ISSN 0016-7029, Geochemistry International, 2006, Vol. 44, No. 8, pp. 808–813. © Pleiades Publishing, Inc., 2006.
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Hydroextrusion as a Possible Mechanism for the Ascent of Diapirs, Domes, and Mantle Plumes

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Received December 27, 2004

Abstract—A possible mechanism of the ascent of material within the Earth's crust and mantle is the mechanism of hydroextrusion, i.e., the effect of squeezing of material under excess pressure. The major factors that predetermine the high plasticity of the material and its ability to produce hydroextrusions are high lithostatic pressures and temperatures. The phenomenon of hydroextrusion can be most clearly illustrated by the example of the origin of salt diapirs. The driving force of hydroextrusions of material in the crust and mantle is excess pressure, which can result from lateral differences between the densities of rocks (as is the case during the development of salt diapirs) and phase transitions associated with a volume increase. When the material of the upper mantle undergoes partial melting with the derivation of basaltic melts at depths of 60–100 km, excess pressures reach 80 MPa, whereas the plasticity limit of 20% melted rocks is no higher than 5 MPa. As a result, the partially molten material is forced from the melting region toward zones with lower lithostatic pressures. A local temperature increase in the transitional zones in the Earth's mantle at positive dP/dT values of the phase transitions also gives rise to excess pressures, whose values can range from 100 to 800 MPa at a 0.5–3.0% volume change and which can be the driving force during the origin of mantle plumes.

DOI: 10.1134/S0016702906080052

INTRODUCTION

Ascending flows of material in the Earth's crust and mantle are an important constituent of tectonic and thermal processes that facilitate the differentiation of the Earth's material. The lower mantle material ascends with mantle plumes to the bottom of the lithosphere and undergoes partial melting in the upper mantle at depths of 60–100 km. Fluxes of basaltic melts derived at these depths intrude into the Earth's crust and induce its partial melting. The granitic melts thus produced maintain vertical flows at the upper levels. Salt deposits in sedimentary rocks feed salt diapirs, which are manifestations of another type of ascending flows. Deglaciation of the Earth's surface is also associated with the development of dome-shaped uplifts, which can be regarded as the result of vertical material flows. The most conspicuous and deepest seated flows occur in the form of mantle plumes, which originate from the transitional zone of the upper mantle and, perhaps, also from layer D at the core–mantle boundary.

The driving force of all of these flows is traditionally thought to be gravitational instability caused by the heterogeneous density of the mantle and crustal material and results in the ascent of less dense material in the gravitational field [1]. We believe that, along with this mechanism, a notable contribution at high lithostatic pressures can be made by plastic flows in compliance with the mechanism of hydroextrusion.

HYDROEXTRUSION MECHANISM

Hydroextrusion is the process of the plastic flow of solid material under high hydrostatic pressures. A pressure increase is associated with a drastic change in the deformation style, so that the material that is brittle under normal pressure acquires the ability to plastically flow under the effect of high pressure [2]. The principal difference of hydroextrusion from deformations of material under the effect of mechanical forces is underlain by the fact that uniform (hydrostatic) pressure significantly increases the plasticity of material compared to that under purely mechanical treatment at a normal pressure.

The measure of the plasticity of material is its ultimate ductility ε, equal to

$$\varepsilon = \ln\left(\frac{S_0}{S_p}\right),$$

where S_0 is the initial cross-section surface, and S_p is the cross section of the sample neck at failure. The dependence of ε on hydrostatic pressure is described by the equation

$$\varepsilon = \varepsilon_0 + k(P - P_l),$$

where ε is the strain at failure under pressure P; ε_0 is the strain at failure without pressure; P_l is the limiting pressure (starting at this value, ε becomes dependent on pressure); and k is a phenomenological proportionality coefficient. In the general form, the function $\varepsilon(P)$ has a configuration demonstrated in Fig. 1 [2].

The mechanism of hydroextrusion as a type of a forced flow mechanism is principally different from the buoyant ascent of a lighter material in that the former can operate only if a boundary exists at which stress can be accumulated to maintain the plastic flow of the material toward the region with a lower lithostatic pressure. This can be clearly illustrated by the example of salt diapirs. Salt starts produce domes when the amplitude of the local lithostatic pressure variations at the roof of the layer $\Delta P > \Delta\sigma_l$, where $\Delta\sigma_l$ is the differential stress corresponding to the onset of salt plastic flow. This mechanism can be convincingly illustrated by the model experiments conducted by T. Parker and A. McDowell. They determined that for a dome to start growing on the upper boundary of a bitumen layer (which modeled salt), grooves or pits should be made on the surface of the overlying layer of a loose material. The local pressure gradient beneath the pits at the upper boundary of the bitumen layer facilitates the upward squeezing of the bitumen, and this process eventually produces a dome (Fig. 2) [3]. Salt ascends under the effect of excess pressure (but not due to its lower density), as is evident from numerous examples when salt intrudes into the upper part of the stratigraphic section whose rocks are less dense than the salt itself, and also from the development of positive topographic features filled with salt on the surface [3].

The aforementioned mechanism of the squeezing of a salt diapir differs from the hydroextrusion mechanism utilized for metal die casting in that the development of a diapir does not require a matrix with a channel through which the metal flows. In the situation with a diapir, the channels are produced during the process of squeezing where the lithostatic pressure is lower than elsewhere, because of the heterogeneity of the rock layer overlying the salt stratum.

A mathematical description of the mechanism responsible for the development of salt domes as a consequence of gravitational instability was proposed by Dobrin [4] and can be easily modified for the situation of a hydroextrusion by substituting $\Delta\rho z g$ for $\Delta\sigma_l$. This yields the following system of equations:

(1) for the squeezing force

$$F_S = 2\pi R\Delta\sigma_l;$$

(2) for the viscous drag force

$$F_{VD} = \frac{2\pi}{\omega}R\eta z\frac{dz}{dt};$$

(3) for the turbulent resistance of the diapir head

$$F_T = \frac{1}{2}\varphi\pi R^2\rho_1\left(\frac{dz}{dt}\right)^2,$$

where $\Delta\rho$ is the difference between the densities of the salt and host rock, R is the dome radius, g is the gravitational acceleration, z is the dome height, φ is the Newtonian resistance coefficient, ρ_1 is the density of the host rock, t is the time when dome starts to ascend, and η is the viscosity of the material through which the dome moves.

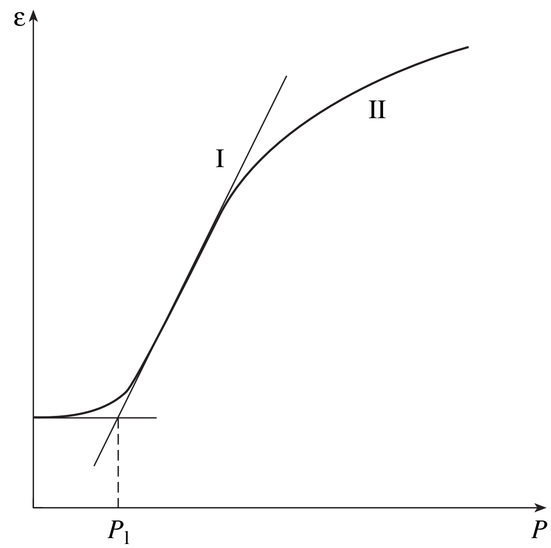

Fig. 1. Ultimate ductility during sample failure under pressure P. (I) $P < P_l$, $\partial\varepsilon/\partial P \approx 0$; (II) $P > P_l$, $\partial\varepsilon/\partial P > 0$ [2].

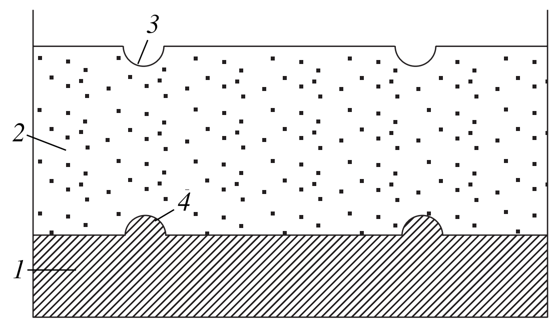

Fig. 2. Experimentally modeled origin of domes [10]. (*1*) Layer of bitumen; (*2*) layer of loose material; (*3*) pit on the surface of the loose material layer; (*4*) dome growing in the bitumen layer.

The effect of temperature on the plastic characteristics of a material under a hydrostatic pressure is such that the integral effect of temperature and pressure leads to a drastic increase in the plasticity and a simultaneous decrease in the strength. Figure 3 presents the dependence between the strain and deformation of lherzolite at various temperatures and pressures of 1000–2000 MPa [5]. Figure 4, which was drawn using the materials shown in Fig. 3, displays the temperature dependence of stress at a constant strain (equal to 10%). It can be seen that a stress of 25 MPa at a temperature of 1400°C is sufficient for lherzolite to pass into a plastic state and be squeezed toward a region with a lower lithostatic pressure. Conceivably, this mechanism acts

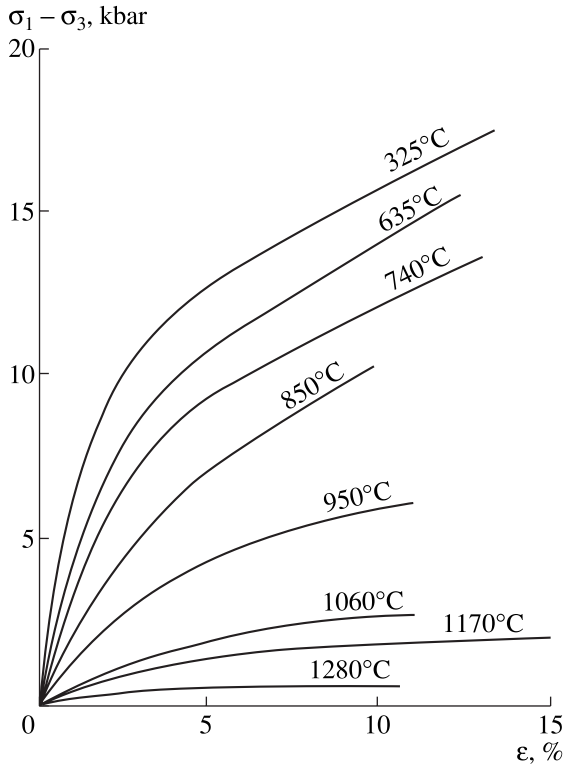

Fig. 3. Dependence between strain and stress in lherzolite at different temperatures [9].

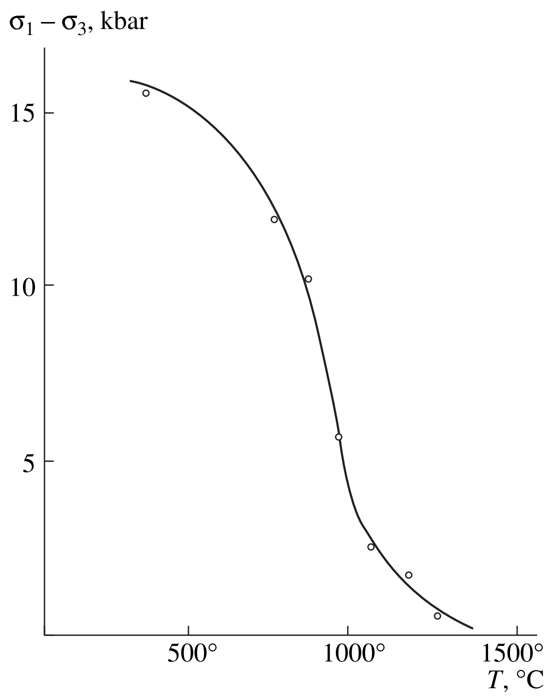

Fig. 4. Temperature dependence of stress in lherzolite at 10% strain.

during the origin of ultramafic protrusions, which are widespread in foldbelts.

A drastic decrease in the strength of the rock and an increase in its plasticity takes place when the first portions of melt are produced in it. Figure 5 demonstrates the dependence between the stress and strain for granite at various degrees of its melting at a temperature of 800°C and a pressure of 300 GPa [6]. As can be seen in this plot, when the rock contains 20% melt, the strain at which plastic flow starts to decrease to 5 MPa.

PHENOMENON OF HYDROEXTRUSION RELATED TO PHASE TRANSITIONS

A pressure needed to squeeze material in compliance with the hydroextrusion mechanism can also be generated within a closed volume if the material undergoes phase transitions associated with a volume increase, for example, partial melting. The process of partial melting has a double effect: first, the appearance of melt decreases the stress at which the plastic flow of the material can begin (Fig. 5), and, second, the simultaneous volume increase, due to melting, increases the pressure within the partial melting region relative to the lithostatic pressure. For example, a volume increase by

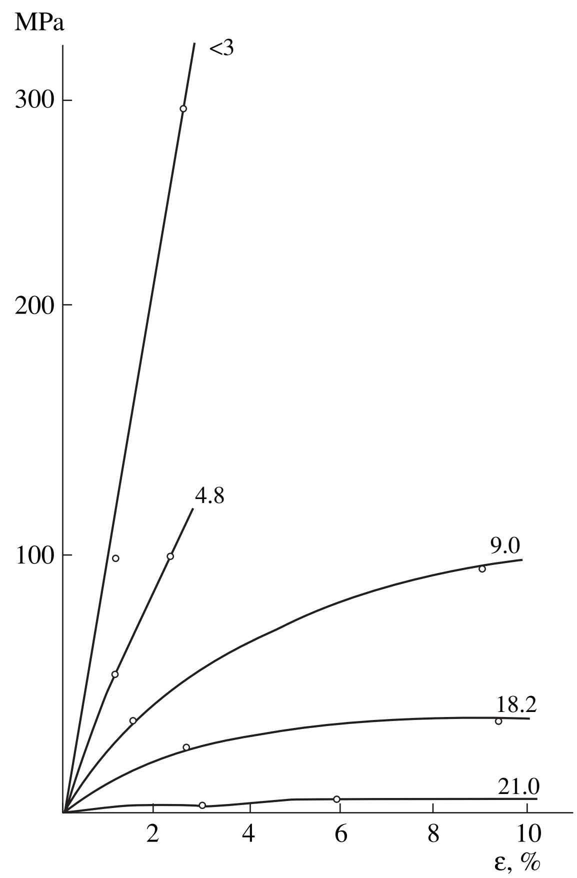

Fig. 5. Dependence of the differential stress and strain in granite on the melt concentration in the rock. Numerals near the lines show melt concentrations.

1% during the partial melting of the upper mantle material at depths of 60–100 km and the origin of basaltic melt results in a pressure increase by 20–30 MPa within the melting region.

The actual excess pressure in the melting zone can be roughly estimated from the height to which the melt can ascent in active volcanoes. The lava lake in Nyiragongo volcano is located at a height of 3200 m a.s.l., which corresponds to an excess pressure of 80 MPa (at a melt density of 2.5 g/cm^3). Taking into account that the stress required for a hydroextrusion at partial melting is equal to 5–10 MPa, the excess pressure exerted in this situation is high enough to squeeze a mixture of crystals and melt toward a zone with a lower lithostatic pressure. Conditions favorable for hydroextrusion occur during the development of granite–gneiss domes. The boundary above which the stress needed to squeeze the granitic melt is accumulated corresponds to the isotherm constraining the solidus of the rock from which the granitic melt is derived.

The ability of a partially melted material to produce hydroextrusions makes it possible to draw more definite conclusions concerning the permissible degree of partial melting under high lithostatic pressures and the means of melt separation from the solid crystalline residue. This problem is still solved purely speculatively, and, depending on the model assumed by the researcher, the degree of partial melting can reportedly vary from a few percent to complete melting.

Experiments on the partial melting of rocks under static conditions [7, 8] fail to settle this problem. As follows from Fig. 5, as soon as 20% partial melting is reached, the plastic limit of a mixture of melt and crystals decreases to 5 MPa, and the mixture itself can now be hydraulically forced out the melting zone.

In order to understand how a melt can be separated from the residue during squeezing, one should consider the state of material in the zone where the anatectic granite melt is generated. These zones are characterized by the development of multistage isoclinal folding, with the axial planes of the folds subparallel to the schistosity, a feature suggesting that the material of migmatization zones flew nearly horizontally, conformably with the stratification [9, 10]. This disharmonic folding is commonly thought to develop in relation to thrusting parallel to the axial surface of the folds [10]. Evidently, this is not the only possible explanation of the unusual deformations of rocks in the zone of anatexis. The experimental modeling of the laminar flow of material consisting of strata of different viscosity [11] indicates that these deformations are produced in open systems during flows under the effect of pressure perpendicular to the flow direction (Fig. 6). The flow is associated with the differentiation of the mixture into layers of distinct viscosity, which are enriched or depleted in the melt. The velocities of these layers are different, and the melt gradually looses crystals and homogenizes [12].

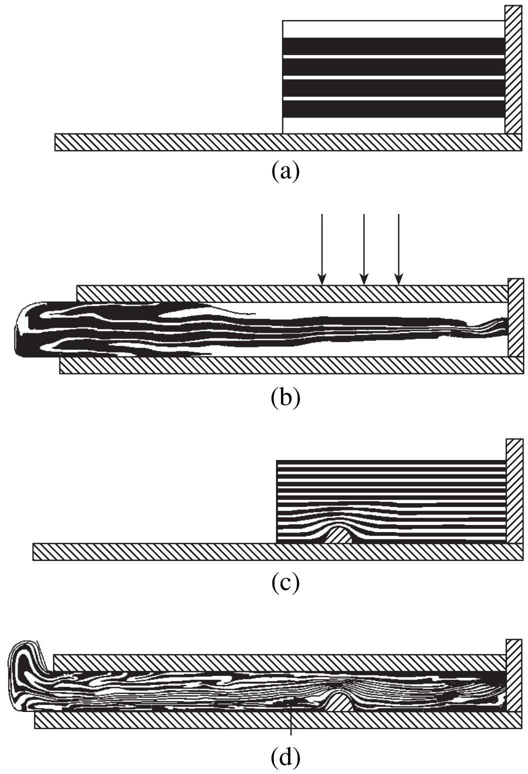

Fig. 6. Laminar and sublaminar flow of a stratified sequence with layers of different viscosities: white—material of elevated viscosity, dark—material of lower viscosity. Arrows indicate the direction of pressure. (a, b) Initial state; (c, d) material after deformation [7].

Hydroextrusions can appear in the transitional zone of the mantle when it is approached by heat fluxes from the mantle–core boundary. When the material of the transitional zone is heated at a positive dP/dT of the phase transition, the stability fields of the less dense phases should descend to greater depths, and the layer where the denser modification was stable should be characterized by a phase transition associated with a volume increase and the generation of excess pressure in the transitional zone. A volume increase by 1% at a depth of 650–700 km brings about a pressure increase by 200–300 MPa, which is sufficient for the squeezing of the material of the transitional zone towards a region with a lower lithostatic pressure. According to Grachev [13], stress in mantle plumes ranges from 100 to 800 MPa, which corresponds to a 0.5–3% volume change during the phase transition. The calculations conducted by Barsukov and Urusov [14] indicate that volume changes during phase transitions in the mantle can be as great as 4%.

If the ascent of a mantle diapir is associated with its partial melting, the process of hydroextrusion can become avalanching in character, and the partly molten material should be forced to the surface and make room for portions of material newly arriving from the transitional zone. As a consequence of this process, hot mate-

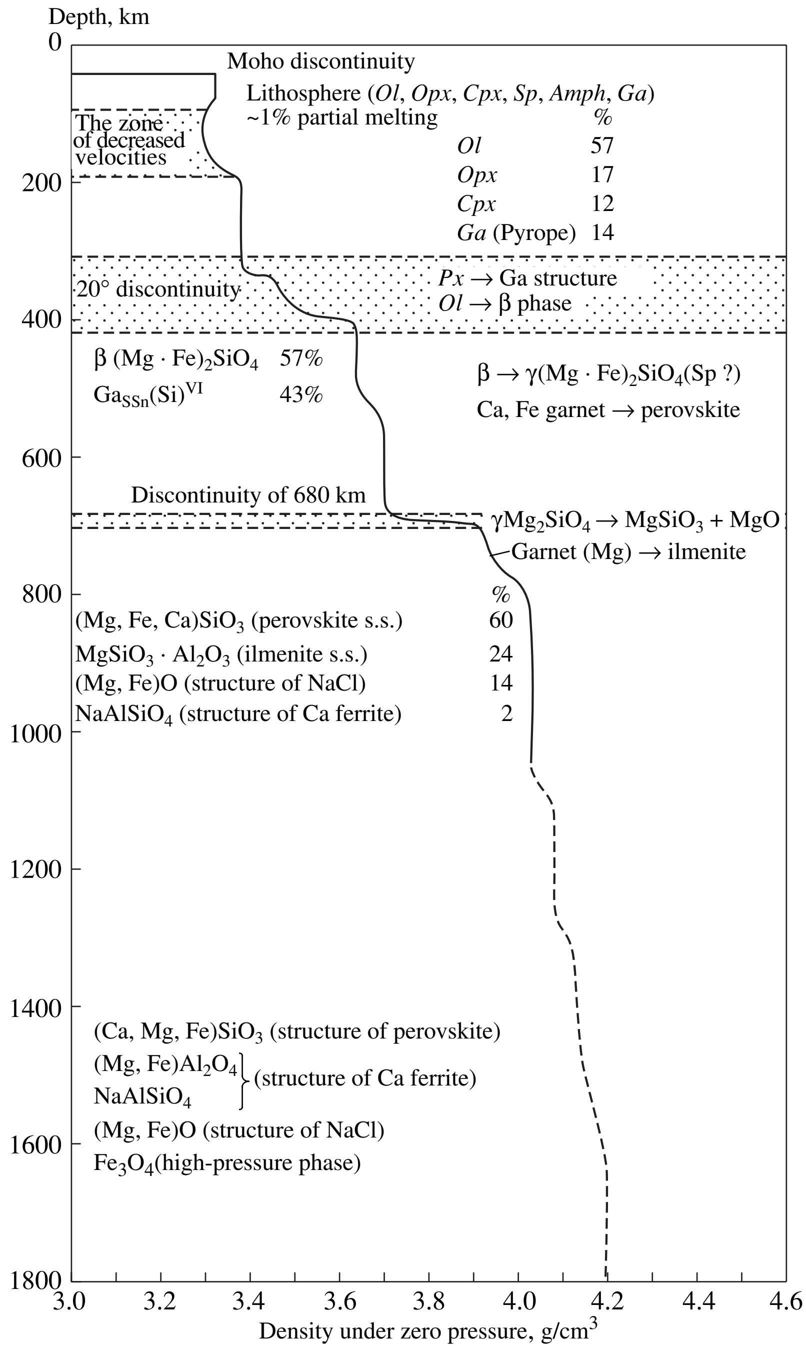

Fig. 7. Structure of the Earth's upper mantle [15].

rial from the upper mantle should ascend to the transitional zone, and, eventually, a long-lived mantle plume can be formed with roots in the lower mantle. If the upper mantle has a structure as shown in Fig. 7 [15] and the volume changes during phase transitions are as calculated in [14], the structure of this upper mantle region is the most suitable for the development of powerful vertical flows.

Of course, the list of examples of hydroextrusions in the Earth's crust and mantle can be extended. There are good reasons to believe that the mechanism of hydroextrusion operates when the hydrostatic equilibrium is restored upon the ice load on the surface is relieved after deglaciation. For this mechanism to be triggered, it is sufficient that mantle material at a certain depth reaches the limit of its transition into a plastic state under the effect of lithostatic pressure and high temperature and starts to flow toward zones with lower pressures. The degree of lithostatic compensation can correspond to different depths in discrete regions of the planet.

CONCLUSIONS

The squeezing of material under high lithostatic pressure towards regions with a lower stratigraphic load seems to be one of the principal mechanisms responsible for the development of vertical flows of material in the Earth's crust and mantle. The excess pressure needed to initiate this mechanism can be caused by a laterally uneven distribution of rock densities, as is the case when salt diapirs grow in sedimentary sequences or when phase transitions are associated with a volume increase, for example, during partial melting. This mechanism can also operate during the origin of mantle plumes if the plume is formed in the upper mantle transitional zone, where a local temperature increase induces the origin of new crystalline phases of lower density.

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