polar caps buffer atmospheric pressure.

Kahn's theory has another implication, apart from the explanation of the low surface pressure. If he is correct, the climate of Mars has evolved linearly over geological time, rather than cyclically. This represents a major challenge to current theories of martian climatic history, which generally invoke a periodic exchange of carbon dioxide between reservoirs in the regolith–atmosphere–cap system to explain the polar layered terrains[2-5]. The exchange, driven by variations in the orbital parameters of Mars, can result in surface pressures that vary from 0.1 mbar at low obliquity (11.7°), to about 15 mbar at high obliquity (37.1°). These variations are thought to modulate the transport and deposition of dust and water into polar regions, so giving rise to the layered terrains. Over many obliquity cycles, the mechanism would substantially deplete the regolith reservoir and eliminate cyclical climatic changes, because conversion of carbon dioxide into carbonates on Mars is irreversible.

Not surprisingly, there are many uncertainties over the plausibility of Kahn's mechanism. Among them are availability of cations, such as Mg^{2+} and Ca^{2+}, for carbonate chemistry; the dependence of P^* on heating and soil properties; and whether or not the favoured regions for carbonate formation could be resupplied with water. It would also be worth knowing just how much liquid water is required. Furthermore, no signature of the vast amount of carbonate that must have been produced has been unequivocally identified. Kahn's discussion of these points is mostly qualitative; the basic physics of the process, therefore, remains to be demonstrated. Nevertheless, it is an intriguing idea that merits serious attention. ☐

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Geophysics

Transient mantle rheology

from J. Weertman

CONSIDERATION of the ways in which solids can deform leads to the conclusion that the viscosity of the Earth's mantle should increase with depth. This agrees with our current ideas about the thermal structure of the interior of the Earth. Hence it came as a surprise to find that analyses[1-3] of glacial rebound and complementary Earth satellite data indicate that the mantle viscosity does not increase with depth but is almost a constant, with a value of about 10^{21} Pa s. Until now, this has presented a dilemma to those studying the physical structure of the Earth and its consequences for plate tectonics but, in this issue of *Nature*, W.R. Peltier[4] shows that the problem can be resolved if transient creep is taken into account.

The modern study of the creep deformation of the Earth's mantle started with the suggestion[5] that the mantle might deform plastically through the diffusional transport of atoms between grain boundaries, the mechanism now known as Nabarro–Herring creep[5,6]. Using the Nabarro–Herring creep theory, R.B. Gordon[7] found that the mantle viscosity increases with depth. His result is readily understood. The greater the difference between the actual temperature at a given depth and that at which mantle rock first starts to melt, the larger the expected value of the viscosity. The further rock is from its melting temperature the 'colder' it is (even if its actual temperature is quite high) and the more difficult it is to make the rock creep. As the mantle convects, its thermal profile should be approximately adiabatic. The adiabatic temperature presumably increases much less rapidly with depth than does the temperature at which melting commences and hence it would not be surprising to find that viscosity increases with depth in the mantle.

This conclusion is not dependent on the choice of the creep mechanism which is used to obtain an estimate of the mantle viscosity. Any such mechanism gives faster creep the closer the temperature is to the melting temperature. It also is not dependent on whether the creep mechanism gives rise to a linear, newtonian creep equation ($\dot{\varepsilon}=\sigma/\nu$) or to a non-newtonian creep equation such as a power-law creep equation ($\dot{\varepsilon}=c\sigma^n$). Here ε is the creep rate, σ is the stress, ν is the viscosity and c and n are constants. (For non-newtonian creep an effective viscosity is defined to be equal to $\nu=\sigma/\dot{\varepsilon}$. The effective viscosity for nonlinear creep requires that a standard stress level or strain rate be specified.)

That the mantle viscosity is almost constant could be explained, of course, if the ratio of the actual temperature over the melting temperature were constant throughout the mantle. It is more likely, however, that this ratio decreases with depth. It could also be explained if mantle creep obeys a power law[8] and the creep stress increases with depth at a suitable rate. But the glacial rebound stresses decrease with depth. One possible way out of the dilemma is to bring transient creep phenomena into the analysis. In analyses carried out up to now it has been assumed implicity that only steady-state creep equations need be considered.

Analyses of isostatic geoid anomalies[9,10] indicate that the lower mantle has viscosity an order of magnitude greater than that of the upper mantle and hence than the lower mantle viscosity as determined from glacial rebound. But geoid isostacy operates on a timescale of the order of 10^8 years rather than the 10^4–10^5 years for glacial rebound. Peltier[4] investigates whether the order of magnitude difference of viscosity of the lower mantle as deduced from the two phenomena could arise if the glacial rebound method measures a predominantly transient creep strain rate and if the isostatic geoid anomaly method measures a more steady-state creep strain rate.

Peltier makes an explicit calculation by use of a linear creep equation that reduces to a steady-state equation at long times but is a transient equation at shorter times. This equation is for a Burgers's solid[11] which, when springs and dashpots model the solid, is simply a Zener standard linear solid in series with a dashpot. For uniaxial stress–strain the equation he used can be written as $\ddot{\sigma}+(\sigma/\tau)+(\mu^*\sigma/\nu\tau)=\mu\ddot{\varepsilon}+\mu^*(\dot{\varepsilon}/\tau)$ where the dot stands for time differential, τ is a decay time, μ and μ^* are elastic moduli and ν is the long-term viscosity. Peltier uses this equation only for the lower mantle. For the upper mantle he uses a Maxwell solid (spring and dashpot in series) with the equation $\dot{\varepsilon}=(\dot{\sigma}/\mu)+(\sigma/\nu)$. He is able to show that it is possible to reconcile the two values of the viscosity of the lower mantle. He points out that further constraints on the transient creep contribution to lower mantle deformation may require reexamination of the analysis of Richards and Hager[10].

Since Peltier's paper was submitted for publication, a paper by Sabadini, Yeun and Gasperini[12] has appeared in which a transient creep analysis also based on a Burger's solid has been carried out. The results and conclusions are very similar to those of Peltier. Clearly, the study of the rheology of the mantle is entering a new period in which many possible creep mechanisms are being considered as rate controlling, and in which the theorists have become capable of carrying out quite sophisticated studies involving transient creep of mantle rocks. ☐

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