superheating depends on epitaxy between the contained solid and the coating/host metal, and it is possible that that an incoherent interface might not permit substantial superheating.

Further evidence concerning the surface role in melting is provided by ion-channelling studies¹⁷ using proton sensing beams on an atomically clean (110) surface of a heated lead crystal. The solid-liquid transition begins 40 K below the equilibrium bulk T_m , and the thickness of the molten surface layer increases dramatically close to the bulk T_m , being as much as 20 layers within a fraction of 1 K of that temperature. This implies second-order (continuous) melting at the surface, and thus raises in general terms the question of the order of transformation of the melting process at a surface; Frenken and van der Veen¹⁷ quote recent theoretical work¹⁸ on atomic ordering at a surface (for example,

of Cu₃Au) which proves that an order-disorder transformation that is first-order in the bulk can be second-order (continuous) at the surface. That prediction has been confirmed by several experimental studies of Cu₃Au. Indeed, Frenken and van der Veen claim, but do not prove, that the Lipowsky/Speth approach¹⁸, when applied to melting, predicts a liquid-film thickness diverging proportionally to $[T_0/(T_m - T)]$, where T_0 is constant, which is consistent with their own experimental results for lead.

Thus, taking together all the new evidence the almost unavoidable conclusion is that melting does indeed begin as a continuous vibrational instability at the solid surface of a solid-solid boundary. □

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Mantle geophysics

Variable viscosity makes waves

from David A. Yuen

BOUNDARY-layer instabilities develop in thermal convection, when the driving buoyant forces are sufficiently strong. In the laboratory one can monitor these hydrodynamic events in constant-viscosity fluids, or in temperature-dependent viscous fluids such as corn syrup or silicone oil. The flow law of mantle materials,

Schematic indication of variation with depth of temperature- and pressure-dependent viscosity $\eta(T, p)$. The times are given by t_1 and t_2 with t_2 greater than t_1 . Arrow denotes the trend caused by the aging of the lithosphere. A low viscosity zone would be present at a depth of around 100 km.

however, depends strongly on both the temperature and the pressure. Up to now, the importance of temperature- and pressure-dependent viscosity has not been widely appreciated, mainly because of the proliferation of laboratory and numerical experiments on constant or temperature-dependent viscosity fluids. Recent work

by W.F. Haxby and J.K. Weissel¹ may have put temperature- and pressure-dependent viscosity back in the limelight.

In their analysis of Seasat altimeter data Haxby and Weissel find lineated patterns of gravity anomalies and sea-surface height variations occurring over the younger portions of the fast-moving plates in the Pacific and Indian oceans. Haxby and Weissel suggest that these lineations, with wavelengths in the range of a couple of hundred kilometres, are caused by small-scale convective instabilities in the upper mantle beneath the oceanic lithosphere at plate ages as young as 5 million years. Previously, convective instability, based on constant viscosity models, has been advocated to explain the flattening of the sea floor from the conductive cooling predictions at plate ages greater than about 80 million years². For secondary convection to be triggered beneath the young sea floor, the effective viscosity locally can be estimated to be about 10^{19} poise, which is substantially less than the mean upper mantle viscosity inferred from glacial isostasy. From the dominant wavelengths of the undulations over young oceanic crust, Haxby and Weissel then reckon from linear stability arguments that the thickness of this convecting layer is about 100 km. Such localized cells may evolve within a low viscosity channel (see figure), which is a consequence of the intrinsic temperature- and pressure-dependent nature of mantle viscosity in the presence of temperature fields near the ridge.

The idea that a layer of pronounced low viscosity is needed to induce at an early age instabilities of the cold upper bound-

ary layer was advanced in 1981³ and confirmed later by numerical computations^{4,5}. Because the thermal boundary layer thickens with age of the sea floor, the low-viscosity zone becomes less pronounced with time (see figure) and moves deeper into the mantle. This downward migration of the low-viscosity well would influence the wavelengths of the gravity anomalies with age. Finite-amplitude calculations⁶ predict the wavelengths would increase more rapidly than the observations. This suggests that these signatures were frozen in the growing elastic portion of the oceanic lithosphere.

Temperature- and pressure-dependent viscosity may also be influential in thinning the lithosphere, caused by the impingement of a hot plume coming from the upward migration of the low-viscosity zone (reverse t_2 and t_1 in the figure). This process would involve a positive-feedback mechanism, as the viscosity well becomes more pronounced and the local viscosity drops down sharply with greater amounts of penetration by the plume⁷. For this reason, the formation of seafloor swells by mantle plumes should be investigated numerically from the point of temperature- and pressure-dependent viscosity, rather than from numerical or laboratory studies⁸ in which a low, constant viscosity fluid is assumed.

Besides its role in upper mantle dynamics, temperature- and pressure-dependent viscosity can be important in several situations involving deep mantle circulation. For example, the adiabatic temperature gradient in the lower mantle is linked strongly to the parameters of the flow law, such as the activation volume and the Gruneisen parameter. Too large an activation volume (greater than 6 ml per mole), would lead to super-adiabatic temperature gradients in the lower mantle⁹.

For geodynamicists to be further convinced of the importance of temperature- and pressure-dependent viscosity in mantle convection, corroboration of these initial exciting findings of small-scale convection at young ages² is needed. More work should show that these gravity perturbations do not have a lithospheric origin. □

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