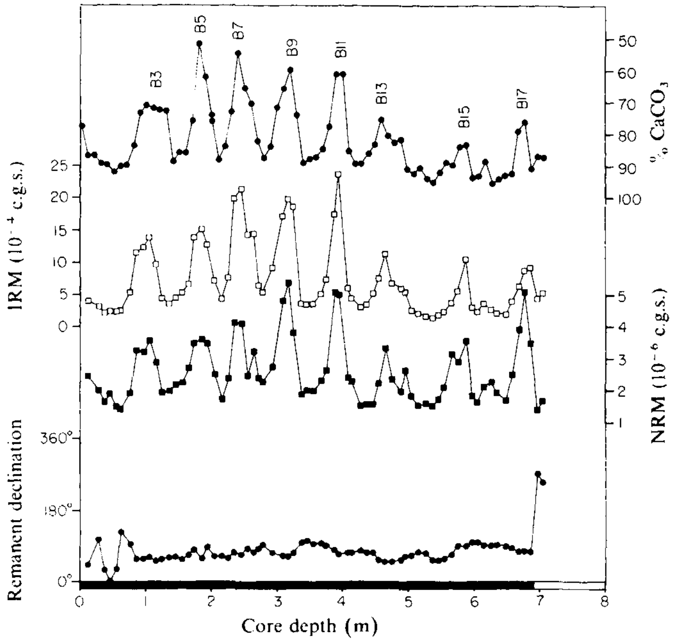

Fig. 2 Lithological and palaeomagnetic record in deep-sea sediment core RC11-209. Shown from the top are down-core logs of: *a*, calcium carbonate content (% $CaCO_3$ with scale inverted)[22]; *b*, IRM; *c*, intensity of NRM; *d*, the declination direction of NRM. The NRM and IRM parameters are after alternating field demagnetization at 100 Oe. The 180° shift in declination at 690 cm is interpreted as the Brunhes/Matuyama boundary, age 730 kyr. In this area of the world ocean, high (low) carbonate contents correspond to glacial (interglacial) intervals, for example, the carbonate low labelled B3 correlates to oxygen isotope stage 5 in Fig. 1.

for late Pleistocene sediments from the Atlantic, Caribbean, North Pacific as well as other areas of the Southern Ocean[17,18].

Factors likely to influence the intensity of NRM are the quantity of magnetic material, typically magnetite, in the sediment and the strength of the geomagnetic field at the time the remanence was acquired[19–21]. The good correlation between NRM intensity and the ^{18}O curve observed here ($r = 0.74$) may therefore signify a close relationship between geomagnetic field and climate, as has been suggested on the basis of similar comparison, assuming that variations in magnetic mineralogy can be discounted as an important contributing factor. The magnetic susceptibility provides a measure of the concentration of magnetic material and in this core is found to be highly correlated to NRM intensity ($r = 0.85$). The assumption that NRM intensity is simply related to geomagnetic field strength is therefore not supported. Moreover, although other non-calcareous but non-magnetic components are likely to contribute to the total sediment composition, for example biogenic silica and clay minerals, the high inverse correlation between k and $CaCO_3$ ($r = -0.93$) shows that to a good approximation the magnetic material occurs in fixed proportion to the non-carbonate fraction which in turn varies as the complement to the measured carbonate content in these sediments. In such circumstances, variations in magnetic susceptibility can be interpreted to have climatological significance, in an analogous manner to that ascribed to carbonate variations.

On the basis of these relationships, the observed correlation between NRM intensity and climate (for example, the ^{18}O record) can be largely accounted for as due to an intermediary lithological effect, that is, decreased carbonate contents during glacials result in increased concentrations of magnetic material which in turn contribute to higher NRM intensities. Absence of positive evidence for a correlation of geomagnetic field and climate change is apparent even using a more representative index of relative geomagnetic field strength, obtained by normalizing the NRM intensity of each sample by its magnetic susceptibility. The correlation between this palaeointensity index (NRM/k) and the ^{18}O climatic curve is negligible ($r = 0.04$).

Another example of how NRM intensity can be more dependent on lithology than geomagnetic field is seen in deep-sea core RC11-209 (lat. 3°39′ N, long. 104°4′ W). Previous litho-, bio- and magnetostratigraphical studies indicate that this core is representative of the Pleistocene sedimentary history of the equatorial Pacific[22]. Figure 2 shows a comparison of carbonate content, isothermal remanence (IRM, a parameter like magnetic susceptibility which is proportional to content of magnetic material) and NRM intensity values for the upper part of the core, down to the level marked by a 180° shift in remanent declination which is correlated to the Brunhes–Matuyama geomagnetic reversal[22], now dated at 730,000 yr BP (ref. 23). There is less detail than in core RC11-120 because of a lower deposition rate but the same kind of correlations can be seen over a longer time interval. High carbonate values in RC11-209 again generally correspond to reduced magnetic mineral contents ($r = -0.93$ for $CaCO_3$ versus IRM) which seem to account for reduced sediment magnetizations ($r = 0.86$ for IRM versus NRM). Even though an oxygen isotope climatic record is not available for core RC11-209, it is well known that high carbonate contents correspond to high global ice volumes or glacial intervals in Pleistocene pelagic sediments from the equatorial Pacific[16,22,24], exactly opposite to the phase relationship interpreted for carbonate variations and climate in southern Indian Ocean core RC11-120. Therefore, whereas high NRM intensities characterize sediments deposited during glacial intervals in one region (for example, RC11-120), high NRM intensities are associated with sediments deposited during interglacials in another (for example, RC11-209). This is a further indication that the assumption that NRM intensity provides a reliable record of geomagnetic field intensity change is suspect, since geomagnetic intensity and climatic variations are expected to have a similar phase relationship globally. Interestingly, a weak positive correlation ($r = 0.52$) between NRM/IRM and $CaCO_3$ is observed in RC11-209 which can optimistically be related to some geomagnetic–climatic dependency or more likely results from an inadequacy in the normalization by IRM to take into account fully the strong lithological effect on the NRM.

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