it provides one more example of the way in which human activities tend to result in the acceleration of natural nutrient cycles.

EARTH'S MANTLE

Non-Newtonian Flow

from our Geomagnetism Correspondent

ALTHOUGH the precise nature of the force driving the drifting continents and spreading ocean floors is still a matter of dispute, it is generally agreed that the drifting and spreading processes involve large-scale flow in the Earth's upper mantle and possibly in the lower mantle as well. But what sort of flow? Most quantitative models of mantle behaviour have been based on the assumption that flow is Newtonian; that is, that the mantle obeys the laws which characterise Newtonian fluids. Post and Griggs (*Science*, **181**, 1242; 1973), however, have now challenged this view, basing their case for non-Newtonian flow in the mantle on both field observations and laboratory experiments.

Interestingly, the field observations are those relating to the isostatic uplift of Fennoscandia—the classic phenomenon used in the earliest attempts to determine the mantle's viscosity. When the glacial ice receded from Fennoscandia about 10,000 years ago, the remaining surface depression was partly removed by immediate elastic rebound. Since then, however, there has been continuous isostatic adjustment during which the shape of the depression has remained roughly constant and for which the current rate of uplift is everywhere proportional to the magnitude of the depression. Post and Griggs believe that these properties indicate a special type of behaviour which they term 'proportional relaxation' and in which the ratio of the effective shear stresses at any two points remains constant with time while the stress amplitudes decrease asymptotically to zero.

The validity of proportional relaxation as defined by Post and Griggs rests on the assumption that the mantle is incompressible. In this case, the stress distribution in the mantle will be consistent with the surface depression and the total viscous dissipation will always be at a minimum. As long as the shape of the stress distribution in the mantle depends on the shape of the surface depression but not on its magnitude, it then follows that the viscous dissipation will remain at a minimum if the surface elevations and the original stresses are multiplied by the same factor. Thus if the shape of the surface depression does not change with time (as in Fennoscandia), nor will the shape of the stress distribution. In short, there is proportional relaxation.

The general form of the law of flow in the mantle chosen by Post and Griggs is $\dot{\epsilon}_s = B(z)\tau^n$, where $\dot{\epsilon}_s$ is the steady state effective strain rate, B depends only on depth (z), τ is the effective shear stress, and n is a constant. For Newtonian flow n would be 1 and, as can be shown from the general flow law, the logarithm of the remaining uplift at the centre of the uplifting area would vary linearly with time. But from the remaining uplift in Fennoscandia, Post and Griggs show there is no such linearity, and n is 2.85, 3.21 or 3.58, respectively, for the three published estimates of the remaining Fennoscandian uplift (150 m, 180 m and 210 m). In other words, as long as the proportional relaxation model is valid (which requires, among other things, that n be independent of stress), postglacial uplift in Fennoscandia requires non-Newtonian flow in the mantle with an n value of 3.2 ± 0.3.

The second part of the case rests on deformation experiments with dunite, whose chief constituent, olivine, is generally thought to be an important constituent of the upper mantle. Creep and high temperature relaxation experiments on dunite from Mt Burnett show that the best-fitting value of n is 3.18 ± 0.18. This is in excellent agreement with the n value obtained from uplift and is thus consistent with the idea of non-Newtonian mantle behaviour. In view of the large number of assumptions used in the reanalysis of Fennoscandian uplift, Post and Griggs would regard such close numerical agreement as fortuitous. But whatever the precise figure, the flow certainly seems to be non-Newtonian; and plate tectonic models involving mantle motion should incorporate it.

LOW TEMPERATURE PHYSICS

Superconducting Bridges

from our Condensed Matter Correspondent

THE interesting structure which appears in the current-voltage characteristics of very small superconducting bridges at subharmonic values of the energy gap can be attributed to the effects of Josephson radiation generated in the bridge itself, according to Gregers-Hansen, Hendricks and Levinson, of the University of Copenhagen, and Pickett, of the University of Lancaster (*Phys. Rev. Lett.*, **31**, 524; 1973).

The Josephson effect is a phenomenon which occurs when two regions of superconductor are coupled together through a very weak link. The link can either be a short narrow bridge made of the same material, as in the present case, or it can be an exceedingly thin layer of insulator which electrons can traverse

Glaciation and the Chalky Boulder Clay

MANY years ago, Harmer (*Jub. Vol. geol. Ass.*, **103**; 1909; and *Proc. Yorks. geol. Soc.*, **21**, 79; 1928) concluded that the distribution of Chalky Boulder Clay in Britain was brought about by two distinct ice streams. The first passed from the North Sea to parts of the Lincolnshire Wolds and was then deflected southwards, fanning out into East Anglia and the Midlands; the second entered across the present north coast of Norfolk and came into contact with the North Sea Drift. The boundary between the two deposits has long been in dispute, but, even more fundamentally, there has been disagreement over the number of glaciations involved. Harmer believed that both streams were of the same glaciation; but more detailed studies carried out during the late 1940s and early 1950s apparently suggested that two glaciations were concerned—the lower Lowestoft and the upper Gipping. The second view then prevailed until the late 1960s when the controversy was revived.

In *Nature Physical Science* next Monday (October 15), Perrin *et al.* report a detailed study which suggests that, in fact, the Chalky Boulder Clay represents only one glaciation. Samples of Boulder Clay from eleven sites previously ascribed to the Lowestoft glaciation and twelve sites ascribed to the Gipping glaciation have been analysed for mechanical composition, calcium carbonate content, heavy mineral percentages and clay mineral content. As far as mechanical composition is concerned, no systematic differences are observed between Lowestoft and Gipping samples. Calcium carbonate content is more variable, but the trends are consistent with gradual assimilation of chalk by ice moving in the directions described by Harmer. Nor are any significant variations observed in heavy mineral percentages and clay mineral content. In view of the compositional consistency over a wide area (14,000 km^2), Perrin and his colleagues conclude that the involvement of two glaciations cannot be substantiated. Moreover, the one glaciation concerned is the Lowestoft; there is no evidence for the effects of a later Gipping glaciation.

As Perrin *et al.* point out, however, even if the Chalky Boulder Clay represents a single glaciation, its origin remains in doubt. The oft-stated assumption that much of the matrix was derived from the Jurassic clays must be ruled out on compositional grounds; and the virtual absence of Triassic or Pennine debris militates against westerly or north-westerly sources. For the time being, a North Sea origin still seems the most likely.