Editor's note D. L. Anderson is currently an Emeritus Professor of Geophysics at California Institute of Technology (Caltech). He received a B.S. in Geology and Geophysics from Rensselaer Polytechnic Institute in 1955 and a Ph.D. in Geophysics and Mathematics from Caltech in 1962. He is a fellow of numerous renowned scientific societies with many commendations for his contributions to Earth Sciences. He was elected to the American Academy of Arts and Sciences in 1972, the National Academy of Sciences in 1982 and the American Philosophical Society in 1990. He has received the Emil Wiechert Medal of the German Geophysical Society, the Arthur L. Day Gold Medal of the Geological Society of America and the Gold Medal of the Royal Astronomical Society, the Bowie Medal of the American Geophysical Union, the Crafoord Prize at the Royal Swedish Academy of Science. He was also conferred on the National Medal of Science in 1999 by President Clinton. He is a past President of the American Geophysical Union.

Don's scientific contributions are enormous and has trained many geophysicists who are today's world leaders. He claimed himself as a seismologist, but his recent research, beginning in mid-1980s, has mostly focused on geochemistry, which he used as a means, in combination with solid Earth geophysics, to learn how the Earth works. Don Anderson's name has become even better known in more recent years among Earth scientists of younger generations because of his enormous effort in convincing the community that mantle plume hypothesis is doubtful, which pleases some, but displeases many more——he is an independent thinker with great insights into problems, instead of following the mainstream models. He strongly believes that mantle plumes are not needed, because they do not exist, and plate tectonics theory is adequate to explain not only Earth processes along-plate boundaries, but also within-plate processes such as "hotspot" volcanisms, earthquakes etc. It is possible that the mainstream mantle plume model may still be valid, but it is also possible that "the truth may sometimes lies in the minds of minority". Time will tell, but debates will certainly expedite the revelation of the truth.

In this invited contribution, Don simply argues that physical properties of earth materials obtained in the laboratory and at low pressures do not apply to conditions of deep mantle. Elevated pressures at deep mantle conditions may not allow the development of lateral thermal buoyancy contrast, thus preventing the initiation of mantle plums. The elevated pressure also increases viscosity and reduces the efficiency of heat transfer, thus preventing the development of very narrow cylindrical forms of "plumes" in the deep mantle. He maintains that chemical stratification of the Earth is inherited from the process of Earth formation, and present-day material exchange between shallow and deep mantle is limited. Subducted oceanic lithosphere may not go into the Earth beyond ~1000 km, in contrast to some popular view of reaching the core-mantle boundary. I personally invited Don to make this contribution to Chinese Earth Science community not necessarily because I accept all of Don's interpretations, but I wish to see our Chinese scientists, in particular the younger generations, to develop independent ways of thinking, and to accept or refute ideas based on careful thinking and based on serious understanding of the observations.

(Yaoling Niu, Executive Editor, Department of Geosciences, University of Houston)

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Simple scaling relations in geodynamics: the role of pressure in mantle convection and plume formation

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Abstract **Scaling relations are important in extrapolating laboratory experiments to the Earth's mantle. In planetary interiors, compression becomes an important parameter and it is useful to explore scalings that involve volume. I use simple volume scaling relations that allow one to extrapolate laboratory experiments and upper mantle behavior, in a thermodynamically self-consistent way, to predict lower mantle behavior. The relations are similar to the quasi-harmonic approximation. Slabs and plates have characteristic dimensions of hundreds of kilometers and time constants of 100 million years, but the volume scalings predict order of magnitude higher values in the deep mantle. The scaling relations imply that the deep mantle is a sluggish system with ancient features. They imply irreversible chemical stratification and do not favor the plume hypothesis.**

Keywords: scaling relations, volume-dependent properties, sluggish flow in deep mantle, chemical stratification, no mantle plumes.

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Pressure decreases interatomic distances in solids, which has a strong non-linear effect on such properties as thermal expansion, thermal conductivity, and viscosity, all in the direction of making it difficult for small-scale thermal instabilities to form in deep planetary interiors. As a result, convection is sluggish and is large scale at high-pressures; it does not in any way resemble widely-perceived narrow mantle plumes of cylindrical form. The Boussinesq approximation assumes that density, or volume (V), is a function of temperature (T) but that and all other properties are independent of T, V and pressure (P), even those properties that are functions of V. This approximation, although it is thermodynamically (and algebraically) inconsistent, appears to be useful at low pressures; it is widely used to analyze laboratory convection and is also used in geodynamics, including whole mantle convection simulations. Sometimes this approximation is supplemented with a depth dependent viscosity or with T dependence of parameters other than density. It is preferable to use a thermodynamically self-consistent approach. To a first order, the physical properties of solids depend on interatomic distances, or lattice volumetric strain, and to a second order, on what causes the strain (T, P, composition, crystal structure etc.). This is the basis of Birch's Law[1], the seismic equation of state[2,3], various laws of corresponding states and the quasi-harmonic approximation.

Scaling parameters are available for volume-dependent properties[3]. These can be written as dimensionless (i.e. no units) volume derivatives:

Lattice thermal conductivity:	$\mathrm{d}\ln K_{\mathrm{L}}/\mathrm{d}\ln V \sim 4$,
Bulk modulus:	$\mathrm{d}\ln K_{\mathrm{T}}/\mathrm{d}\ln V \sim 4$,
Thermal expansion:	$\mathrm{d}\ln \alpha/\mathrm{d}\ln V \sim -3$,
Viscosity:	$\mathrm{d}\ln \nu/\mathrm{d}\ln V \sim 40—48$

1 Scaling to deep mantle conditions

The thickness of the thermal boundary layer (TBL) at the boundary of a fluid cooled from the above or heated from the below grows as

$$h \sim (\kappa t)^{1/2},$$

where κ is the thermal diffusity, $K_{\mathrm{L}}/\rho C_{\mathrm{p}}$ and t is time.

The TBL becomes unstable, and detaches from the surface (or from an overlying brittle or elastic layer) when the local Rayleigh number

$$Ra = \alpha g(\delta T)h^3/\kappa\nu$$

exceeds about 1000[4]. The new parameters are acceleration of gravity (g) and the temperature increase across the TBL (δT).

For parameters appropriate for the surface of the Earth the TBL becomes unstable at a thickness, h, of about 100 km[4], in good agreement with geophysical estimates of the thickness of the plates. The time-scale for this to happen is about 10^8 a. The top boundary is very viscous and stiff, and the top instability (called subduction) is controlled, in part, by faulting other than viscous deformation. So, a viscous instability calculation is not entirely appropriate but the actual lifetime of oceanic plates is approximately 10^8 a. For the bottom boundary, the deformation is more likely to be purely viscous. The implications of the volume scalings are that temperature effects on viscosity are likely to be much less in the lower mantle than at the surface. The viscosity within the boundary layer may not therefore be significantly smaller than that outside the boundary because of its higher temperature.

The specific volume at the base of the mantle is 64% smaller than that at the top[3]. The critical thickness of the lower TBL, neglecting radiative heat transfer, is therefore about 10 times larger than at the surface, or about 1000 km. If there is an appreciable radiation or chemical component to the density, then the scale-lengths in the lower mantle can be greater than this. Radiation increases the conductivity, and chemical stratification increases the stability of a layer. In any case, the observed tomographic anomalies in the lower third mantle are very large[5], much larger than upper mantle slabs (cold "plumes"), consistent with the scaling theory. The ultra-low velocity regions near the base of the mantle are likely to represent chemical anomalies and partial melt zones, not purely thermal anomalies. The velocities are too low to be thermal alone ——they require a loss of rigidity, as in a fluid. Claims of narrow plumes are common when only the first arriving P-waves are used in tomographic studies. Narrow anomalies can result when isolated ray bundles sample a large anomaly. Tomographic models that use large amounts of data, including surface waves, S-waves, reflections, waveforms and free oscillations, are less likely to have artifacts than models based on P-waves alone.

If the lower mantle TBL layer is of the order of 1000 km thick and the temperature rising across it is about 1000 K, then the volume scalings of the thermal parameters mean that the Rayleigh number of the lower mantle is about $10^3—10^4$ lower than the number calculated for whole-mantle convection and zero-pressure properties. The lifetime of the lower TBL, and therefore the ages of lower mantle thermal features are $>10^9$ a and possibly the age of the Earth. If radiation increases the thermal diffusivity by a factor of 8, this reduces the timescale by a further factor of 4. The surface TBL cools rapidly and becomes unstable quickly because of the magnitude of the thermal properties. The same theory, scaled for the density increase across the mantle, predicts large-scale and long-lived features above the core. Narrow, rapidly rising plumes are certainly precluded. The interest of the geophysical community in the plume hypothesis is based on laboratory injection experiments which cannot simulate the high Prandtl number of the mantle or the effects of pressure on thermal properties. The parameter range of most geodynamic calculations and experiments is outside the plausible mantle range of the mantle.

2 Temperature

Temperature and pressure both affect the volume of a solid and it is the volume that is the scaling parameter in the quasi-harmonic approximation and other equations of state. Pressure suppresses the effect of temperature on thermal expansion and, therefore, on all volume dependent properties. Under lower mantle conditions P, composition and phase changes become the important controls on volume, buoyancy and seismic parameters. In general, T and P play opposing roles. One exception is the radiative part of the thermal conductivity. This increases as T^3 and possibly contributes to high thermal conductivity of the deep mantle. Model calculations show that taking this into account can significantly affect the thermal history of the mantle and the style of mantle convection[6]. In the present context this is important since P and T combine to increase the importance of non-convective heat transfer and to suppress, or decrease the vigor of mantle convection.

3 The low-spin transition in iron

Fe and Mg have similar ionic radii at low-pressure and substitute readily for each other in upper mantle minerals. Fe/Mg is more-or-less uniformly partitioned among the major minerals. Spinels can have higher Fe-contents (thus low Fe/Mg) but the amount of Fe in the major phases controls the transparency to radiation, unless almost all the FeO is in a small volume fraction of very FeO-rich phases, which may be possible in the deep mantle. FeO content and low temperatures suppress the role of radiative transport of heat in the upper mantle. Radiative heat transfer (vs. conduction and convection) does not require a material medium (it works through air or even vacuum). Heat can be transferred by radiation through glass and transparent crystals, particularly at high temperatures, unless the amount of Fe reduces the transparency. Fe undergoes a spin-transition at high pressures with a large reduction in ionic radius[7,8]. The major minerals in the deep mantle are predicted to be almost Fe-free perovskite [$MgSiO_3$] and Fe-rich magnesio-wustite [(Mg,Fe)O]. This has several important geodynamic implications. Perovskite, being the major phase, will control the thermal conductivity and viscosity. Radiative conduction is expected to be high in Fe-poor minerals and viscosity is expected to be low[8]. Over time, a dense magnesio-wustite-rich layer may accumulate, irreversibly, at the base of the mantle, and, in addition, may interact with the core. The lattice conductivity of this iron-rich layer will be high and the amount of heat radiated through the crystal lattice should be low but the trade-offs are unknown. A thin layer convects sluggishly (because of the h^3 term in the Rayleigh number) but its presence slows down the cooling of the mantle and the core. The overlying FeO-poor layer may have high conductivity. This part of the mantle will also convect sluggishly. If it represents about one third of the mantle (by depth) it will have a Rayleigh number about 30 times less than Rayleigh numbers based on whole mantle convection and orders of magnitude less than Ra based on $P = 0$ properties. A post-perovskite phase in the deep mantle may have similar effects.

The low thermal expansivity at high pressures means that moderate jumps in intrinsic density between successively deeper layers in the mantle can permanently stabilize chemical layering[9−11]. Layers having high density and high temperature can cause lateral temperature gradients in the layer in which the upwelling plumes are confined but cannot advect these lateral temperature gradients into the overlying layers. A convectively stable layer (low Rayleigh number) will not have any lateral temperature gradients. Unreasonably high and lower mantle temperatures do not occur since most of the radioactivity is in the crust and upper mantle[3], and heat is conducted, or radiated away.

4 Discussion

The effect of pressure on physical properties plus the upward transfer of large-ion-lithophile elements, including the radioactive elements, results in an irreversibly stratified mantle that is almost opposite to current global geochemical and geodynamic models. The deep mantle layers probably have higher Fe and Si contents than pyrolite and less U, Th and K than the shallow mantle. Mid-plate volcanism is probably controlled by the stress state of the lithosphere and variable fertility of the upper mantle rather than by narrow thermal plumes from the deep mantle. A partially molten and heterogeneous asthenosphere is consistent with melting relations in volatile-bearing rocks. Pressure effects mean that the injection experiments and Boussinesq calculations used to support the plume hypothesis are not relevant to the Earth.

5 Summary

Pressure, the spherical shape of the Earth (the area of the core-mantle boundary is much less than the surface area) and the distribution of radioactive elements in the mantle break the symmetry between the surface and lower TBLs of the mantle. The surface TBL is responsible for plate tectonics and for organizing convective motions in the upper mantle[4,5,12]. The lower TBL heats slowly since only a small amount of heating is available, from either the mantle or the core[3]. This contributes to the sluggishness of deep mantle convection. The slow heating and the inferred low thermal buoyancy requires that enormous features must develop to carry away any heat not conducted or radiated away. This is in marked contrast to conditions at the surface. Pressure also contributes to the chemical stratification of the mantle and the inability of temperature to overcome intrinsic density contrasts[9]. At high pressures, temperature has little effect on density and other physical properties. The exception is radiative conductivity which reinforces the P effect on lattice conductivity in the direction of suppressing both large-scale and small-scale mantle convection in the deep mantle. Mantle convection is evidently characterized by narrow downwellings and broad diffuse upwellings[13], being opposite of the plume model[14] but consistent with plate tectonics and mantle tomography[5]. Fig. 1 shows the differences

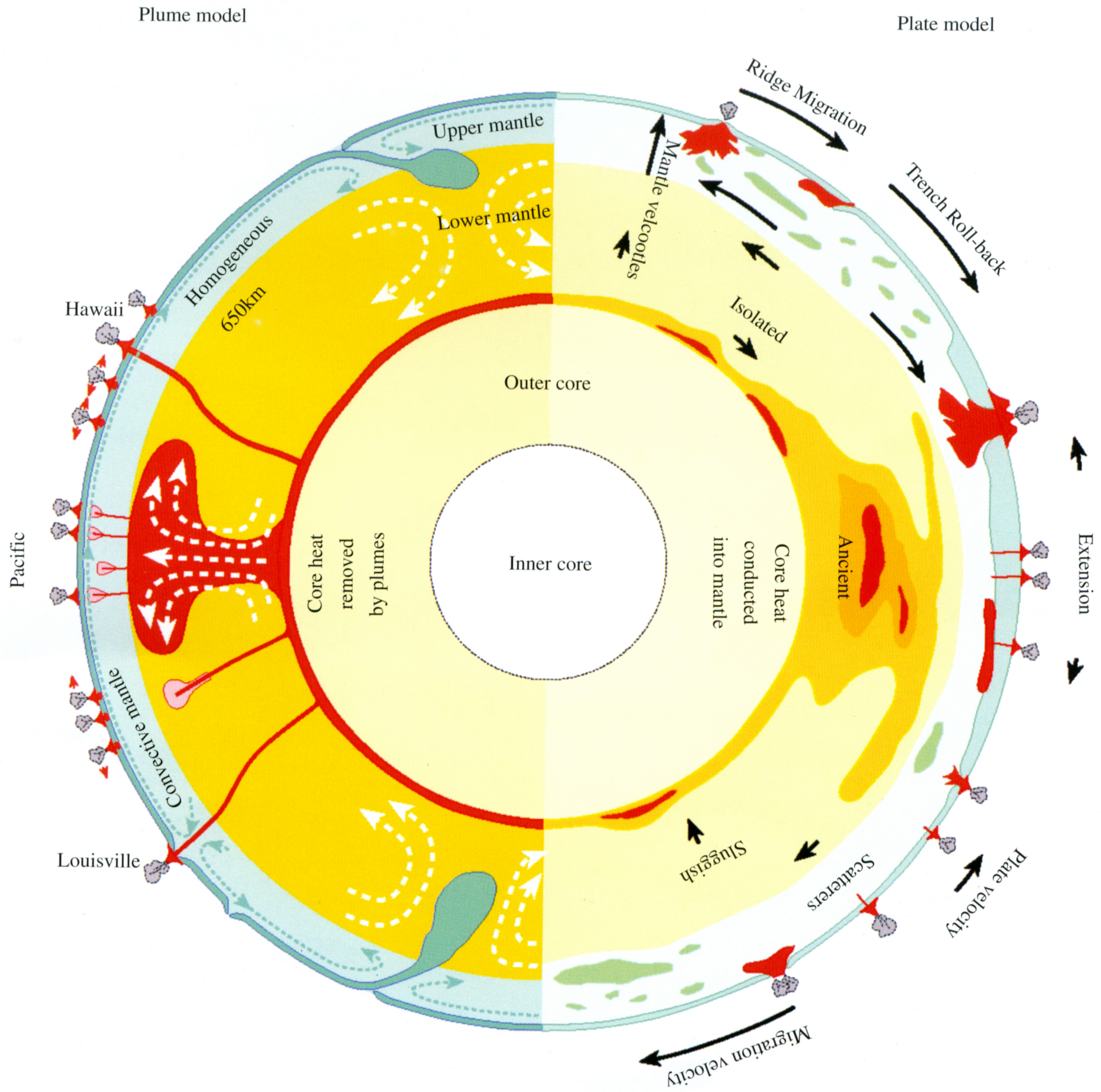

Fig. 1. A schematic cross-section of the Earth showing the plume model (to the left, from Courtillot et al.[15]) and the plate model (to the right). The left side illustrates three proposed kinds of hotspots/plumes. In the deep mantle, narrow tubes (inferred) and giant upwellings coexist. Melting anomalies are localized by narrow upwelling plumes, which bring material from great depth to the volcanoes. In the various plume models, the deep mantle provides the material and the deep mantle or core provides the heat for hotspots; large isolated but accessible reservoirs rather than dispersed components and sampling differences account for geochemical variability. Deep slab penetration, true polar wander, core heat and mantle avalanches are important. Red regions are assumed to be hot and buoyant; blue regions are cold and dense. The schematic is based on fluid dynamic experiments that ignore pressure effects and have low viscosity relative to conductivity, in contrast to mantle properties argued for in this article. The right side indicates the important attributes of the plate model, variable depths of recycling, migrating ridges and trenches, concentration of volcanism in tensile regions of the plates, inhomogeneous and active upper mantle, isolated and sluggish lower mantle, and pressure-broadened ancient features in the deep mantle. Low-density regions in both the shallow and deep mantle cause uplift and extension of the lithosphere. Melting anomalies are localized by stress conditions and fabric of the plate and fertility of the mantle. Large-scale features are consistent with the viscosity-conductivity-thermal expansion relations of the mantle. In the plate model the upper mantle (down to about 1000 km, the Repetti Discontinuity) contains recycled and delaminated material of various ages and dimensions. These materials equilibrate at various times and depths. Migrating ridges, including incipient ridges and other plate boundaries, sample the dispersed components in this heterogeneous mantle. The upper 1000 km (Bullen's Regions B & C) is the active and accessible layer. The deep mantle (Regions D and D″), although interesting and important, is sluggish and inaccessible. The geochemical components of MORB, OIB, etc. are in the upper mantle and are mainly recycled surface materials.

between the classical plume model, and a geodynamic model that puts volume scaling into effect (schematic).

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