impulse lies well within the meridional plane. Fast changes within transition paths are also apparent in sedimentary records but are often disregarded as possible disturbances of sedimentary or other origin. Perhaps in the light of the Steens Mountain results they will merit new consideration.

If the second episode reflects an excursion of the geomagnetic field that is unrelated to the polarity reversal, the Steens Mountain record provides evidence that the field behaviour associated with these two phenomena is different. The core processes during reversals and excursions would, at least in this case, not be intimately related. In particular, the hypothesis of K.A. Hoffman¹⁴ that palaeomagnetic excursions are aborted reversals would not be valid.

Although Prévot *et al.* certainly have written an important chapter, the history of palaeomagnetic records of transitions is not finished. Our knowledge of the transition field should be increased by multiple and detailed records of the same reversals. Thus, records from sedimentary sequences offer the most promising per-

spectives. In particular, very important results can be expected from records with very high sedimentation rates. This should allow time resolution in a range similar to that which is possible for volcanic rocks and so should lead to a reconciliation of the sedimentary and volcanic records. □

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Climate modelling

The climate as natural oscillator

from Gerald R. North

THE Earth's climate exhibits great variability at timescales centred at 100, 41 and 20 kyr, as shown convincingly by J. Hays *et al.* (*Science* **134**, 1121; 1976) using data from marine sediments. As these oscillations happen to be the dominant periods of the variations in the Earth's orbital elements (eccentricity, obliquity and perihelion at summer solstice), they have stimulated a revival of the astronomical theory of the Quaternary glaciations (see *Milankovitch and Climate* eds Berger, A. *et al.* Reidel, Dordrecht, 1984).

Steady-state atmospheric climate models show remarkably little sensitivity to orbital changes, leading to a major crisis in climate theory over the past decade. An interesting line of reasoning has been pursued by Barry Saltzman and colleagues (for example, *J. atmos. Sci.* **41**, 3380; 1984). To avoid the issue of sensitivity, Saltzman suggests that the system is a natural nonlinear oscillator with a period of about 100 kyr. The tiny orbital forcing merely acts as a pacemaker providing a phase and precise frequency to lock with.

Although it is premature to call the Saltzman theory conclusive, its elegance and generality make it essential reading for ice-age buffs. The model is highly idealized, keeping track of only a few important dependent variables. It consists of a set of first order (in time) differential equations — the prognostic equations — for the perturbed variables: land-ice volume, sea-ice volume and deep ocean

temperature. The differential equations are coupled through simple polynomial forms up to the third degree in powers of the variables. The solution for equilibrium (all variables vanishing) exists, but it is unstable to infinitesimal perturbations from equilibrium for reasonable values of the coefficients in the system. The free solution state is quickly drawn away from the origin to a limit cycle with a period of about 100 kyr.

The dominant physical process in the model is the sea ice cover. When it is large, the planet has a large albedo leading to an overall cooling and further growth of ice volume by expansion of the freezing line towards the equator. On the other hand, large areas of ice-covered ocean inhibit evaporation and therefore starve the glaciers. Other feedbacks, such as inhibition of heat transport towards the pole under the sea ice and the subsequent buildup of deep ocean temperature, act in the same general manner. If the time constants for these processes are different enough they can lead to oscillations with rather asymmetrical growth and decay time characteristics. The longest time constant introduced in the problem as a parameter is about 7 kyr in the thermal inertia of the deep ocean. The nonlinear dynamics of the system translates this relatively short timescale into the much longer natural oscillation period. The sharp termination of ice volume in the data is one of the unanswered questions about the 100-kyr

cycles. This sawtooth time series, consisting of slow ice growth and abrupt terminations, seems to be a natural property of the Saltzman model, arising from the differences in time characteristics of the individual components. Parameter sensitivity studies show that the essential character of the oscillation is unchanged by small departures from the nominal values.

Although the Saltzman model is attractive because of its logical consistency and systematic formulation, it is not alone in the arena of contenders for ice-age glory. M. Ghil and colleagues (*J. geophys. Res.* **88**, 5167; 1983) suggest an oscillator model based on a short natural period (about 10 kyr). When driven by the Milankovitch frequencies, the solutions exhibit combination tones, one of which is near the 100-kyr period. In their theory, R. Peltier and J. Hyde (*J. atmos. Sci.*, in the press) emphasize feedbacks associated with the bedrock response. The latter theory does not exhibit free undamped oscillations, but it does seem to have a strong response at the 100-kyr period when driven by a forcing frequency near a harmonic of this natural period, say 20 kyr.

There has never been a shortage of ice-age theories, because many of the component processes of the system cannot yet be modelled. The result is a group of schemes replete with free parameters and fudge factors — the Saltzman theory has about 10 such factors and others are comparably endowed. The biggest challenge facing the ice-age system theorist seems to be finding a risk that a model can run in the face of hard evidence as opposed to fitting the lone time series of ice volume. In terms of fitting the ice volume time series it is hard to surpass the phenomenological model of J. Imbrie and J. Z. Imbrie (*Science* **207**, 943; 1980), purely because of its simplicity. The model included one time constant for ice volume growth, one for its decay and a scale parameter for the forcing strength. The result was a rather good fit to the sawtooth time series. The main task now faced by modellers is to construct theories that derive these parameter values from more fundamental principles.

The Achilles heel of simplified theories modelling time behaviour of ice volume is their sensitivity to the parameterization of snowfall over the ice sheets. This is especially grim as the most detailed general circulation models of the atmosphere seem unable to compute the precipitation rates adequately, particularly near the poles — just where it counts in an ice-age theory. The next decade may lead to a better understanding of such precipitation, producing a breakthrough comparable to geological evidence in terms of eliminating classes of ice-age theories. Meanwhile, modellers can explore the vastness of parameter space unconstrained by cruel realities. □

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