Effects of Lithospheric Strength on Convection in the Earth's Mantle

by

Clinton Phillips Conrad

Abstract

Convection in Earth's mantle is driven largely by horizontal density gradients that form when cold, dense, mantle lithosphere descends into the mantle interior, either through subduction for plate-scale flow, or as localized convective instability beneath lithospheric plates. The deformation associated with these processes is resisted by the extreme temperature-dependence of the lithosphere's strength. Ways in which lithosphere deformation affects convection in the mantle are examined here, by comparing both theory and the results of numerical experiments.

Convective instability at the base of a cold thermal boundary layer with temperature- and strain-rate-dependent viscosity is investigated by defining a quantity, termed here the "available buoyancy," that takes into account the tradeoff between cold temperatures both promoting and resisting convective instability. This quantity can be used to determine approximately whether, and how fast, convective instability grows. Horizontal shortening is also included, which tends to increase gravitational instability, allowing up to 60% of the mantle lithosphere to be convectively removed. The subsequent influx of hot, buoyant, asthenosphere could cause rapid surface uplift.

For plate-scale flow, subduction zone deformation may resist convection. This possibility is studied here using a regional finite element model of subduction. This model shows that for sufficiently strong lithosphere, convection is resisted more by the bending deformation of a subducting plate than by shearing of the underlying mantle. Such behavior can be explained by a variation of boundary layer theory that includes an analytic expression for the energy required to bend a viscous plate. For the mantle, the bending resistance should control plate velocities if the effective lithosphere viscosity is greater than about 10^{23} Pa s. This produces a reasonable distribution of plate velocities for Earth and may reconcile models for its thermal evolution with surface heat flow observations. These results are verified using a new method for implementing subduction that parameterizes plate bending within a small region of a mantle-scale convection model. This model also shows that small-scale convection, by removing the basal part of the oceanic lithosphere, can decrease the bending resistance and thus may be an essential aspect of plate tectonics on Earth.

Thesis Co-Supervisor: Bradford H. Hager, Professor of Earth Sciences
Thesis Co-Supervisor: Peter Molnar, Senior Research Associate

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Chapter 1

Introduction

The Earth is thought to lose heat primarily through convective heat transfer expressed at the surface by rigid motions of tectonic surface plates. In particular, plate tectonics allows hot mantle rock to be exposed to cold surface temperatures as it travels from ridges to trenches. The resulting conductive cooling accounts for over 60% of Earth's total heat flow [e.g., *Sclater et al.,* 1980] and forms a cold thermal boundary layer known as the oceanic lithosphere. Because the oceanic lithosphere is colder than the underlying mantle, it is also denser (Figure 1.1a). This unstable density structure causes the oceanic lithospheric to dive into the mantle interior at subduction zones (Figure 1.2a), creating large horizontal temperature gradients that drive convective flow. In fact, cold subducted slabs are thought to drive plate motions, and thus convection of the mantle as a whole, by pulling on the surface plates to which they are attached [e.g., *Chapple and Tullis*, 1977; *Forsyth and Uyeda*, 1975; *Hager and O'Connell*, 1981; *Lithgow-Bertelloni and Richards*, 1995]. This pattern of convection is summarized by boundary layer theory, in which, as first described by *Turcotte and Oxburgh* [1967], the oceanic lithosphere forms the upper boundary layer of convection in the mantle and actively participates in convective circulation there.

Because the strength of mantle rock depends strongly on temperature, Earth's cold surface temperatures also cause the lithosphere to be stiffer than the underlying mantle. Laboratory experiments suggest that the temperature-dependence of diffusion or dislocation creep should create several orders of magnitude variation in the effective viscosity of mantle rocks for the temperature variations expected for the oceanic lithosphere (Figure 1.1b). The extreme strength of mantle rocks at low temperatures causes mantle convection to be expressed at the surface as the movement of rigid tectonic plates. This temperature-dependent strength should also tend to resist the deformation required for cold, dense, lithosphere to participate in convective downwelling.

Numerical studies of convection with a stiff upper boundary layer show that if temperature-induced viscosity contrasts through the boundary layer exceed $10^3 - 10^5$, deformation at the surface becomes sufficiently difficult that convection occurs beneath a “stagnant lid” [e.g., *Christensen,* 1984b; *Davaille and Jaupart,* 1993; *Moresi and Solomatov,* 1995; *Ratcliff et al.,* 1997; *Solomatov,* 1995]. In this case, short-wavelength convective downwellings, of the type first described by *Howard* [1964], remove fluid that is sufficiently warm to flow from the base of a cold, rigid, surface layer. The stagnant fluid at the surface is “frozen” in place by its strength and thus can not participate in convection, despite its significant excess density. Although this is not the dominant style of convection on Earth, convective downwelling may still occur at the base of lithospheric plates. For example, the flattening of the linear relationship between the seafloor depth and the square-root of its age at 80 million years can be explained by processes that limit the thickness to which plates can grow [e.g., *Parsons and Sclater,* 1977; *Stein and Stein,* 1992]. One such process is small-scale convection [e.g., *Davaille and Jaupart,* 1994; *Marquart et al.,* 1999], which could be initiated once cooling has thickened the lithosphere sufficiently for it to become unstable.

Dense, potentially unstable, mantle lithosphere may also accumulate at the base of a plate because of tectonic convergence at Earth’s surface. Horizontal shortening thickens the crust and creates mountain belts, and may also thicken the mantle portion of the lithosphere. If this thickening is sufficient to cause the mantle lithosphere to become convectively unstable, its basal portion may be removed by gravitational instability [e.g., *Fleitout and Froidevaux,* 1982; *Houseman, McKenzie and Molnar,* 1981]. The replacement of this material by hot, buoyant asthenosphere should then

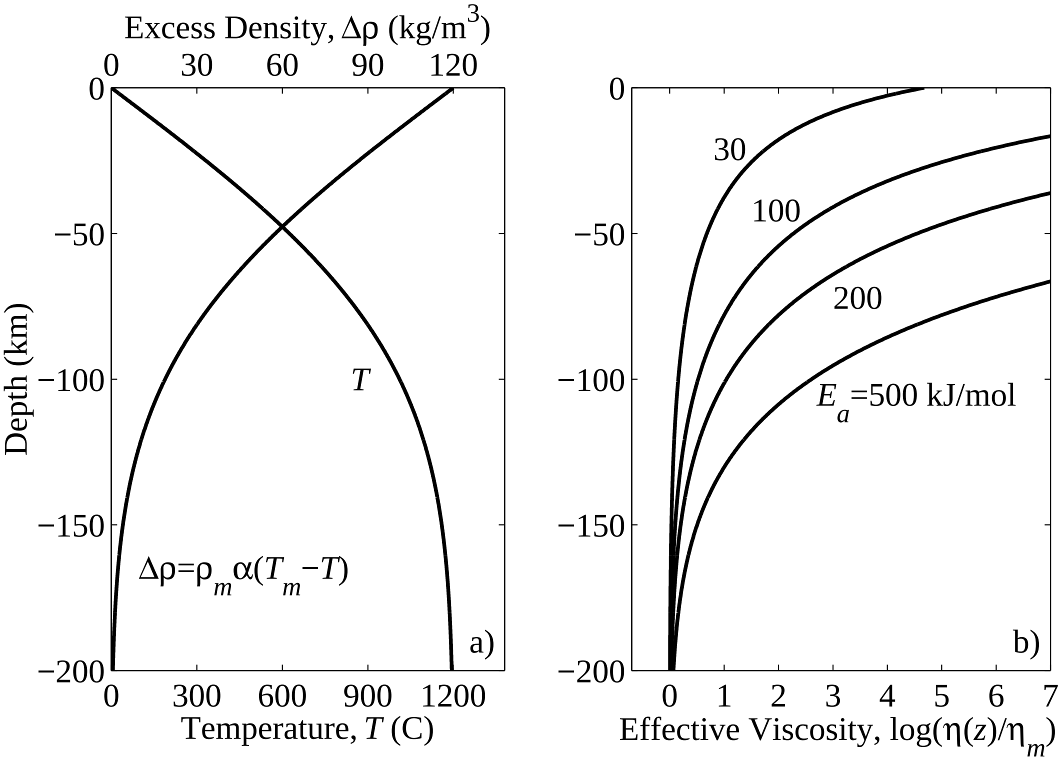

Figure 1.1: Typical depth-dependence of (a) temperature and density and (b) viscosity expected for oceanic lithosphere that is $t_c \sim 80$ million years old. Here temperature is that of a cooling halfspace using a thermal diffusivity of $\kappa = 10^{-6}$ m^2 s^{-1} [e.g., *Turcotte and Schubert*, 1982, pp. 163-167]. The increase in excess density with lower temperatures is given by $\Delta\rho = \rho_m \alpha(T_m - T)$, where $\rho_m = 3300$ kg m^{-3} is the mantle background density and $\alpha = 3 \times 10^{-5}$ K^{-1} is the thermal expansivity. The effective viscosity, η, is given by the constitutive law for diffusion or dislocation creep [e.g. *Kohlstedt et al.*, 1995] and is shown here on a log scale relative to the viscosity of the interior mantle, η_m. The activation energy, E_a, is shown by laboratory measurements to be between 200 and 500 kJ/mol, values that produce extreme variations in viscosity, as shown in (b). For the coldest temperatures, other deformation mechanisms, such as brittle faulting, may limit rock strength. Nevertheless, the strength of cold, dense lithosphere should limit the mantle's ability to utilize its significant negative buoyancy for driving convection.

lead to rapid surface uplift, later followed by extension [e.g., *England and Houseman,* 1989; *Houseman and Molnar,* 1997; *Molnar, England, and Martinod,* 1993; *Neil and Houseman,* 1999]. Furthermore, if the mantle lithosphere deforms according to a nonlinear stress-strain relationship, horizontal shortening should weaken the entire lithospheric layer, making it more prone to convective instability [*Conrad and Molnar,* 1997; *Molnar, Houseman, and Conrad,* 1998]. Later, the strain-rates associated with the growing instability itself should decrease the lithosphere's strength, accelerating unstable growth [*Canright and Morris,* 1993; *Houseman and Molnar,* 1997]. Although the entire thickness of the mantle lithosphere probably does not participate in this type of convection, localized convective instability may be observable at the surface as an episode of rapid uplift.

Thus, convective instability at the base of continental lithosphere (Figure 1.2b) should be enhanced by horizontal shortening and non-Newtonian viscosity, but should also be resisted by the temperature-induced strength of lithospheric rocks. In this thesis, I investigate the conditions under which the base of a cold boundary layer might become convectively unstable, and in doing so introduce a general method for taking into account variations in viscosity and density through the layer (Chapter 2). This analysis includes the effects of non-Newtonian viscosity and horizontal shortening (Chapter 3), and can be applied to a variety of conditions that may lead to local-scale convective instability at the base of the lithosphere.

Although, the temperature-dependence of mantle viscosity should be sufficient to force the mantle to convect beneath a stagnant lithospheric layer, Earth's surface plates are clearly mobile and participate in convection. Thus, subduction zones must somehow be weak enough to permit the rapid localized deformation that is required for the entire thickness of the oceanic lithosphere to descend into the mantle interior where it can drive mantle-scale convection. In particular, a subducting plate must bend and slide past an overriding plate in order for it to subduct (Figure 1.2a). The weakening mechanism that allows subduction is not well understood, but may be associated with brittle fracture of lithospheric rocks [e.g., *Moresi and Solomatov,* 1998]. In fact, the significant seismicity of Wadati-Benioff zones above ~ 200 km depth is

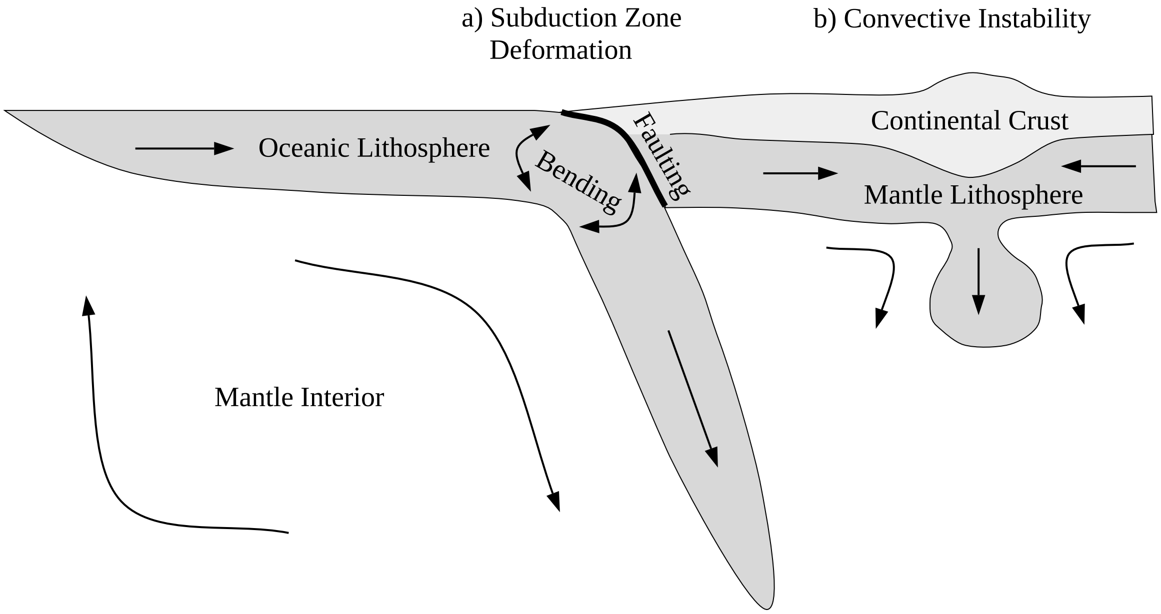

Figure 1.2: A cartoon showing the two styles of lithosphere-influenced convection that are investigated here. First, mantle-scale convection is facilitated by the downwelling of the oceanic lithosphere in a subduction zone, as shown in (a). Although subduction allows the entire lithospheric layer to participate in convection, it should also significantly resist convective motions because it requires the lithosphere to bend and slide past an overriding plate, deformation that is made difficult because the lithosphere is strong. Smaller-scale convection, shown in (b), may occur at the base of continental lithosphere, but is also resisted by lithosphere strength. Localized convective instability of this type may ultimately remove the basal portion of the mantle lithosphere, and should be enhanced by mechanical thickening of the lithospheric layer. Both types of convection utilize the negative thermal buoyancy of the cold mantle lithosphere, but are resisted by the lithosphere's temperature-induced strength.

evidence for deformation of a subducting slab by brittle fracture as it both bends and unbends within the subduction zone [e.g., *Bevis*, 1986; *Engdahl and Scholz*, 1977; *Hasegawa et al.*, 1994; *Isacks and Barazangi*, 1977; *Kawakatsu*, 1986]. Brittle fracture is an inelastic deformation mechanism, meaning that it requires an expenditure of energy by the convecting mantle. Furthermore, because the mantle behaves as a temperature-dependent viscous fluid, additional energy must be spent deforming subduction zone material in a viscous way. Because these deformation mechanisms dissipate energy, they resist the flow of oceanic lithosphere into the underlying mantle. Thus, although subduction zones must be weak enough to allow subduction to occur, they may also provide a significant source of resistance to mantle-scale convection.

Boundary layer theory, as it is typically applied to the convecting mantle, assumes that convective flow is primarily resisted by viscous deformation of the mantle interior. If, however, the bending of the lithosphere at subduction zones provides additional resistance of comparable magnitude, the rate of convection should be significantly slower than is predicted by standard boundary layer theory. To determine the possible influence of lithosphere deformation on convection, I use a local-scale model of subduction to examine the energy dissipated by a bending slab with an effectively viscous rheology (Chapter 4). By including this additional energy in a global-scale energy balance, an altered version of boundary layer theory can be developed. This version describes a style of convection in which plate speeds are slower than would be expected for an isoviscous mantle because they are partially dependent on lithospheric strength. In this case, the rate of convective heat transfer should also depend on lithospheric strength, which could have implications for the Earth's thermal evolution (Chapter 5).

To demonstrate, in a numerical model, convection that is slowed by the resistance to bending at subduction zones, I introduce a new method for implementing subduction in a mantle-scale model of convection (Chapter 6). This method parameterizes lithospheric deformation at a subduction zone by enforcing a global energy balance that includes an expression for the energy dissipated by a bending plate. In this model, the deformation within the subduction zone does not need to be resolved in detail, which allows different models for this deformation to be implemented easily. In Chapter 6, I use this model to verify the predictions made by the version of boundary layer theory developed in Chapters 4 and 5 that includes viscous plate bending. In the Earth, other deformation mechanisms such as brittle fracture or plastic flow are likely to influence subduction zone deformation. This new method for implementing subduction should make it possible to examine the effects of these other deformation mechanisms on global convective flow without requiring the development of complicated finite element gridding schemes and the accompanying computational effort.

In summary, the cold lithosphere not only drives convective flow through its significant negative buoyancy, but also resists this flow through its strength. In this thesis, I compare theory and the results of numerical calculations to investigate modes of lithospheric deformation that allow the dense mantle lithosphere to be utilized for driving convection, despite its strength. In particular, I examine mechanisms for the deformation of a strong lithospheric layer and discuss how this deformation may affect convection in Earth's mantle, both at small scales appropriate for convection at the lithospheric base (Figure 1.2b), and at large scales appropriate for mantle-wide convection (Figure 1.2a).