Role of a low-viscosity zone in stabilizing plate tectonics: Implications for comparative terrestrial planetology

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Abstract

[1]   Earth's near-surface layer, its lithosphere, is broken into quasi-rigid plates that form the upper thermal boundary layer for mantle convection. Since the discovery of plate tectonics, it has been widely conjectured but only recently demonstrated that this peculiar style of convection may be facilitated by an upper mantle low viscosity zone (LVZ) over which the plates glide easily. The LVZ, or "asthenosphere," concept dates from 19th century investigations of isostatic support of mountain belts and is supported by modern evidence for a seismic low velocity zone and by studies of postglacial rebound and dynamic compensation of the Earth's gravity field. Here we show in both two-dimensional (2-D) Cartesian and 3-D spherical Earth models that combining a pronounced LVZ and a plastic yield stress to allow localized weakening of the cold thermal boundary layer results in a distinctly plate tectonic style of convection, with ~30% toroidal surface motion for the 3-D case. Recycling of water into the upper mantle at subduction zones is a plausible cause of Earth's LVZ, whereas Venus is dry and lacks both an LVZ and plate tectonics.

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1. Introduction

[2]   A low viscosity zone (LVZ) separating the base of the lithosphere from the deeper mantle has been postulated on the basis of a variety of evidence [see, e.g., *Cathles*, 1975; *Hager and Richards*, 1989; *Mitrovica*, 1996], and this rheological LVZ is probably related to the seismic "low velocity zone" found beneath oceanic and tectonically active regions at depths of 100-300 km [e.g., *Hales et al.*, 1968; *Grand and Helmberger*, 1984]. The role of an LVZ in regulating or promoting plate tectonics has not previously been systematically investigated in full convection models, because geodynamicists have only recently achieved the capability to simulate extreme viscosity contrasts and shear failure in the lithosphere. Using a new numerical modeling technique well suited to this challenge [*Yang and Baumgardner*, 2000], we investigate here an important and straightforward question: Given a reasonable failure mechanism for the lithosphere, does an LVZ facilitate a plate tectonic style of mantle convection?

[3]   Plate treatment persists as a serious challenge to mantle convection modelers, because it is difficult to simulate shear failure at plate boundaries. Approaches include highly nonlinear (non-Newtonian) viscous creep [*Weinstein and Olson*, 1992], prescribed frictional faults, strain rate weakening rheologies, and viscoplastic yielding [*Bercovici*, 1993; *Zhong et al.*, 1998; *Tackley*, 2000b] (see also *King et al.* [1992] for a comparison of several methods for numerical simulation of plates in mantle convection models). *Moresi and Solomatov* [1998] recently explored the effects of strongly temperature dependent viscosity combined with a plastic yield stress: the former causes the cold upper boundary layer (lithosphere) to be strong, while the latter allows this boundary layer to fail locally in regions of high

stress. *Moresi and Solomatov* [1998] identified three styles of convection similar to those described earlier by *Weinstein and Olson* [1992] for non-Newtonian lithospheric behavior: (1) a "frozen lid" regime at high yield stress in which the cold upper boundary layer is immobile, (2) a "mobile lid" regime at low yield stress in which ubiquitous plastic failure of the lithosphere yields a continuously mobile upper boundary layer, and (3) a "transitional" regime that switches episodically between the frozen and mobile regimes. Regime 1 appears applicable to Mars (a "one-plate" planet) and the Moon, while regime 3 may describe the distributed deformation and episodic overturn of Venus' lithosphere [*Strom et al.*, 1994; *Weinstein*, 1996a, 1996b; *Moresi and Solomatov*, 1998]. However, no stable plate-like (Earth-like) regime was identified.

[4]   Three-dimensional mantle convection models show that a low-viscosity upper mantle promotes convection in a few large elongated cells bounded by a network of linear downwellings [*Bunge et al.*, 1996]. This discovery suggests that a sublithospheric LVZ might stabilize a plate-like convection regime in the system explored by *Moresi and Solomatov* [1998]; specifically, a regime in which the horizontal motions of the upper boundary layer are stable, piecewise-constant, and separated by narrow zones of high rates of strain. Further indications that this might be so come from mechanical models of plates that show that one needs an LVZ in order for lithosphere to remain plate-like near fault zones [*Zhong et al.*, 1998]. Here we demonstrate that an LVZ acts strongly to stabilize plate tectonics, first exploring model parameter space with computationally less demanding two-dimensional (2-D) models, and then demonstrating similar plate-like behavior in 3-D spherical calculations.

2. Methods

[5]   We use a matrix-dependent transfer multigrid method [*Alcouffe et al.*, 1981; *Yang and Baumgardner*, 2000] to solve the momentum equation with strong spatial variations in viscosity. The 2-D models are executed in a long box of 4 - 1 aspect ratio (512 - 128 cells) that is internally (radioactively) heated, cooled from the top, and insulated at the bottom, with free-slip top and bottom boundaries and wraparound end boundary conditions. Earth-like values are used for mantle depth (2890 km), density (3400 kg/m^3), thermal expansivity (2.5 - 10^{-5}/K), thermal conductivity (4 W/m-K), specific heat (1000 J/kg-K), and radioactive heating (5 - 10^{-12} W/kg).

[6]   We use a strongly temperature-dependent Newtonian-viscous/perfectly plastic rheological law with an activation energy of 100 kJ/mole, a mantle-averaged viscosity consistent

with postglacial rebound studies [*Cathles*, 1975; *Mitrovica*, 1996], and a plastic yield stress that we vary in this study. The activation energy used here is reduced about a factor of 5 from laboratory values [*Karato and Wu*, 1993] but still produces 6 orders of magnitude in viscosity variation over the temperature range of the models. In a classic study, *Christensen* [1984] showed that the combination of non-Newtonian ($n = 3$) power law rheology combined with more realistic activation energies results in convection resembling Newtonian convection with activation energies similar to that used here. For the present purpose of studying the effects of an LVZ, Newtonian rheology with a reduced activation energy is an appropriate approach.

3. Cartesian 2-D Results

[7]   Figure 1a shows a map of viscosity versus. temperature and strain rate for a lithospheric yield stress of 80 MPa. High strain rates lead to low effective viscosity and local reduction of the effect of cold temperature in the upper boundary layer, giving rise to shear failure in the lithosphere above mantle upwellings and downwellings.
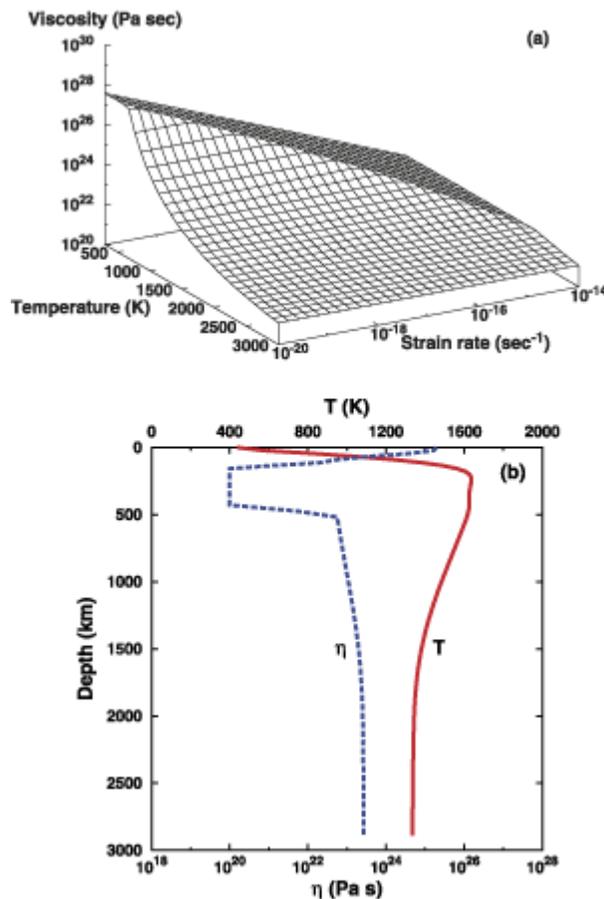

Figure 1.   *(a) Map of viscosity versus temperature and strain rate for a*

Newtonian (linear) viscous fluid with exponential dependence of viscosity upon temperature and a plastic yield stress of σ_y = 80 MPa. One may consider the lithosphere to be pervasively faulted, so that frictional slip may occur in any orientation when a characteristic fault strength, or yield stress, is exceeded. When the local second stress invariant exceeds the yield stress, the local viscosity is reduced until the local stress is reduced to the yield stress value (thus decreasing the local strain rate.) Otherwise, viscosity is proportional to exp(E/RT), where the activation energy E is 100 kJ/mole, R is the ideal gas constant, and T is temperature. This results in ~6 orders of magnitude viscosity contrast across the full range of temperatures in the convection models. (b) Temperature (solid red line) and viscosity (dotted blue line) versus depth in the mantle for a vertical profile about halfway between upwelling and downwelling structures in Figure 2b. Viscosity is reduced by a factor of 100 when the temperature reaches a value characteristic of the base of the lithosphere. This reduction is maintained to a depth of 500 km, at which point the viscosity increases by a factor of η* = 1000. The reference viscosity in each calculation is adjusted to maintain an overall mantle viscosity consistent with postglacial rebound values [Cathles, 1975; Mitrovica, 1996].

[8] We introduce an LVZ in our models by prescribing an interval of reduced viscosity, perhaps caused by the presence of volatiles, probably water [*Hirth and Kohlstedt*, 1996; *Karato and Jung*, 1998], just below the thermal boundary layer (Figure 1b). When the mantle geotherm (solid red line) exceeds a temperature that represents the lower extent of the lithosphere, viscosity is reduced by a factor of 100. This low viscosity continues to an arbitrary cutoff depth of 500 km, at which point the viscosity increases by a factor of η*, which we vary from 1 to 10,000, resulting in a "notch" in the viscosity curve (dotted blue line, Figure 1b). This procedure for introducing an LVZ has the advantage of allowing low viscosity to intrude naturally to shallow depths beneath warm upwelling zones while preserving the high viscosity of cold downwellings. We have found that weakening beneath ridges (perhaps due to partial melting) is important in promoting plate-like behavior, a finding similar to that of *Tackley* [2000a], who has recently shown that a sublithospheric "asthenosphere" weakened due to partial melting is effective in producing plate-like behavior. We note, however, that partial melting may actually strengthen the mantle rather than weaken it [*Hirth and Kohlstedt*, 1996], whereas geophysical arguments for the existence of an LVZ based on observations do not constrain its cause or detailed geometry.

[9] All models have been run to secular equilibrium to characterize their behavior with respect to the LVZ viscosity contrast η* and the yield stress σ_y. Model behavior is not strongly dependent on Rayleigh number [*Moresi and Solomatov*, 1998] (see, e.g., *Davies* [1986] for a definition), whose volume-averaged value for the models shown is ~3 - 10^8. A model with σ_y = 80 MPa and η* = 1000 is illustrated in Figure 2a (log

viscosity) and 2b (temperature). The LVZ intrudes beneath spreading zones and is absent beneath convergence zones. Thermal heterogeneity for this snapshot is dominated by two slowly migrating convergence zones. (The geotherm shown in Figure 1b is taken from this case, midway between zones of convergence and divergence.) Convection appears "normal" in Figure 2b, but the horizontal surface velocity profile in Figure 3 (solid green line) shows that the upper boundary layer is almost perfectly plate-like, with broad regions of constant velocity separated by highly localized zones of intense strain. This behavior is quite stable in time.
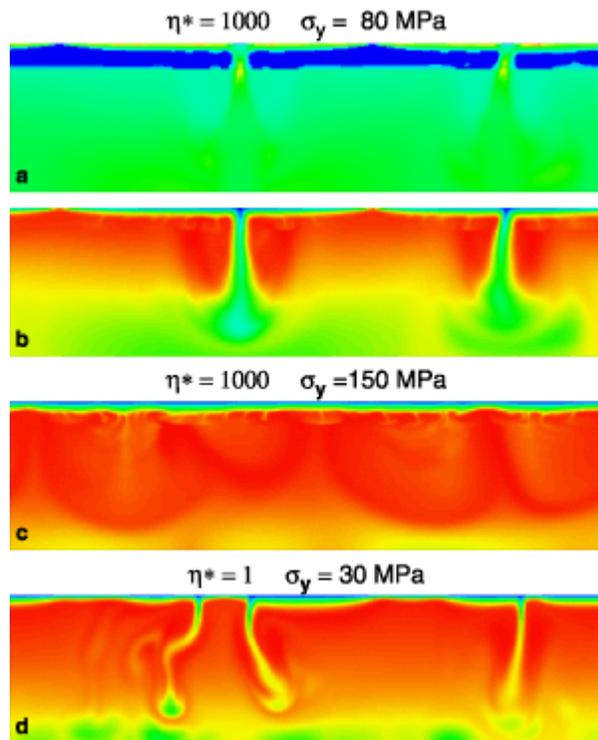

Figure 2. *(a) Log viscosity for the plate-like case, with blue representing low viscosity (10^{20} Pa s) and red high viscosity (1.3 - 10^{28} Pa s). The LVZ is interrupted by two large cold downwellings, and it intrudes near the surface at the two major upwellings. (b) Temperature for the plate-like case, with blue cold (44°C) and red hot (1437°C). Note the slightly subadiabatic lower mantle fed by two large, stable downwelling structures. (c) Temperature for the frozen lid case. Note the pervasive small-scale convection beneath the immobile lithosphere. (d) Temperature for the mobile lid case. The thermal heterogeneity structure reflects downwellings that are very unstable in time or chaotic.*
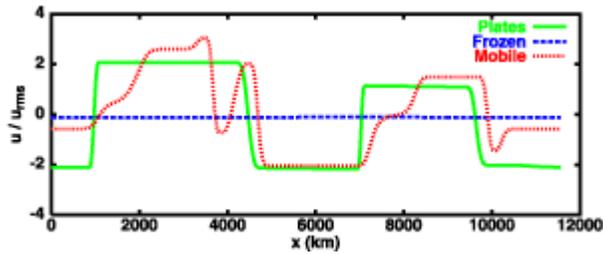
Figure 3. *Horizontal surface velocity profiles for the plate-like (solid green line), frozen lid (dashed blue line), and mobile lid (dotted red line) cases. Horizontal velocities are normalized by the average horizontal velocity of the mantle interior. This normalization clearly distinguishes the frozen and mobile lid cases, even though both show distributed strain in the lithosphere. The plate-like case is distinguished by an almost perfectly piecewise-constant horizontal velocity profile and by its remarkable stability in time.*

[10] Figure 2c shows the temperature contours for an otherwise identical case, but with increased σ_y = 150 MPa. Increased yield stress prevents failure of the upper boundary layer, rendering it immobile (Figure 3, dashed blue line). Small-scale convection occurs beneath the frozen lid. Figure 2d shows a case with η^* = 1 (no LVZ) and reduced σ_y = 30 MPa, yielding mobile lid behavior. The horizontal surface velocity profile shows isolated patches of constant velocity separated by broad zones of continuous deformation, and convection is very unsteady (chaotic).

[11] A more complete perspective is obtained from the parameter space map in Figure 4, in which σ_y varies along rows and η^* varies along columns. For η^* = 1 (top row), we reproduce the results of *Moresi and Solomatov* [1998], with blue dots indicating the frozen lid regime, red dots a mobile lid, and split dots the transitional regime. (The somewhat plate-like solutions obtained recently in 3-D by *Trompert and Hansen* [1998] correspond to the latter transitional regime.) The results of *Weinstein and Olson* [1992], using a non-Newtonian lithosphere instead of viscoplastic failure, also correspond roughly to the results represented in the first row of Figure 4. As η^* increases, plate-like behavior fills the transitional regime (green bars). Composite symbols in Figure 4. indicate alternation among the different modes of behavior. The plate-like regime broadens (in terms of σ_y) with increasing η^*, verifying systematic stabilization of plate-like behavior by an LVZ for viscosity contrasts 2 orders of magnitude and larger. Smaller viscosity contrasts may suffice for more severe forms of strain rate weakening in the lithosphere [*Bercovici*, 1993]. The development of a broad region of stable, plate-like behavior from a narrow zone of transitional behavior seen in Figure 4. is the main result of this paper and is consistent with the recent 3-

D Cartesian results of *Tackley* [2000a]. We note that Tackley finds more plate-like behavior in 3-D geometry without an LVZ than is found for similar 2-D cases, suggesting that 3-D geometry also favors the formation of plates.
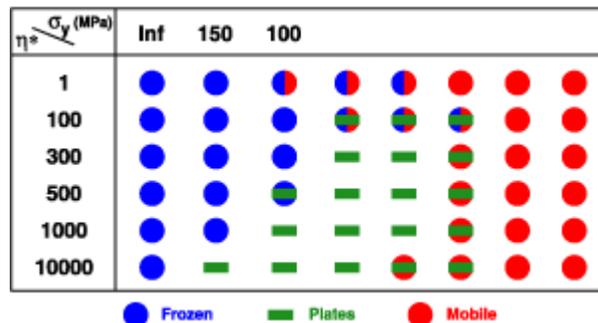

Figure 4. *Character of upper boundary layer (lithosphere) motion ("frozen, plates, mobile") as a function of yield stress and viscosity contrast for the 2-D numerical models. (Note that neither the vertical nor horizontal axes are linear in the model parameters.)*

4. Spherical 3-D Model

[12] Do these 2-D results hold for 3-D spherical geometry? We have executed a case similar to the plate-like case shown in Figures 2a and 2b using a 3-D spherical version [*Yang*, 1997] of the same multigrid finite element method. Heating is again internal, with strongly temperature-dependent viscosity and a plastic yield stress of 140 MPa for the lithosphere and 3 orders of magnitude viscosity reduction in a ~300 km thick LVZ beneath the lithosphere. The calculation was begun from random initial thermal perturbations (random spherical harmonic coefficients) and run for many overturn times (equivalent to ~2 billion years of Earth time) to secular equilibrium. The upper surface boundary condition was free-slip, as was the boundary condition at the core-mantle boundary, throughout the run. The Rayleigh number is reduced about a factor of five from Earth-like values, due to computational limitations.

[13] Figure 5 shows log viscosity and surface velocities for the 3-D spherical model at secular equilibrium. The solution is very plate-like, with localized zones of high strain rate separating large regions of nearly constant angular velocities. Excluding net rotation, ~30% of the surface velocity field is toroidal motion, characteristic of plate motions on a sphere and similar to Earth [*Hager and O'Connell*, 1978; *Lithgow-Bertelloni et al.*, 1993]. The internal thermal heterogeneity spectrum is peaked at spherical harmonic degree 2, also reflecting a pattern of flow similar to Earth [*Su and Dziewonski*, 1991]. *Tackley* [2000a]

shows comparisons between cases with and without an LVZ in 3-D Cartesian geometry at modest Rayleigh number and demonstrates the increased "plateness" of surface motions induced by an LVZ. The 3-D spherical run shown in Figure 5 is mainly for demonstration and a more thorough exploration of parameter space in spherical geometry and at more Earthlike conditions (increased spatial resolution of plate "boundaries" and higher Rayleigh number) awaits the availability of considerably greater computational resources. Neither Tackley's nor our models give rise to transform-like plate boundaries, so that another piece of the rheological puzzle still remains elusive, probably owing to the isotropic nature of the failure law used so far in these convection models.
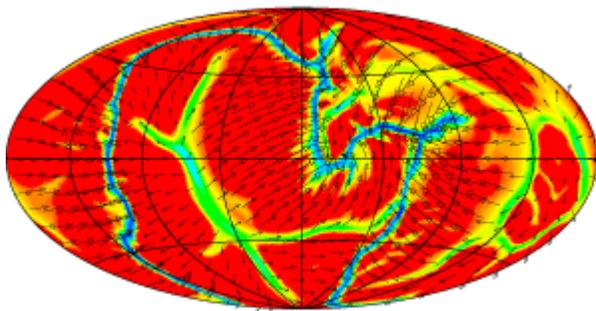

Figure 5. *Surface planform of convection for the 3-D spherical calculation. The color contours are for log viscosity, with deepest blue corresponding to 10^{22} Pa-s and red corresponding to 3×10^{23} Pa-s. High strain rate zones (blue and green) separating plates show reduced viscosity due to plastic yielding. An LVZ (not shown) of viscosity contrast 1000 lies beneath the lithosphere. Arrows show the surface velocity field, which is plate-like in character. The largest arrows represent velocities of 8.3 cm/yr. Grid resolution is ~50 km (compared to 25 km for the 2-D models), which is the finest mesh we can run on the 128 processor Cray T3E. Finer resolution would allow us to model higher Rayleigh number convection and hence reduce the width of the weak zones between the plate-like regions. The reduction in Rayleigh number, relative to the 2-D models, is via an increase in specific heat, rather than by decreasing viscosity. For the 3-D model the radial viscosity variations defining the LVZ are smoother than for the 2-D models, with the sublithospheric reference viscosity reduced by a constant factor of 1000 from ~140 to 400 km depth relative to both the surface and to the lower mantle. The yield stress in this case is 140 MPa, a value that may have just yielded frozen lid behavior in the 2-D models (see Figure 4.). Given that we are now in spherical geometry, that the Rayleigh number is reduced, and that the LVZ structure is smoother, it is not surprising that the yield stress range for plate-like behavior is shifted slightly.*

5. Discussion

[14] The mechanism by which an LVZ promotes plate tectonics is not entirely obvious. The LVZ reduces tractions on the base of the lithosphere, making plates less likely to deform except in established zones of failure. However, even without a plastic

failure rheology, a low-viscosity upper mantle promotes a style of convection with widely separated linear downwellings [*Bunge et al.*, 1996], an effect that is not well-understood, and both mechanisms clearly contribute to plate-like behavior. It is important to recognize that it is not merely a weak zone beneath the plates that induces stable, plate-like behavior over a broad parameter range. In fact, models with strong but "breakable" plates over a weaker mantle fail in this regard, as is apparent from previous work [e.g., *Weinstein and Olson*, 1992; *Moresi and Solomatov*, 1998]. Rather, plate-like behavior is promoted by a channel of low viscosity, or weakness, beneath a breakable lithosphere. In fact, cases we have run with much narrower LVZ's exhibit plate-like behavior just as readily as those summarized in Figure 4.

[15]   Several cautions are in order before applying the results of this study: First, our viscoplastic failure law causes plate boundary formation in response to instantaneous local stresses. In reality, Earth's plate boundaries appear to persist indefinitely as weak zones, as ancient plate boundaries are commonly reactivated during plate motion rearrangements [e.g., *Gurnis et al.*, 2000]. The values of σ_y for which we obtain plate-like behavior (50-150 MPa) are reasonable for Earth's lithosphere [*Brace and Kohlstedt*, 1980]. However, major established fault zones may be weaker (10-20 Mpa) [*Lachenbruch and Sass*, 1980; *Zoback et al.*, 1987], and other failure laws may better describe the formation and persistence of plate boundaries. The values of $\eta*$ and the thickness of the LVZ channel we have used are larger than some estimates [*Hager and Richards*, 1989; *Mitrovica*, 1996], so it will be important to determine how different lithospheric failure mechanisms affect the LVZ characteristics required for plate-like behavior to occur. We also note that our models are applicable mainly to Earth's oceanic lithosphere and do not account for the effects of continental lithosphere and crust on plate tectonics. The fact that much subduction of oceanic lithosphere occurs along continental margins, the likelihood that the LVZ is greatly diminished, if not completely absent, beneath continental lithosphere [*Ricard et al.*, 1991], and the fact that plate tectonics often does not apply to continental interiors all suggest avenues for more sophisticated modeling work in the future.

[16]   With these qualifications in mind our results suggest the following qualitative interpretation of the tectonic styles of Venus, Earth, and Mars: Mars is a frozen lid planet. Earth is dominated by a plate tectonic style of convection due to a pronounced LVZ and weak fault zones in the lithosphere, both of which may be related to the presence of water in the upper mantle and crust [*Hirth and Kohlstedt*, 1996; *Karato and Jung*, 1998; *Brace and Kohlstedt*, 1980]. Venus, whose composition and size are similar to Earth, may be transitional between

mobile and frozen regimes, with possible episodic overturn of its lithosphere [*Strom et al.*, 1994], or is perhaps in the frozen regime, with episodic volcanic resurfacing [*Reese et al.*, 1999]. Venus lacks both free water and an LVZ, which may explain its lack of plate tectonics [*Phillips*, 1990; *Solomon et al.*, 1991; *Kaula*, 1990, 1995]. Recycling of volatiles at subduction zones may hydrate Earth's upper mantle, in turn promoting plate tectonics (and subduction), suggesting a potentially important feedback mechanism.

Appendix A: Notes on Validation of Numerical Methods

[17]   The 2-D code used in this study was benchmarked for constant viscosity convection in *Travis et al.* [1990], and the variable viscosity version of the code is described in detail by *Yang and Baumgardner* [2000]. No 2-D benchmark exists for the strong viscosity variations and high Rayleigh numbers treated in this paper, although the general agreement of our results with those of *Tackley* [2000a] may be considered as a qualitative benchmark at these extreme conditions.

[18]   The 3-D spherical code TERRA was benchmarked for constant viscosity convection by *Bunge* [1997], who found good agreement (1.5% or less differences) with the results of *Glatzmaier* [1988] for Nusselt number, peak velocities, and peak temperatures. Table A1 summarizes the Nusselt number results for two standard 3-D spherical convection cases that have been computed by a number of authors:

[19]   These benchmark cases are for relatively low Rayleigh number, and there are no time-dependent or variable viscosity benchmarks (of which we are aware) for 3-D spherical convection. The variable viscosity formulation of TERRA is described by *Yang* [1997]. The accuracy of the multigrid momentum solver for TERRA was demonstrated by *Baumgardner and Frederickson* [1985], who compared numerical solutions of the Poisson equation on the sphere with analytical solutions. The momentum solver also gives excellent (<2% error for harmonic degrees 1-8) agreement with analytical solutions [*Hager and O'Connell*, 1981] for instantaneous poloidal flow generated by internal density anomalies. Efforts are underway within the geodynamics community to establish a set of benchmarks for high Rayleigh number, variable viscosity convection.

Acknowledgments

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