Ice Ages and Geomagnetic Reversals

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CANADA

1. Climatic Cooling related to Geomagnetic Reversals?

There have been speculations on the relationship between climatic cooling and polarity reversals of the earth's magnetic field during the Pleistocene (Kawai et al. 1975, Rampino 1981, Krishnamurthy et al 1986, and Jacobs 1984 for a review). Two of the common criticisms on this relationship have been the reality of these short duration geomagnetic events and the accuracy of their dates. Champion et al. (1988) have reviewed recent progress in this area. They identified a total of 10 short-duration polarity events in the last 1 Ma and 6 of these events have been found in volcanic rocks, which also have K-Ar dates. The nomenclature and the estimated ages for these events are shown on the top of Fig.1a. Events with age dated from volcanic rocks are shown as solid bars, those from sedimentary rocks as stippled bars. Also, typeface and size of the names represent the degree of confidence in the exact age or existence of that polarity event. Following Rampino (1981), the eccentricity of the earth's orbit over the past 1.2 Ma is also calculated (Berger 1977) and plotted with the stacked oxygen isotope data (with the SPECMAP time scale, Imrie et al 1984) at the bottom of Fig.1a.

An inspection of Fig.1a shows that during the last 600 ka, where the 100 ka cycle (due to eccentricity) was the dominant signal in the oxygen isotope data, magnetic polarity events seem to occur near times of maximum eccentricity and rapid glaciation, thus giving some support to a possible climate-magnetic reversal connection. For t > 600 ka, the correlation is not as good - although there is an apparent correlation between times of maximum eccentricity and the Kamikatsura event, the end of the Jaramillo and the Cobb Mountain event. If the ages of these older events are revised according to Shackleton et al. (1990), then all of these older events, except the Kamikatsura, appear to occur near eccentricity maxima (Fig.1b).

Anyhow, Champion et al. (1988) found that the mean of the polarity interval lengths (in Fig.1a) to be close to the 100 ka main orbital eccentricity period of the earth, they therefore suggested that linkage between geomagnetic, paleoclimatic and possible underlying earth orbital parameters should be further studied.
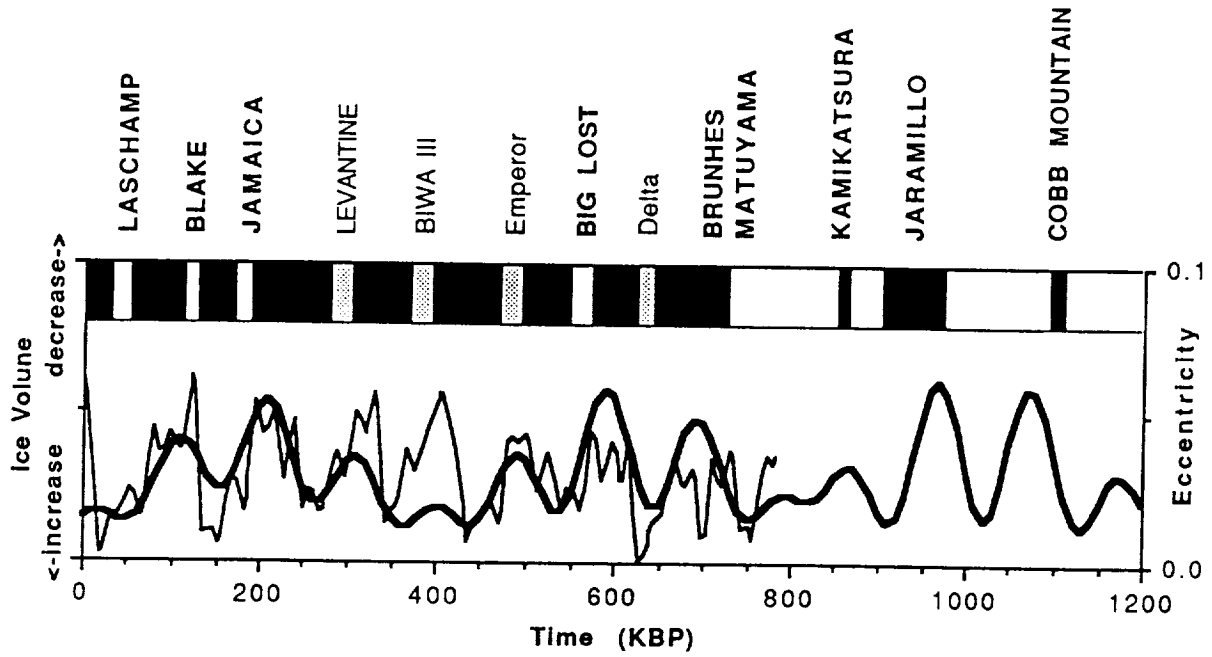
Fig.1a Correlation of the polarity events with the eccentricity of the Earth's orbit, and δO^{18} (ice volume) variation over the past 1.2 Ma.
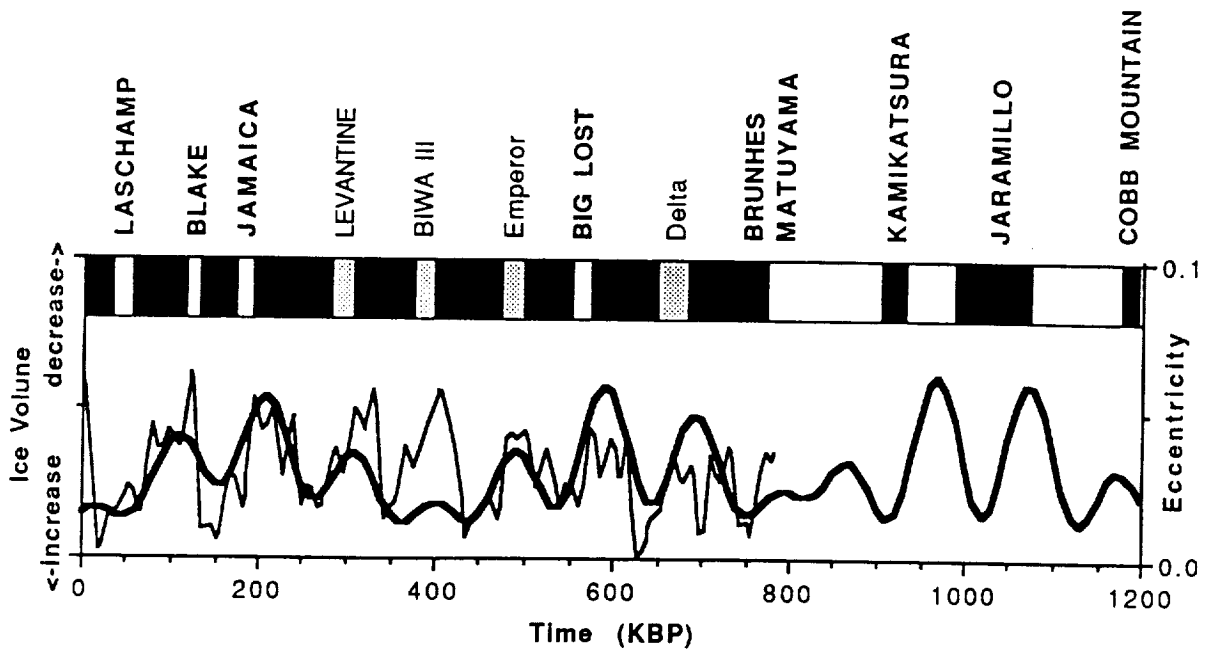

Fig.1b Same as Fig.1a, except ages greater than 600 ka are modified according to Shackleton et. al (1990)

2. Mechanisms that relate climatic cooling & Geomagnetic Reversals

Supposing that the speculated relationship between climatic cooling and geomagnetic reversals actually exist, two mechanisms that assume climatic cooling causes short period magnetic reversals will be investigated. It should be noted that this is NOT an attempt to explain the occurrence of ALL the magnetic polarity events in terms of glacial advances, for it is obvious that magnetic reversals has occurred throughout the history of the earth - even during times when there is no glaciation. Therefore, the mechanisms that we investigate operates only within the Pleistocene and it should be clear that other mechanisms, with different time scales, may be operative at the same time and they may be responsible for the reversals outside this epoch.

2.a Core-Mantle Boundary Topography

A possible mechanism results from the variation of topographic interaction across the core-mantle boundary (CMB). For example, the formation of large bumps or depressions at the CMB will set up Taylor columns in the core (Hide, 1969), disrupt the flow which drives the geodynamo and possibly change the geomagnetic field. The critical height for topographic coupling to be effective has been estimated to be around 1 km .

Gubbins and Richards (1986) have investigated the effect of thermal and subduction-induced topography and have concluded that both have the right magnitude to cause coupling. However, the thermal time scale is of the order of 100 Ma whereas changes in topography due to subduction is about 10 Ma. Since polarity reversals can occur several times in 1 Ma, there must be other phenomena which cause the short time scale variations in topographic coupling during the Pleistocene. Now, the period of a glacial cycle is about 100 ka and for a 3 km thick ice sheet, the depression at the earth's surface is about 1 km. Thus, depending on how rapid this deformation attenuates with depth, glacial induced topography at the CMB, if suitably located, may be able to enhance (or diminish) the coupling due to thermal and subduction-induced topography such that the total coupling can exceed (or fall below) the threshold value required to disrupt core flow.

The topography of the CMB due to glacial loads at the earth's surface has been calculated for 3 different earth models L1, L2 & L3 which has lower mantle viscosities of 10^{21}, 3×10^{21} and 10^{22} Pa-s respectively. The ice model consists of 3 centers of glaciation corresponding to the Laurentide, FennoScandian and Antarctic ice masses which has total mass equivalent to a sea level drop of 100 meters and whose glacial history consists of 30 cycles of glaciation, the last of which is plotted in Fig.2a. The result of this calculation is described in Wu (1990) which shows that the maximum topography occurs underneath the Laurentide ice center and the time variation of this maxima is shown in

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Fig.2c. In view of its smallness in height and its location relative to other topographic highs as deduced from seismic tomography, glacial induced CMB topography is not expected to be able to significantly modulate total coupling and modify core flow today.

2.b Transfer of Rotational Energy to the core

An alternate mechanism is the transfer of rotational energy into the fluid core: the redistribution of water masses during glaciation and deglaciation will cause the moment of inertia of the earth to change - for example, when water is taken from the ocean basins and is locked in the ice sheets near the pole, the moment of inertia will decrease. By the conservation of angular momentum, the decrease in the moment of inertia must be accompanied by an increase in the angular velocity of the mantle. If the increase in velocity at the bottom of the mantle exceeds the 0.03 cm/sec flow velocity in the fluid core (estimated from the westward drift of the non-dipole component), then the transfer of angular momentum into the core would disrupt the convective heat engine inside and possibly result in a change in magnetic polarity (Doake 1977, Muller & Morris 1986).

The change in velocity at the bottom of the mantle due to the simple glaciation/deglaciation model described earlier is plotted in Fig.2b. The solid line, the dotted line and the dashed line correspond to earth models L1, L2 and L3 respectively. The stripped area in the middle indicates that the velocity at the bottom of the mantle is below the preexisting flow velocity in the fluid core. From Fig.2b it can be seen that model L1 (and possibly L3 near glacial minimum) can produce velocity changes comparable to the existing flow in the core.

Given that a 100m change in sea levels can produce velocity changes at the bottom of the mantle to be comparable to the existing flow in the core, the next question concerns how energy is transferred from the mantle to the core. The mantle and the core can interact by electromagnetic coupling, viscous coupling and topographic coupling. If the roughness of the CMB exceeds the thickness of the viscous hydromagnetic boundary layer, then topographic coupling becomes the dominant mechanism . Although the topography induced by glacial loads has been shown to be too small to cause coupling, the topography due to density loads in the mantle exceeds the critical value and possibly provides the coupling mechanism to transfer rotational energy into the core to cause geomagnetic reversals.

3. Conclusion

In conclusion, the variation in CMB topography induced by the surface glacial loads has the correct time scale but not the amplitude, unless the maxima are suitably located, to significantly modify the total coupling mechanism and disrupt the flow pattern in the core resulting in geomagnetic field reversals. The transfer of rotational energy from the mantle to

the core via topographic coupling is a more likely candidate, provided that the change in sea level is of the order of 100 meters and the coupling is via thermal and subduction induced topography.

4. Questions and Future Work

More precise dates and the establishment of the reality of some polarity events (eg. the Emperor & Delta events) are required to establish/disprove the controversial relationship between climatic cooling and geomagnetic reversals. In the compilation of Champion et al (1988), some of the events have rather large uncertainties in their age, and, as shown in Fig.1, the correlation of some of the older events with eccentricity maxima depends critically on their age.

Opponents to a climate-magnetic reversal relationship often question whether polarity events observed in different parts of the world but with approximately the same age can be correlated and whether they correspond to the same global events. Another question is whether there are only 8 polarity events in the Brunhes, for, if more events are discovered, then there may be no correlation between polarity events and eccentricity maxima. Clearly, cores in different parts of the earth, with more complete record and dates are needed to answer these questions.

Even when the relationship between climate and magnetic reversals is established, the next question is which is the cause and which is the effect? If magnetic field is the cause, then the question is why they do not always cause climatic cooling (eg. during the Cretaceous)? If climatic cooling is the cause, then, are there other mechanisms?

A better seismic tomographic map of the CMB would confirm whether glacial induced topography can modulate total coupling and modify core flow. Glacial induced topography is rejected because, in seismic tomographic maps of the CMB (Morelli & Dziewonski 1987, Creager & Jordan 1986), no topographic hills/troughs seem to exist underneath Laurentia. These seismic tomographic maps are, however, not consistent with each other and therefore have some degrees of uncertainty in them.

More work is needed to understand the details of the core-mantle coupling mechanisms and how energy and angular momentum can be transferred from the mantle to the core.

Finally, even after this is achieved, questions still remain as to how this energy and momentum are going to disturb the flow field and the convective engine of the core? how a polarity reversal comes about ? and why the reversals are often so brief?
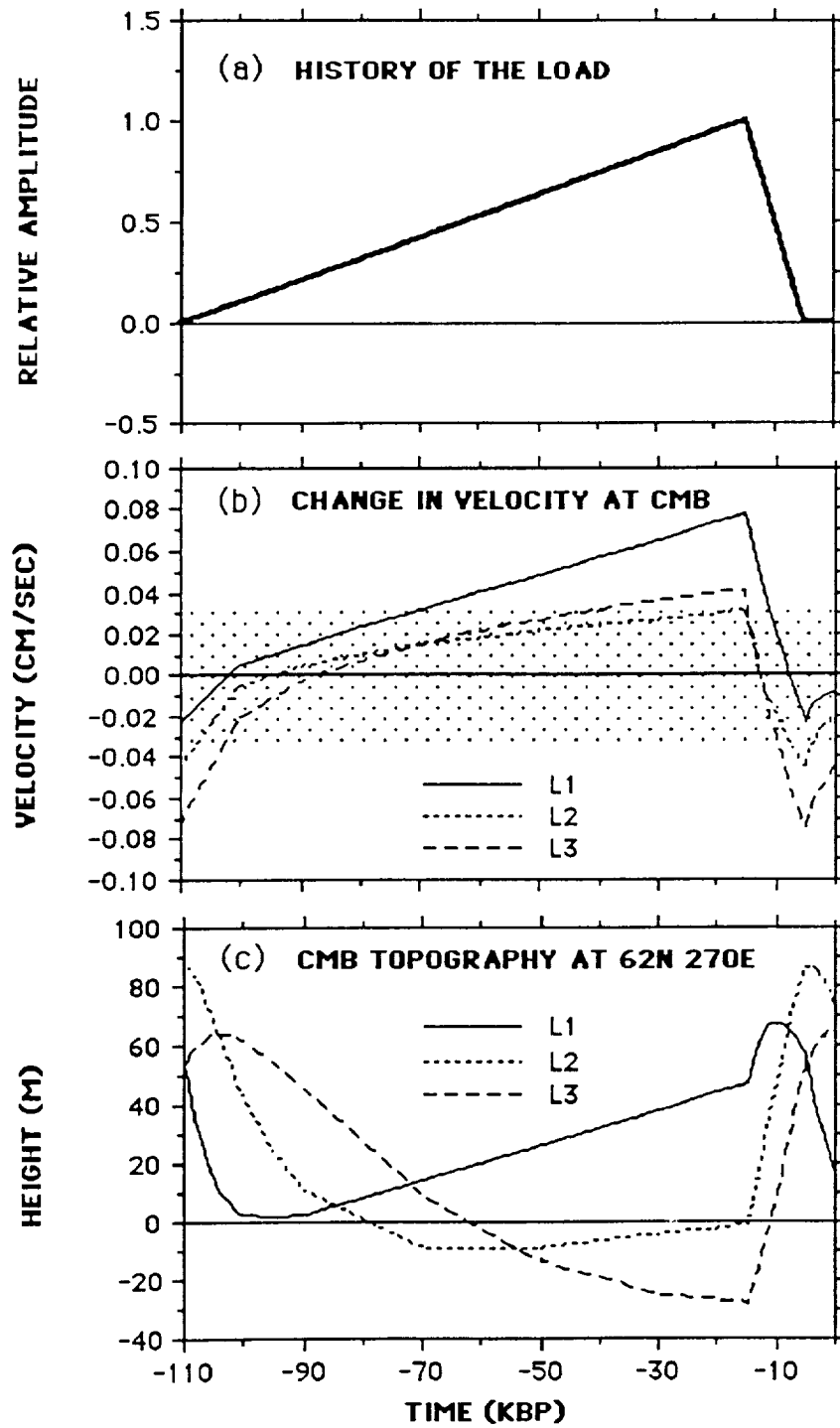
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Fig.2 (a) The last cycle of the saw-tooth load history. (b) The time history of the change in velocity at the bottom of the mantle due to increased spin rate of the mantle. (c) The time evolution of the CMB topography under the Laurentide ice center for the 3 earth models.

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