

## Ice sheets and continental drift

GARTH W. PALTRIDGE

*Antarctic Cooperative Research Centre, Box 252C, Hobart, Tasmania 7004, Australia*

**ABSTRACT.** Cycles of ice-sheet loading during glacial periods of the Earth's history induce horizontal velocities in the uppermost mantle which may be of the same order as those of continental drift. Given some non-linear mechanism which ensures preferential movement in the one direction, a climatically induced component of continental drift is therefore possible during glacial periods such as the Quaternary. If so, one might expect that component of drift is intermittent on time-scales between 20 and 100 ka, i.e. on time-scales of observed ice-volume variations which, at least over the last 700 ka, have been related to the Earth's orbital variations.

MANY investigations have confirmed Wegener's (1912) suggestion that on geological time-scales the various continents "drift" from one position to another on the surface of the Earth (e.g. Vine and Matthews, 1963; Westoll, 1965). Maps are now available (Smith and Briden, 1977; Schmidt, 1988) which purport to trace the positions of the continents as far back as 600 Ma. Considering only the last 150 Ma for which the positional evidence from palaeo-reconstruction is reasonably solid, there was a break-up of Gondwana in the Southern Hemisphere (effectively, Wegener's "flight from the pole" of South America, South Africa, India and Australia) and a break-up of Laurasia in the Northern Hemisphere as Eurasia and North America moved away from one another to form the Atlantic Ocean. The mechanism for continental drift is presumably related to large-scale convection in the Earth's mantle (Peltier, 1989; Olson and others, 1990). One qualitative picture is of a fluid but highly viscous mantle in which up-wellings and down-wellings generate horizontal flows at its surface which carry the floating continental plates. The source of the convection is generally assumed to be differential heating from the core. Divergence of the plates is most clearly seen in the patterns of magnetic anomalies developed at the spreading mid-ocean ridges (e.g. Veevers and others, 1991).

Since the early work of Walcott (1973), Cathles (1975) and others, there have been many studies of the *vertical* displacement and subsequent isostatic rebound of those continental plates (or parts of plates) which are subject to extra loading by ice sheets during periods of glaciation. It is largely from these studies that information on the elasticity and rigidity of the lithosphere, and on the vertical profile of viscosity in the mantle, are derived. This note points out that the *horizontal* components of flow in the mantle induced by the regular (?) cycling of ice-sheet loading and unloading may be of the same order as the observed velocities of continental drift, i.e. some  $\text{cm a}^{-1}$ . Thus, given some non-linear mechanism which ensures preferential movement in the one direction, it is possible, at least for those periods of the Earth's history including the Quaternary when there was significant glaciation, that there could be a climatically induced element to continental drift.

Figure 1 shows the theoretical south to north flow rates of the surface of the upper mantle as a function of latitude

at various times during a single 30 ka cycle of ice-sheet loading and unloading of the Antarctic continent. The flow rates were calculated using a very simple "2½ dimensional" numerical model with parameters as described in the caption to the figure. It envisages a horizontally uniform upper mantle whose viscosity varies with depth  $z$  according to the calculations of Cathles (1975); namely,  $1.0 \times 10^{22}$  Poise at all depths down to 1000 km except for a low-viscosity channel ( $4.0 \times 10^{20}$  Poise) in the uppermost 100 km. The continental plate corresponding to Antarctica is imagined to float on the mantle from the South Pole to  $70^\circ$  S, and the rest of the mantle has a free surface at  $z = 0$ . The mantle material is assumed to be inelastic, incompressible and Newtonian. The imposed ice-sheet cycle is a sinusoidal height variation with an amplitude of 1000 m, about half the present thickness of the ice on Antarctica.

The choice of a 30 ka cycle for the illustrative purpose of Figure 1 was not random. During prolonged periods of the Earth's glaciation the volume of ice fluctuates on various time-scales with, at least over the last 700 ka, readily observable periods of the order of 20, 40 and 100 ka. They appear to be related to orbital variations of the Earth about the Sun (Van Woerkum, 1953; Raymo and others, 1990). The last major glacial cycle in the Northern Hemisphere was of the order of 100 ka, and much of the work on isostatic rebound (e.g. Tushingham and Peltier, 1991) has assumed a build-up and decay of ice volume over a period of that order. Significant modulation of ice volume at the shorter time-scales occurred during that and previous cycles, and the illustrative 30 ka cycle was chosen here simply as an order-of-magnitude representation of those shorter time-scales.

Figure 1 reflects the obvious response to extra pressure on Antarctica. Material of the mantle is squeezed from beneath the plate to create a surface sloping downward towards the north and a horizontal component of velocity which at any latitude is a maximum at the surface and which (during the loading part of the cycle) decreases with distance along the great circle away from the Antarctic source. The relaxation-time constant of the model system is about 18 ka (this is from calculations with the model itself), so that during the later part of the cycle, when the load of

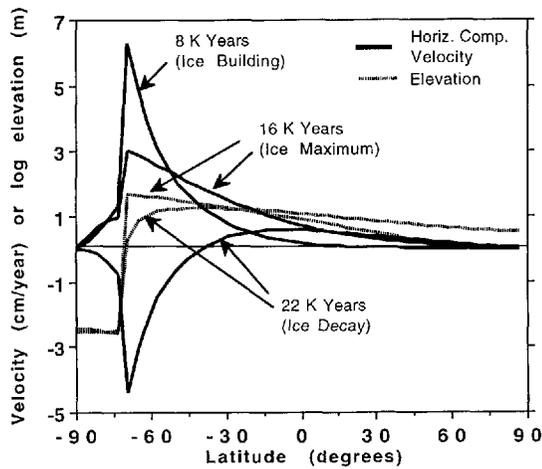


Fig. 1. Computed mantle elevation  $H$  (dashed lines) and south to north mantle-surface flow rates  $v$  (solid lines) as a function of latitude  $x$  at various times  $t$  in a single 30 ka cycle of ice-sheet loading of Antarctica, according to the following numerical model which solves the one-dimensional steady-state viscous-flow equation  $dp/dx = -\mu(z)d^2v/dz^2$ . Grid spacing: 225 intervals of latitude from South to North Pole, 20 depth levels from  $z = 0$  to  $z = z_d = 1000$  km, one interval in the east-west ( $y$ ) direction of unit width at the Equator but varying as  $\cos x$ . Viscosity profile  $\mu(z)$  as given in the text. Excess pressure  $p$  due to imposed ice load on Antarctica (from  $x = -90^\circ$  to  $-70^\circ$ ) =  $p_0(x, t) = \rho gh(t)$  where  $h(t) = h_0 - h_0 \cos(2\pi t/30000)$  with  $h_0 = 1000$  m,  $g$  = acceleration due to gravity and  $\rho$  = density of ice =  $1000 \text{ kg m}^{-3}$ . Viscous transfer in the horizontal direction is translated into mantle elevation  $H(x)$  and hence excess pressure assuming density of mantle =  $4000 \text{ kg m}^{-3}$ . Flow-boundary conditions of  $v(x, z_d) = 0$ ,  $v(x, 0) = 0$  at all  $x$  from  $-90^\circ$  to  $-70^\circ$ ,  $dv/dz = 0$  elsewhere. The time step was 1 year.

ice is reducing, there is still a northward velocity at latitudes close to the North Pole.

The system as described is linear, so that flows in the mantle induced by the increased pressure beneath Antarctica during the loading part of the glacial cycle are reversed during the unloading part of the cycle. If the loading-unloading cycle is regularly repeated, the system settles down to a form of steady state where the average velocities over a complete cycle are zero. To propose that the ice-loading process is significant in the context of long-term continental drift requires one to propose also some form of non-linear hysteresis which favours flow (or, at least, the actual movement of floating continental plates) in one direction. It is not difficult to suggest a number of possible mechanisms. It is very difficult to justify them. The simplest suggestion (more or less in line with the modern investigations of plate tectonics and the formation of mid-ocean ridges) is that magma from the mantle wells up into the opening between two diverging continental plates, where it cools and solidifies to a material which is highly resistant to compression but poorly resistant to expansion (Jaeger and Cook, 1976). A floating continent which is carried in one direction by horizontal flow in the mantle would therefore be restrained from moving backward when the flow in the mantle reverses. Perhaps the main attraction of the suggestion is that it might in principle be checkable, since it implies a component of continental drift which is intermittent on the time-scale of several tens of

thousands of years. Such checking would require, say, development of some technique for examining the Quaternary stratigraphic chronology of the mid-ocean ridges at a level of detail much greater than that allowed by present magnetic-reversal stratigraphy.

Setting aside questions about what might be the most appropriate profiles of density and viscosity to use in a model, the present calculations involve a number of gross simplifications. For instance, the depth of the model is confined to that of the upper mantle (about 1000 km) simply to give some "floor" at which to set a boundary condition of zero velocity. (There is some evidence (Bott, 1971) to suggest that convection does not penetrate the boundary between the lower and upper mantle, although this does not necessarily excuse the neglect in the present context of viscous flow in the lower mantle. In any event, a larger model depth would yield greater velocities at the surface.) For instance, again, the "free" mantle surface is equivalent to assuming that drag of the continental plates by mantle flow is a viable mechanism for drift (Forsyth and Uyeda, 1975).

Despite the various simplifications, when the model is used to compute the present-day horizontal velocities associated with the most recent post-glacial rebound of North America, the results (see Fig. 2) are remarkably similar to those of James and Morgan (1990), whose whole-Earth model includes specific consideration of such things as visco-elasticity of the mantle and rigidity of the lithosphere. The smaller velocity of the James and Morgan model near the ice-sheet edge is probably due to their (more realistic?) assumption of a parabolic height profile across the ice sheet, and to the smoothing effect of the lithosphere included in their model.

Figure 3 shows computed average mantle-surface velocities where the averages at each latitude are taken over the loading half of a sinusoidal loading-and-unloading cycle. An increase of cycle time from 30 to 100 ka reduces the average velocities by a factor of 2, as might be expected anyway from consideration of the time constant of the system. If the low-viscosity channel is removed, so that all levels of the mantle have a viscosity of  $1.0 \times 10^{22}$  Poise, the velocities at angular distances greater than  $60^\circ$  from the glacial centre (i.e. from the South Pole) are reduced to levels below  $0.1 \text{ cm a}^{-1}$ . The importance of the low-viscosity channel in determining the distribution of horizontal velocity is also apparent in the comparisons of Figure 2.

Figure 4 shows the geographical distribution of mantle-surface flow rates computed as the vector sum of the great-circle flow rates associated with ice loading of Antarctica and of a continent of equivalent size centered on  $70^\circ \text{ N}$ . The picture is broadly (very broadly) consistent with the present movement of the continents, i.e. roughly south-north in the Southern Hemisphere and roughly east-west in the Northern Hemisphere. "Roughly" should be emphasized here. It can be gauged by reference to the known patterns of sea-floor spreading as, for instance, in Press and Siever (1982). While the result in no way suggests that the mechanism suggested here is the primary cause of continental drift (either now or in glacial periods of the past), it is at least possible that the process amplifies certain directional components of an already established drift.

In summary, the existence of extended glacial periods

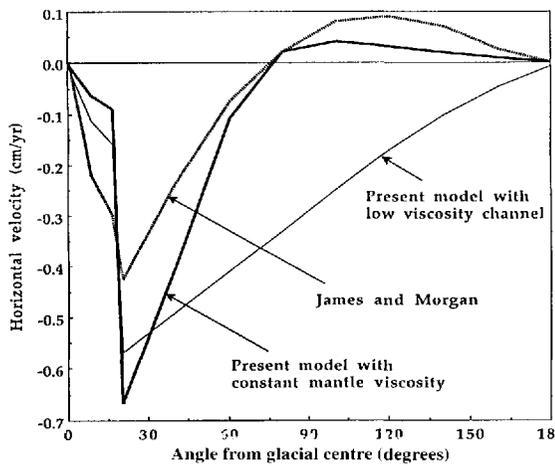


Fig. 2. Present-day horizontal component of mantle–surface velocities (positive away from the glacial centre) as a function of angular distance from the centre of the last North American ice sheet, which is assumed to have increased linearly in height from zero to a maximum (1 km) over a period of 90 ka, and decreased linearly back to zero by 100 ka (i.e. by 6000 a BP). The dashed curve is from the detailed model of James and Morgan (1990), the thick solid curve is from the present model with a constant mantle viscosity of  $1.0 \times 10^{22}$  Poise (as for James and Morgan), and the thin solid curve shows the effect of a low-viscosity channel as discussed in the reference to Figure 1.

on Earth seems to require a continent either to be very near a Pole or to have a significant fraction of its surface at high elevation (Budd and Smith, 1979). The Earth has been largely ice-free for much of its history but, during glacial periods such as the Quaternary, the cyclical loading and unloading of ice may contribute significantly to continental drift. The main proviso is that there exists some non-linear mechanism associated with plate–mantle interaction which acts as a “ratchet” to ensure preferential movement of the continental plates in the one direction.

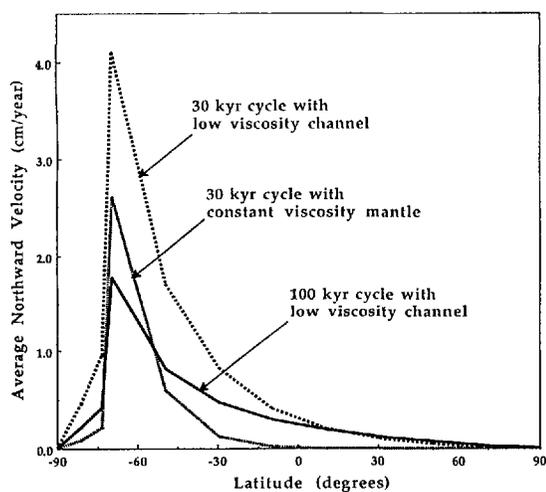


Fig. 3. Time-averaged northward velocities for the “increasing load” half of a South Polar sinusoidal ice-sheet cycle. The curves refer to a 30 ka imposed cycle with a low-viscosity channel in the upper mantle (i.e. comparable with the conditions in Figure 1), a 30 ka cycle with a constant mantle viscosity of  $1.0 \times 10^{22}$  Poise and a 100 ka cycle with a low-viscosity channel as in Figure 1.

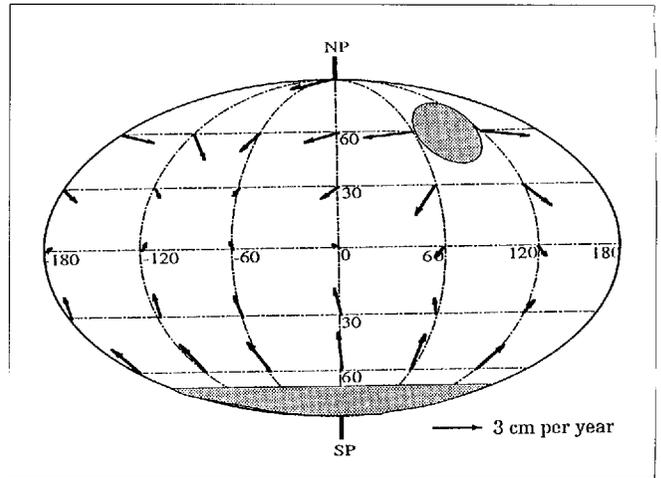


Fig. 4. Geographical distribution of mantle–surface velocities for two ice sheets positioned as shown by shaded areas, each at 16 ka into an ice-loading cycle as in Figure 1. The calibration arrow outside the globe of length is equivalent to a velocity of  $3.0 \text{ cm a}^{-1}$ .

REFERENCES

Bott, M. H. P. 1971. *The interior of the Earth*. London, Edward Arnold.  
 Budd, W. F. and I. N. Smith. 1979. The growth and retreat of ice sheets in response to orbital radiation changes. *International Association of Hydrological Sciences Publication 131* (Symposium at Canberra 1979 *Sea Level, Ice and Climate Change*), 369–409.  
 Cathles, L. M. 1975. *The viscosity of the Earth’s mantle*. Princeton, Princeton University Press.  
 Forsyth, D. and S. Uyeda. 1975. On the relative importance of the driving forces of plate motion. *Geophys. J. R. Astr. Soc.*, **43**, 163–200.  
 Jaeger, J. C. and N. G. W. Cook. 1976. *Fundamentals of rock mechanics*. London, Chapman and Hall, Ltd. and Science Paperbacks.  
 James, T. S. and W. J. Morgan. 1990. Horizontal motions due to post-glacial rebound. *Geophys. Res. Lett.*, **17**, 957–960.  
 Olson, P., P. G. Silver and R. W. Carlson. 1990. The large-scale structure of convection in the Earth’s mantle. *Nature*, **344**, 209–215.  
 Peltier, W. R. 1989. In Peltier, W. R., ed. *Mantle convection: plate tectonics and global dynamics*. New York, Gordon and Breach, 1–22.  
 Press, F. and R. Siever. 1982. *Earth*. San Francisco, Freeman and Co.  
 Raymo, M. E., W. F. Ruddiman, N. J. Shackleton and D. W. Oppo. 1990. Evolution of Atlantic–Pacific  $\delta^{13}\text{C}$  gradients over the last 2.5 m.y. *Earth Planet. Sci. Lett.*, **97**, 353–368.  
 Schmidt, V. A. 1988. *Continental drift*. (Hypercard Program from Geoimages, 1307 Ridgemont Dr., Austin, Texas 78723.)  
 Smith, A. G. and J. C. Briden. 1977. *Mesozoic and Cenozoic paleo-continental maps*. Cambridge, Cambridge University Press.  
 Tushingham, A. M. and W. R. Peltier. 1991. A new global model of late Pleistocene deglaciation based upon geophysical predictions of post-glacial relative sea level change. *J. Geophys. Res.*, **96**(B3), 4497–4523.  
 Van Woerkum, A. J. J. 1953. The astronomical theory of climate change. In Shapley, H., ed. *Climate change*. Cambridge, MA, Harvard University Press.  
 Veevers, J. J., C. McA. Powell and S. R. Roots. 1991. Review of seafloor spreading around Australia. 1. Synthesis of the patterns of spreading. *Aust. J. Earth Sci.*, **38**, 373–389.  
 Vine, F. J. and D. H. Matthews. 1963. Magnetic anomalies over ocean ridges. *Nature*, **199**, 947–949.  
 Walcott, R. I. 1973. Structure of the Earth from glacio-isostatic rebound. *Ann. Rev. Earth Planet. Sci.*, **1**, 15–37.  
 Wegener, A. 1912. Die Entstehung der Kontinente. *Peterm. Mitt.*, 1912, 185–195, 253–256, 305–309.  
 Westoll, T. S. 1965. Geological evidence bearing upon continental drift. In “A symposium on continental drift”. *Phil. Trans. R. Soc. A.*, **258**, 12–26.

The accuracy of references in the text and in this list is the responsibility of the author, to whom queries should be addressed.