Physics of the Earth and Planetary Interiors 241 (2015) 65–76

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

A regime diagram of mobile lid convection with plate-like behavior

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ARTICLE INFO

Article history:
Received 10 May 2014
Received in revised form 6 January 2015
Accepted 9 January 2015
Available online 19 January 2015

Keywords:
Planetary evolution
Mantle convection
Subduction
Lithosphere

ABSTRACT

Terrestrial planetary bodies that undergo solid-state convection can exhibit a variety of tectonic styles, from stagnant lid one-plate planets to those with a mobilized lithosphere. For modeled planetary convection the de facto mode of recycling of lithosphere into the planetary interior is typically achieved through 2-sided and symmetric downwelling flows. However, lithosphere recycling on Earth occurs in a distinctly 1-sided mode known as subduction. Using numerical models of mantle convection in which the viscosity of planetary mantle material is strongly temperature-dependent, yet maintains a finite material strength as dictated by its yield stress, we investigate the continuum of mobile lid convection with plate-like behavior. The models span a parameter space of Rayleigh number and plate strength, and explore convective systems with low yield stresses resulting in weak subduction hinges that bend easily and highly deformable subducted slabs. Three distinct modes are found to occur in convective systems with weak plates: the stagnant lid mode, 2-sided downwelling mode, and a mode that alternates between 1-sided subduction and 2-sided downwellings. We classify the style of convective downwelling for a range of models and show that mode selection strongly depends on the combination of surface mobility and strength of the downgoing plate. Using these measurements, we have developed a regime diagram that can predict whether a particular system will be in one of those three modes.

1. Introduction

While several models of plate tectonics and mantle convection exist, both analog and computational, in nature plate tectonics is only observed on Earth. Terrestrial planets elsewhere in the Solar System are thought to convect in the stagnant lid regime (Schubert and Turcotte, 2001; Bercovici, 2003). Numerical models of mantle convection do not typically produce "Earth-like" subduction (1-sided and asymmetric) without including some ad hoc treatment to ensure the overriding plate remains on the surface. More typically, models produce a mobile lid with concentrated zones of convergence that recycle lithosphere from both sides of a quasi-symmetric 2-sided downwelling (Tackley, 2000). Subduction on Earth is generally thought to be 1-sided (Bercovici, 2003), though others have suggested that at convergent margins the lower lithosphere from both plates might be consumed in a more general downwelling (Tao and O'connell, 1992).

In addition to stagnant lid and mobile lid (2-sided downwellings), numerical models generate a greater number of convective systems such as sluggish lids and episodic mobile lids (Solomatov and Moresi, 1997; Crameri et al., 2012; Gerya et al., 2008; O'Neill, 2012; Lenardic and Crowley, 2012; O'Rourke and Korenaga, 2012). The existence of planetary convective systems in models which are unobserved in nature (and the ability to modify models to change the type of resulting convection) suggests that there are parameters which control convective styles, however some combinations of parameters may be unphysical. It is necessary to understand how, and with what effect, parameters modify model results. A regime diagram which maps out a parameter space and associates parameter combinations with convective styles might reveal which parameters, and in what combinations, convective modes exist and what form they adopt. Regime diagrams have been successfully generated for evaluating convective behavior based on intrinsic properties of the systems (Kincaid and Olson, 1987; Gerya et al., 2008; Landuyt and Bercovici, 2009; Stegman et al., 2010; Korenaga, 2010). Other work shows a unique set of parameters could allow for more than one stable regime (Lenardic and Crowley, 2012). Our limited observational information can be combined with regime diagrams to advance understanding of planetary behavior (O'Neill, 2012).

This approach has been extended for evaluating the likelihood of mobile lid convection on super-Earth exoplanets, i.e. planets outside our solar system with mass between 1 to 10 times the mass of Earth. There remains debate as to whether mobilization is less likely (O'Neill and Lenardic, 2007; Kite et al., 2009; Stein

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http://dx.doi.org/10.1016/j.pepi.2015.01.002
0031-9201/

et al., 2013; Noack et al., 2013), more likely (Valencia et al., 2007; Foley et al., 2012), only weakly influenced by size (Korenaga, 2010) or size-dependent based on other model parameters (van Heck and Tackley, 2011). In addition to mass, surface temperature may mark a boundary between mobile and stagnant lid regimes (Lenardic et al., 2008; Landuyt and Bercovici, 2009; Noack et al., 2012; Bercovici and Ricard, 2014) on these planets. Regime diagrams by Foley et al. (2012) show that systems exhibit stagnant lid or mobile lid convection based on damage number, healing number, plate strength and Rayleigh number (*Ra*). The development of models to buttress limited observations of spatially far off planets works equally well in supporting limited information about Earth in times past (Griffin et al., 2014; Harris et al., 2014; Johnson et al., 2013).

While much of previous work has been focused on the question of stagnant lid vs mobile lid, the parameters which control whether a mobile lid system will adopt 1-sided subduction or 2-sided downwellings are not fully understood. Work by Gerya et al. (2008), shows that two otherwise identical models will develop either 1-sided subduction or 2-sided downwellings based upon the ability of subducted slabs to dehydrate at depth and allow fluids released into the mantle wedge to help decouple the overriding plate from the downgoing plate. Gerya et al. (2008) presented a regime diagram showing regimes of 1-sided subduction or 2-sided downwellings in the space of hydrated rock versus slab strength, where slab strength appears to be the stronger control on the system. However Crameri et al. (2012) have published results based on models which do not incorporate the dehydration of subducted slabs at depth. These results show the system will engage in 1-sided subduction or 2-sided downwellings based on the existence of a free plate surface and weak crust. Models featuring a free plate surface and a crustal layer of weak material subduct in the 1-sided mode while models that lack those features develop 2-sided downwellings.

Thus, in order to consider a planet's tectonic evolution, it is essential to more fully address the details of how lithosphere gets recycled. The question as to why Earth has plate tectonics has only been answered partially thus far, so knowing why "Earth-like" subduction occurs will complete our understanding in that regard. Slab strength has been identified to play a significant role in controlling subduction dynamics because it determines the resistance to bending that plates must overcome in order to subduct. Considerable insight into the mechanical strength of the plates can be gained by studying the bending and stretching of thin viscous sheets (Ribe, 2001; Ribe, 2003). This study looks at convective systems with strongly temperature-dependent viscosity and explicitly accounts for the mechanical strength of plates. We are able to generate convective scenarios that result in stagnant lid convection, 1-sided subduction and 2-sided downwellings and identify those systems that exhibit transient behavior and switch between modes. We show that the convective vigor and the overall strength of the plates in the system determine the particular style of convective downwelling. We develop a measure of mobility that provides a single metric for identifying the regimes. We do this with models that have a temperature-dependent rheology, contain pseudo-plastic yielding and a pseudo-free surface but do not include dehydration of slabs at depth nor any affect that such dehydration may have on the mantle wedge.

2. Methods

We develop two-dimensional models of convective systems using the finite volume code, StagYY (Tackley, 2008), which is a numerical model of solid-state mantle convection that solves the conservation equations for mass, momentum and energy. The mantle is modeled as an incompressible material with an infinite Prandtl number approximation.

Dimensional parameters are used and parameters common to all models are given in Table 1. The aspect ratio for all models is 4 to 1, length to depth, with dimensional length of 2800 km and depth of 700 km. The model space is gridded using a regular grid of 1024 × 256 grid points.

2.1. Rheology

The viscosity of a silicate mantle is strongly temperature-dependent, and follows an Arrhenius relation:

$$\eta(T) = Ae^{\frac{E}{RT}} \tag{1}$$

where $\eta(T)$ is the temperature-dependent viscosity, R is the gas constant, T is temperature and E is the activation energy ($240\ \mathrm{kJ\ mol^{-1}}$). The prefactor A is calculated so that a reference mantle temperature of $T_0 = 1600$ K results in a reference viscosity $\eta_{ref} = 1 \times 10^{21}$ Pa s. Fig. 2 shows the temperature dependence of the viscosity with $\eta_{ref} = 1 \times 10^{21}$ Pa s. A cut-off is applied to the temperature-determined viscosity when it falls outside a specified window. In this study the maximum allowed viscosity, η_{max} is varied to modify plate strength and the minimum allowed viscosity is $\eta_{min} = 10^{19}$ Pa s. At the top of the mantle where the temperature is coolest, the temperature-determined viscosity is extremely high but the value of η_{max} is sufficiently high that the lithosphere is essentially rigid on timescales of several convective overturns. This cooler lithosphere also has finite strength, which is represented through a yield strength failure criterion. The yield stress, σ_{yield}, follows Byerlee's law and is pressure dependent,

$$\sigma_{yield} = C + p\mu \tag{2}$$

where C is the cohesion, μ is the coefficient of friction, and p is the hydrostatic pressure. For the bulk of the mantle $C = 0.7$ MPa, $\mu = 0.5$. For the weak crust layer $C = 0.07$ MPa, $\mu = 0.0$. The values chosen here are lower than those typically used in other studies, with the weak crust yielding to very low levels of stress and the strong part of the lithosphere yielding to low values of stress. These choices represent an attempt to explore the system subject to conditions of having weak slabs and weak subduction hinges that allow plates and slabs to easily bend.

2.2. Initial condition

All models are seeded with a similar initial condition. The initial boundary layer thickness is prescribed and must be consistent with the time evolved model. Boundary layer theory provides for

Table 1
Parameters common to all models

Parameter	Description	Value
g	Gravitational acceleration	$9.81\ \mathrm{ms^{-2}}$
ρ_0	Reference density	$3300\ \mathrm{kg\ m^{-3}}$
Z	Depth of the domain	700 km
X	Length of the domain	2800 km
n_z	Vertical grid points	256
n_x	Horizontal grid points	1024
Cp	Heat capacity at constant pressure	$1200.0\ \mathrm{J\ K^{-1}}$
k	Thermal conductivity	$3\ \mathrm{Wm^{-1}\ K^{-1}}$
α	Coefficient of thermal expansion	$3 \times 10^{-5}\ \mathrm{K^{-1}}$
η_{ref}	Reference viscosity at $T = 1600$ K	1×10^{21} Pa s
η_{air}	Viscosity of "sticky air"	1×10^{18} Pa s
δ_{air}	Air layer thickness	100 km
$\delta_{weak\ crust}$	Weak crustal layer thickness	8 km