GEODYNAMICS AND RATE OF VOLCANISM ON MASSIVE EARTH-LIKE PLANETS

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Received 2008 September 12; accepted 2009 May 29; published 2009 July 16

Abstract

We provide estimates of volcanism versus time for planets with Earth-like composition and masses 0.25–25 $M_\oplus$, as a step toward predicting atmospheric mass on extrasolar rocky planets. Volcanism requires melting of the silicate mantle. We use a thermal evolution model, calibrated against Earth, in combination with standard melting models, to explore the dependence of convection-driven decompression mantle melting on planet mass. We show that (1) volcanism is likely to proceed on massive planets with plate tectonics over the main-sequence lifetime of the parent star; (2) crustal thickness (and melting rate normalized to planet mass) is weakly dependent on planet mass; (3) stagnant lid planets live fast (they have higher rates of melting than their plate tectonic counterparts early in their thermal evolution), but die young (melting shuts down after a few Gyr); (4) plate tectonics may not operate on high-mass planets because of the production of buoyant crust which is difficult to subduct; and (5) melting is necessary but insufficient for efficient volcanic degassing volatile partitioning into the earliest, deepest melts, which may be denser than the residue and sink to the base of the mantle on young, massive planets. Magma must also crystallize at or near the surface, and the pressure of overlying volatiles must be fairly low, if volatiles are to reach the surface. If volcanism is detected in the 10 Gyr-old r Ceti system, and tidal forcing can be shown to be weak, this would be evidence for plate tectonics.

Key words: planetary systems – planets and satellites: general – planets and satellites: individual (COROT-7b, HD 40307 b, HD 40307 c, HD 40307 d, Gl 581 b, Gl 581 c, Gl 581 d, Gl 876 d, HD 181433 b, HD 69830 b, HD 69830 c, 55 Cnc e, GJ 674 b)

1. INTRODUCTION

Theory predicts the existence of rocky planets having 1–10 Earth masses (e.g., Ida & Lin 2004). Planets in this mass range are now being detected (Rivera et al. 2005), and next-decade observatories, such as the James Webb Space Telescope and Giant Magellan Telescope, may be able to detect any atmospheres. A planet’s atmosphere will consist of gas (1) accreted from the nebula, (2) degassed during impact accretion, and (3) degassed during subsequent geologic activity. Point (1) will depend on the lifetime of the nebula, whereas (2) and (3) will depend on the volatile abundance of material (Elkins-Tanton & Seager 2008a), and all will be modified by atmospheric escape. Very large planets far from their parent star will retain primitive gas, but smaller planets closer to their parent star will not. Loss rates vary between gases, so planetary atmospheres could be a mixture of gases left over from the initial atmosphere, and those replenished by volcanism. Thermal emission phase curves gathered from extrasolar planets can set bounds on atmospheric mass. Spectral detection of atmospheric constituents with short reference pressure $P_r$, $\frac{\partial V}{\partial S}$ is the adiabat, potential temperature is defined as the temperature a parcel of solid mantle would have if adiabatically lifted to the surface, and $T_{\text{sol}}$ is the solidus, evaluated here at zero pressure. On planets with plate tectonics, the thickness of the crust (the crystallized melt layer) is a convenient measure of the intensity of volcanism. The rate of crust production is the product of crustal thickness, plate spreading rate, and mid-ocean ridge length. The pressure at the base of the crust is the product of crustal thickness, the planet’s surface gravity, and crustal density. A reasonable approximation to the pressure at the base of the crust is the integral of the fractional-melting curve from great depth to the surface (Figure 1(a)).

Venus and Mars lack plate tectonics; their mantles are copped by largely immobile, so-called “stagnant lid” lithospheres, which cool conductively. Because mantle cannot rise far into the stagnant lid, melting can only occur if the temperature at the base of the stagnant lid exceeds the local solidus of mantle rock:

$$T_{m,r} - (P_r - P_{\text{inh}}) \frac{\partial V}{\partial S} \geq T_{\text{sol}}(P_{\text{inh}}),$$

where $T_{m,r}$ is the mantle temperature evaluated at some reference pressure $P_r$, $\frac{\partial V}{\partial S}$ is the adiabat, potential temperature is defined as the temperature a parcel of solid mantle would have if adiabatically lifted to the surface, and $T_{\text{sol}}$ is the solidus, evaluated here at zero pressure. On planets with plate tectonics, the thickness of the crust (the crystallized melt layer) is a convenient measure of the intensity of volcanism. The rate of crust production is the product of crustal thickness, plate spreading rate, and mid-ocean ridge length. The pressure at the base of the crust is the product of crustal thickness, the planet’s surface gravity, and crustal density. A reasonable approximation to the pressure at the base of the crust is the integral of the fractional-melting curve from great depth to the surface (Figure 1(a)).

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$$T_{m,r} - (P_r - P_{\text{inh}}) \frac{\partial V}{\partial S} \geq T_{\text{sol}}(P_{\text{inh}}),$$

where $P_{\text{inh}} = \rho_{\text{inh}} g Z_{\text{inh}}$ is the pressure at the base of the stagnant lid, $\rho_{\text{inh}}$ is the lithospheric density, $g$ is the gravity, and $Z_{\text{inh}}$ is the stagnant lid thickness. This is a more stringent condition than Equation (1) if the adiabat is steeper than the solidus (Figure 1(b)). Io shows yet another style of rocky-planet mantle convection: magma pipe cooling.

Previous studies have examined both rocky planet atmospheres and massive-Earth geodynamics. Elkins-Tanton & Seager (2008a) estimate the mass and composition of super-Earth atmospheres degassed during accretion. Complementary to that study, we emphasize long-term geological activity. There is disagreement over whether plate tectonics will operate on massive
higher gravity favors subduction (Valencia et al. 2007). Another
planets. One previous study uses scaling arguments to argue that
heat production and planetary thermal evolution (Section 3.4).
we find that results differ greatly depending on the mode of
Massive Earths with plate tectonics will produce melt for at least as long as the age of the Galaxy, but stagnant lid planets will not. In Section 4, we analyze the effect of melting on the style of mantle convection. We show that plate buoyancy is likely to be a severe problem and may be limiting for plate tectonics. In Section 5, we relate our results to atmospheric degassing and discuss the possible suppression of degassing (and, perhaps, melting) by the higher ocean pressures expected on massive Earth-like planets. Finally, in Section 6, we summarize our results, justify our approximations and model limitations, and compare our results to solar system data.

2. MODEL DESCRIPTION AND INPUTS

We use a model of internal structure (Section 2.1) to set boundary conditions for a simple model of mantle temperature evolution (Section 2.2), which in turn forces a melting model (Section 2.3). Greenhouse-gas regulation of surface temperature could allow melting and degassing to feed back to mantle thermal evolution (e.g., Lenardic et al. 2008), but we neglect this. Throughout, we assume whole-mantle convection. Rather than attempt to predict exoplanet properties solely from basic physics and chemistry, we tune our models to reproduce the thickness of oceanic crust on present-day Earth.

2.1. Radius and Mantle Depth

Given our assumption of whole-mantle convection, we need to know only the mantle’s outer and inner radii. The crust is thin, so the top of the mantle is ≈ the planet’s radius, R. Valencia et al. (2006) propose the scaling $R/R_{\oplus} = (M/M_{\oplus})^{0.27}$. Here, we use instead the “modified polytrope” of Seager et al. (2007) (their Equation (23)) to set planet radius. However, we take $R/R_{\oplus} = (M/M_{\oplus})^{-0.25}$ in our scaling relationships (13), (14), and (21). To find the core–mantle boundary (CMB) radius for the Seager et al. (2007) scaling, we set mantle mass $M_{\text{mantle}} = 0.675M_{\text{planet}}$ and numerically integrate inward using a pure magnesioperovskite mantle composition, a fourth-order Burch–Murnaghan equation of state, and material properties from Seager et al. (2007). CMB pressure is calculated to be 1.5 Mbar for 1 $M_{\oplus}$, and 2.9 (6.9, 14, 40) Mbar for 2 (5, 10, 25) $M_{\oplus}$.

2.2. Thermal Model

For a convecting mantle with a mobile lithosphere, if heat is generated solely by mantle radioactivity and is equal to heat lost by cooling at the upper boundary layer,

$$Q = \frac{M_{\text{mantle}}}{A} \sum_{i=1}^{4} H_0(i) e^{-\lambda_i t} = Nu \frac{k(T_m - T_s)}{d}$$

$$Nu \approx \left( \frac{g \alpha (T_m - T_s) d^3}{\kappa \nu R_a c_t} \right)^{\beta}$$

$$\nu(T) = v_0 e^{(\lambda t/T_m)} = v_1 e^{(-T_m/T_s)},$$

where $Q$ is the lithospheric heat flux, $A$ is the planet’s surface area, $H$ is the radiogenic power per unit mass, $i = 1–4$ are the principal long-lived radioisotopes ($^{238}\text{U}$, $^{232}\text{Th}$, $^{235}\text{U}$, $^{238}\text{U}$), $\lambda$ is the decay constant, $t$ is the time, $Nu$ (Nusselt number) is the dimensionless ratio of total heat flow to conductive heat flow, $k$ is the thermal conductivity, $T_m$ is the mantle temperature, $T_s$
is the surface temperature, \( d \) is the depth to the CMB, \( g \) is the surface gravitational acceleration, \( \alpha \) is the thermal expansivity, \( \kappa \) is the thermal diffusivity, \( \nu \) is the viscosity, \( Ra_{cr} \) is the critical Raleigh number with value \( \sim 10^3 \), \( \beta \) is 0.3 (Schubert et al. 2001), \( A_0 \) is the activation temperature, and \( T_{nu} \) is the temperature increase (decrease) that decreases (increases) viscosity by a factor of \( e \) (Schubert et al. 2001). Equation (5) contains two equivalent parameterized expressions for \( T \). Values used for these parameters are given in Table 2.

We neglect the pressure dependence of viscosity (Papuc & Davies 2008), which cannot be fully captured by parameterized models. In effect, we assume that the viscosity beneath the upper boundary layer, rather than some volume- or mass-averaged mantle viscosity, determines the properties of the flow.

We use the canonical values for \( H_t \) given by Turcotte & Schubert (2002), who estimate that 80% of Earth’s current mantle heat flux is supplied by radioactive decay. Although Earth’s surface heat flux is well constrained, the fraction of the flux out of the mantle that is due to radiogenic heat production is not. Literature values vary from \( \leq 0.2 \) (Lyubetskaya & Korenaga 2007) to 0.8 (Turcotte & Schubert 2002), with low values increasingly favored (Loyd et al. 2007). Variability in \( H_t \) could swamp any size signal in rates of volcanism, an important uncertainty addressed in Section 3.4. A useful rule of thumb is that a doubling a planet’s concentration of radiogenic elements makes it behave like a planet with double the radius (Stevenson 2003).

Equations (3)–(5) can be solved directly for \( T \). It is then easy to find the mass dependence of temperature (Section 3.1; Figure 2). However, secular cooling significantly contributes to the heat flux at the bottom of the lithosphere, so at a given time a planet will have a higher internal temperature and a higher heat flow than these thermal equilibrium calculations would suggest. Planets of different masses follow parallel cooling tracks (Stevenson 2003), and internal temperature is regulated by the dependence of mantle viscosity on temperature (Tozer 1970). A very simple model for mantle thermal evolution with temperature-dependent viscosity in plate tectonic mode is (Schubert et al. 2001)

\[
\frac{\partial T}{\partial t} = \frac{H}{c} - k_1(T_m - T_{nu})^{(1+\beta)} \exp\left(\frac{-\beta A_0}{T_m}\right),
\]

where

\[
k_1 = \frac{A k}{c d M_{mantle}} \left( \frac{\alpha g d^3}{\kappa \nu \beta A_{cr}} \right)
\]

and \( c \) is the specific heat capacity of the mantle rock.

We integrate this model forward in time from a hot start, using a fourth-order Runge–Kutta scheme. Because of the exponential temperature dependence of convective velocity, the transient associated with the initial conditions decays on a 100 Myr timescale, provided that the planet has a “hot start.” Hot starts are overwhelmingly likely for differentiated massive rocky planets. Our initial condition is \( T_m = 3273 \) K, but our results are insensitive to increases in this value.

For planets in stagnant lid mode, we use the scaling of Grasset & Parmentier (1998)

\[
T_c = T_m - 2.23 \frac{T_m^2}{A_0},
\]
where $T_c$ is the temperature at the base of the stagnant lid; plausible values lead to $(T_m - T_c) \ll T_m$. Then

$$Nu \approx \left( \frac{g a (T_m - T_c) d^3}{\kappa v(T) R a_e} \right)^{\beta}. \quad (9)$$

Since $T_c > T_s$, stagnant lid convection is less efficient at transporting heat than plate tectonics.

2.3. Melting Model

Earth generates 34 km$^3$ yr$^{-1}$ of crust of which 63% is by isoentropic decompression melting at mid-ocean ridges (Best & Christiansen 2001). (This percentage underestimates the contribution of mid-ocean ridge melting to overall mantle degassing, because most of the volatile flux at arcs is just recycled from subducting crust.) After four decades of intensive study, this is also the best-understood melting process (Juteau & Maury 1999). Beneath mid-ocean-ridges, the mantle undergoes corner flow. Melt is generated in a prism with triangular cross section, ascends buoyantly, and is focused to a narrow magma lens beneath the ridge. Petrological systematics require (Langmuir et al. 1992), and most melting models assume (Ghiorso et al. 2002), that the source magmas for mid-ocean ridge basalt melt fractionally or with small residual porosity, separate quickly, and suffer relatively little re-equilibration during ascent. For more massive planets, these remain robust assumptions. Buoyancy forces driving segregation are stronger and, because the pressure at which the solids and adiabat intersect is at a shallower absolute depth, the ascent pathways are shorter. Because of these attractive simplifications and because mid-ocean ridge melting dominates Earth’s crust production budget, we focus on mid-ocean ridge melting in this paper.

Isoentropic decompression melting pathways are distinguished by their values of potential temperature, $T_p$. Actual temperatures of near-surface magmas are lower because of the latent heat of melting, the greater compressibility of melts with respect to solids, and, usually less important, near-surface conductive cooling. All mid-ocean-ridge melting schemes are very sensitive to $T_p$, especially just above the zero-pressure solidus. That is because increasing $T_p$ both increases the pressure at which melting first occurs (lengthening the “melting column”) and also increases the mass fraction of melting ($X$) suffered by the top of the melt column (Figure 1(c)). With the above assumptions,

$$P_{\text{crust}} = - \int_{P_c}^{P_f} X(T, P) dP \quad (10)$$

$$T(P) = T(P + \delta P) - \left( \frac{\partial V}{\partial S} \right) \delta P + \left( \frac{\partial X}{\partial P} \right) L \quad (11)$$

$$T(P_c) = T_p + P_c \left( \frac{\partial V}{\partial S} \right), \quad (12)$$

where $P_f = 0$ in the case of plate tectonics or $P_f = P_{\text{crit}}$ (the pressure at the base of the lithosphere) in the case of stagnant lid convection; $P_c$ is given by the intersection of the adiabat with the solidus, which is the point on the adiabat $(\frac{\partial V}{\partial S})$ where $X = 0, L$ is the latent heat of melting, and $S$ is the entropy.

We use three models for $X(T, P)$. In order of increasing complexity, they are those of McKenzie (1984) as extended in McKenzie & Bickle (1988) (henceforth MB88), Katz et al. (2003) (henceforth K03), and (for plate tectonic models only)
Ghiorso et al. (2002), with the Smith & Asimow (2005) front-end (henceforth pMELTS). MB88 and K03 are similar in that they fit simple functional forms to experimental data, with MB88 more widely used although it is constrained by fewer data. pMELTS is a state-of-the-art model of phase equilibria for compositions similar to Earth’s mantle. We use pMELTS throughout the predicted melting range, even though the model is only calibrated for use in the range 1–3 GPa. For pMELTS, we assume continuous melting with a residual porosity of 0.5% (that is, melt fractions greater than 0.5% are evacuated from the melting zone), and we use the mantle composition inferred to underly Earth’s mid-ocean ridge system (Workman & Hart 2005) with 500 ppm water. Representative results with all these models are shown in Figure 3.

Each model is required to produce 7 km thick basaltic crust, which is the observed value on Earth (White et al. 2001), after 4.5 Gyr on an Earth-mass planet undergoing plate tectonics. We adjust the offset between potential temperature in the melting models, and the characteristic mantle temperature used in the thermal model, to obtain the observed crustal thickness. The required offset $T_m - T_p$ is 741 K, 707 K, and 642 K, for the MB88, K03, and pMELTS models, respectively (Figure 3).

3. MODEL OUTPUT

3.1. Simple Scaling Laws from Thermal Equilibrium Calculations

The simplest possible rocky planet model assumes that the ratio of radiogenic heat production to lithospheric heat flux (the convective Urey number), $U_r = 1$. We take the radiogenic-element concentrations given by Turcotte & Schubert (2002) (Table 1) and use Equations (3)–(5) to set mantle temperature. This is greater for more massive planets because their decreased surface area/volume ratio requires higher heat fluxes (and more vigorous convection) to dispose of the same heat flux. From Equations (3)–(5), but neglecting the dependence of $Q$ on $T_m$,

$$\left( \frac{Ra}{Ra_\oplus} \right)^\beta = \left( \frac{M}{M_\oplus} \right) \left( \frac{A}{A_\oplus} \right) \left( \frac{d}{d_\oplus} \right)$$

which with $R \propto M^{0.25–0.28}$ (Valencia et al. 2006) gives $Ra \propto M^{2.45}$; using this simplification leads to a relation between temperature and mass

$$v(T) \propto M^{-5/4}$$

which when inserted into Equation (5) gives a good fit to the results shown in Figure 2. Similar scaling arguments with $R \propto M^{1/3}$ give $v(T) \propto M^{-8/3}$, i.e., an approximately straight line on a linear–log graph of temperature versus mass (Figure 2).

3.2. Plate Tectonics

We now turn to our time-dependent results.

1. Thermal evolution. As anticipated (Stevenson 2003), mantle temperatures for planets of different masses follow a parallel cooling curve. Planets with $M = 2 (5, 10, 25) M_\oplus$ have potential temperatures 39 K (97 K, 146 K, 221 K) greater than Earth after 4.5 Gyr (Figure 4). There is little difference in thermal evolution between internal structure models: the temperature difference between Valencia et al. (2006) and Seager et al. (2007) is always <15 K (Figure 2). The constant-density planet runs significantly (up to 100 K) colder since it has a much larger surface area, but the same radiogenic-element complement. From now on we use only the thermal evolution calculations for the Seager et al. (2007) internal-structure model.

2. Simple melting models, MB88 and K03. Potential temperature increases monotonically with mass, so the pressure at the base of the crust also increases monotonically (Figure 3). However, the absolute thickness of the crust also scales as the inverse of gravity. In other words, although bigger planets run hotter, higher surface gravity moves the solidus and suppresses melting. For temperatures close to the solidus, the first effect dominates, and increasing planet mass increases crustal thickness (Figures 5(b) and (c)). Young and/or large planets show the opposite trend, with crustal thickness decreasing as planet mass increases. Crustal thicknesses are within a factor of 2 of each other for 1–25 $M_\oplus$ until 8.6 Gyr. After that, the ratio of crustal thicknesses diverges, as melting begins to shut down on the lowest-mass planets. In both models, for planets of intermediate mass and with ages slightly greater than the solar system, increasing mass has only a small (and negative) effect on crustal thickness. However, crust production per unit time increases with increasing mass, because more massive planets have more rapid plate spreading: see Section 5.1.

3. pMELTS, a more complex melting model. pMELTS predicts crustal thickness will increase rapidly with increasing planet mass for massive planets with ages comparable to the solar system (Figure 5(d)). Potential temperatures for these planets are >1500 °C. The predicted crustal-thickness result at these temperatures is suspect, because when $T_\nu > 1460$ °C, pMELTS predicts melting will occur to pressures greater than those for which it has been experimentally calibrated (<3 GPa). Crustal thickness is >1 km even after 13 Gyr in the pMELTS model, even for masses of 1 $M_\oplus$. This is because pMELTS-predicted crustal thickness ramps up slowly to 7 km crustal thickness.

![Figure 4. Effect of increasing planet mass on thermal evolution. Mantle temperatures are adjusted to produce 7 km thick crust with plate tectonics under MB88 melting model at 4.5 Gyr for 1 $M_\oplus$. Dashed line is 1 $M_\oplus$; solid lines are for 5, 10, 15, 20, and 25 $M_\oplus$, with temperature increasing with increasing mass. $T_p = 43$ K.](image-url)
Figure 5. Uppermost panel: evolution of mantle temperature (°C) with time under plate tectonics. Seager et al. (2007) internal structure model. Initial temperature for all models is 3273 K. Lower panel, top to bottom: corresponding crustal thicknesses in meters for MB88, K03, and pMELTS melting modes. Contour interval is 1000 m from 0 to 15,000 m, and 5000 m for larger values. Light gray regions are where melting models are extrapolated beyond their stated range of validity. Horizontal line at bottom right of the MB88 pane corresponds to the cessation of volcanism on 0.25 $M_{\oplus}$ planets after $\sim 12$ Gyr (see the text).

As temperature increases (Figure 3), so contours of constant crustal thickness are spaced more widely in temperature (equivalently, time) than with the other models. As with the other melting models, the planet mass that produces the thickest crust at a given time increases as the planets age.

To summarize, mass dependence increases with time as planets cool toward the solidus, and (for a given mass range) the sign of mass dependence changes with time. This is because of the strongly nonlinear behavior of melt production near the solidus; melting goes from zero to significant over a small range in potential temperature. Low-mass planets approach this temperature by 7–8 Gyr. Their crustal thickness declines more rapidly than on high-mass planets.

3.3. Stagnant Lid

1. Thermal evolution. Because stagnant lid convection is less efficient at transferring heat than plate tectonics, a planet in which plate tectonics is suddenly halted will heat up (the thin solid line in Figure 6). This temperature rise reduces mantle viscosity, so $Ra$ increases. Temperature converges on the evolutionary track of a planet that has always been in stagnant lid mode, with a characteristic convergence timescale of $(H\Delta T_{\text{mode}})/cM_{\text{mantle}} \sim 1$ Ga. A similar argument explains the temperature changes associated with going from stagnant lid mode to plate tectonics. The temperature difference between the tracks is $\Delta T_{\text{mode}} \approx 160$ K for all masses. This is roughly $T_0 \ln ((T_m - T_s)/(T_m - T_c))$, which can be understood by equating the right-hand side of Equations (4) and (9). Therefore, the thermal evolution of stagnant lid planets follows Figure 5(a), but $\approx 160$ K hotter.

2. Stagnant lid melting. Melt production within an ascending column of mantle in stagnant lid mode is truncated at the base of the lithosphere. For the same mantle temperatures, predicted erupted thickness is much smaller (Equation (10)). This effect opposes the increased temperature of stagnant-lid mantles. To produce Figure 7 we use the same mantle-potential temperature offsets as in plate tectonic mode (so the model is still “tuned to Earth”). Most planets run hotter in stagnant-lid mode to the extent that pMELTS cannot be used, as $T_p$ exceeds the range over...
which it is calibrated. The MB88 and K03 models show roughly the same behavior in stagnant lid mode (Figure 7).

For young (<2–3 Gyr) planets, an ascending column of mantle produces more melt in a stagnant lid mode than in plate tectonic mode—the higher temperature matters more than the (small) lithospheric thickness. For somewhat older planets, an ascending column of mantle produces less melt in stagnant lid mode than in plate tectonic mode. The temperature difference is much the same, but the growing lithosphere increasingly truncates the melting column. At a mass-dependent age much less than the age of the Galaxy, melting ceases.

3. What controls cessation of melting? For a given melt production function, all planets in plate tectonics mode will cease volcanism at the same potential temperature. Consequently, a planet’s volcanic lifetime is delineated by an isotherm \( T_p = 1080–1193 \, ^\circ\text{C} \), depending on the melting model. For planets in stagnant lid mode, this is not the case. There is still a one-to-one relationship between temperature and the absolute thickness of the lithosphere. However, the absolute thickness of the melt zone at fixed temperature decreases with increasing gravity, but \( z_{\text{lith}} \) does not. Thus, \( z_{\text{lith}} \) increasingly truncates the melt zone as gravity increases. As a result, there is a temperature range for which low-mass planets can sustain melting in stagnant lid mode, whereas high-mass planets cannot. Over the mass range 1–25 \( M_\oplus \), this temperature range is \( \sim 180 \, \text{K} \). Consequently, in stagnant lid mode, more massive planets run much hotter but cease melting only moderately later than smaller planets (Figure 7).
3.4. Initial Bulk-Chemistry and Initial Radiogenic-Power Variations

“Noncanonical” initial radiogenic-element complements have been suggested for Earth. To evaluate this possibility, we show 1 $M_\oplus$ thermal evolution tracks with radioisotope complements appropriate to “undepleted” mantle (Ringwood 1991), CI chondrites (Anders & Grevesse 1989), and EH chondrites (Nesloney 1995) (Table 1; Figure 8). The CI and “undepleted” tracks show similar behavior to T&S, but the $^{235}$U-rich, $^{238}$U-poor EH chondrite track shows more rapid cooling. Since we use Earth’s observed oceanic crust thickness to tune mantle temperature, it is not particularly important to get the absolute values right, and three of the four radiogenic-element complements tested have similar behavior over geological time.

The long-term thermal evolution of rocky planets depends on the abundance of the long-lived radioisotopes $^{232}$Th, $^{235}$U, and $^{238}$U at the time of planet formation. These are produced only by the rapid neutron capture process ($r$-process) acting on the iron-peak isotopes. This is thought to occur only during explosive nucleosynthesis in stars with 10–20 $M_\odot$ (Chen et al. 2006). In contrast, Si is produced during $\alpha$-chain process by the whole range of massive stars. Th, and especially U, are difficult to detect in stars but europium (Eu), another exclusively $r$-process element, can be readily measured. The average observed stellar abundance of Eu to silicon decreases by a factor of 0.63 as the abundance of heavy elements or metallicity (represented by iron Fe) increases by a factor of 100 to the solar value (Cescutti 2008). The $r$-process appears to be universal and all $r$-process elements scale closely with solar values (Frebel 2008). Therefore, the average abundance of $^{232}$Th, $^{235}$U, and $^{238}$U isotopes can be predicted using the trend of Eu with abundance or metallicity, the age–metallicity relationship of the Galaxy, the star formation history of the Galaxy, and the half-life of each isotope. We adopt a simple linear age–metallicity relationship with an increase of 1 dex (a factor of 2.5) over the age of the Galaxy, with solar metallicity occurring 4.6 Gyr ago (e.g., Pont & Eyer 2004). Figure 9 plots the predicted abundance of the three isotopes using the observed trend of Eu and the Prantzos & Silk (1998) parameterization of the star formation history of the Galaxy. (The predictions are only weakly sensitive to the model of star formation.) The age of the Galaxy is taken to be 13.6 Gyr. All abundances are normalized to the value at the formation of the Sun.

Planets forming early in the history of the Galaxy would have 50% more $^{238}$U, but six times more $^{235}$U, than Earth. The higher abundance is because the amount of radioisotopes in the interstellar medium only reflects massive star formation over a few half-lives, whereas $^{28}$Si and other stable isotopes accumulate over the history of the Galaxy. Therefore, these systems are not U- and Th-rich, they are Si-poor. The high abundance of $^{235}$U could have an important role in the early thermal history of such planets.

The effect of these trends on present-day planets, while still significant, is more modest simply because they are older. Figure 10 plots planet mantle temperature against the age of the
host star. Comparison with Figure 5(a) shows that inclusion of cosmochemical trends in $H_1$ lowers $T_m$ by up to 50 K for young planets, while raising $T_m$ by up to 40 K for old stars, compared to their present-day temperature had they formed with an Earth-like inventory of radiogenic elements.

We have assumed that the major-element composition of planetary mantles is similar everywhere and at all times. This is unlikely to be true in detail: for example, it has been proposed that on early Earth the mid-ocean ridge basalts source was more depleted than at the present day (Davies 2007). Earth’s continent mass fraction may be higher (Rosing 2006), or lower than is typical. More severe variations in major-element composition, with correspondingly major shifts in rheology and in the solidus, can be imagined (e.g., Gaidos 2000; Kuchner & Seager 2005). Even highly oxidized “coreless” planets have been modeled (Elkins-Tanton & Seager 2008b). We leave the geodynamic consequences of such variations as an open subject: a future objective will be to use geodynamic observables to constrain internal structure and bulk composition.

4. EFFECT OF MELTING ON THE STYLE OF MANTLE CONVECTION

We have shown that transitions between plate tectonics and stagnant lid mode have an impact on thermal evolution comparable to that of mass over the range of masses considered in this paper. With this motivation, we now assess whether plate tectonics is viable on more massive Earth-like planets. Our approach will be to use our comparatively robust understanding of melting to examine conditions under which other forms of heat transfer supplant Earth-like plate tectonics. Vertical tectonics, as seen on Io (Moore 2003; Lopes & Spencer 2007) may be thought to take over from horizontal (plate) tectonics when either (1) the thickness of the crust becomes comparable to that of the lithosphere, (2) heat lost by magma transport dominates over conduction, or (3) the crust delaminates. We also assess the likelihood that (4) continental growth or (5) greater plate buoyancy prevents subduction. We present results only for our fiducial calculation with MB88 melting and radiogenic-isotope complements following Turcotte & Schubert (2002).

We assume throughout that surface water is available to hydrate lithosphere rock. Weakening the lithosphere by hydration is thought to be a prerequisite for plate tectonics.

4.1. Crust Thicker Than Lithosphere

If the crustal thickness $Z_{\text{crust}}$ is comparable to the lithospheric thickness $Z_{\text{lith}}$, the lower crust is likely to melt and form buoyant diapirs. Widespread intracrustal diapirism within the oceanic crust is not known on Earth and, if it were a major heat sink for the mantle, would be a substitute for plate tectonics. $Z_{\text{lith}}$ scales as $Q^{-1}$, and on Earth the equilibrium value of $Z_{\text{lith}}$ is $\sim 110$ km (McKenzie et al. 2005). Therefore,

$$\frac{Z_{\text{crust}}}{Z_{\text{lith}}} = \frac{7}{110} \left( \frac{Q}{Q_{\text{Earth}}} \right) \left( \frac{Z_{\text{crust,Earth}}}{Z_{\text{lith}}} \right). \quad (15)$$

We find $Z_{\text{crust}}/Z_{\text{lith}} < 1$ for all planets $> 2$ Gya (Figure 11), so intracrustal diapirism is unlikely within equilibrium lithosphere. Intracrustal diapirism is unlikely to be the limiting factor for super-Earth plate tectonics.

4.2. Magma Pipe Transport Energetically Trumps Conduction

On Earth, heat lost by conduction through thin lithosphere near mid-ocean ridges greatly exceeds heat lost by advection of magma. On Io, the opposite is true: most internally deposited heat is lost by advection of magma through lithosphere-crossing magma conduits—“magma pipes” (Moore 2001). Such a planet, although it may have limited plate spreading, is not in plate tectonic mode; vertical rather than horizontal motion of the material making up the lid is the more important process.

We introduce the dimensionless “Moore number,” $Mo$, in appreciation of the work of Moore (2001, 2003), which we define to be the ratio of magma pipe heat transport, $Q_{\text{magma}}$, to heat lost by conduction across the lithosphere, $Q_{\text{cond}}$. To calculate how this number (analogous to a Peclet number) scales with increased mass, we specify that total heat loss (magma pipe transport plus conduction across the boundary layer) adjusts to match the heat loss across the boundary layer prescribed by the thermal evolution model:

$$Mo = \frac{Q_{\text{magma}}}{Q_{\text{cond}}} = \frac{Q}{Q_{\text{cond}}} - 1. \quad (16)$$

An upper bound on magma pipe transport is to assume that all melt crystallizes completely and cools to the surface temperature. In that case

$$Q_{\text{magma}} = \rho_{\text{crust}}(c_p \Delta T_1 + E_L)Z_{\text{crust}} \Delta t_s \sim c_1 \Delta t_s, \quad (17)$$
where $\rho_{\text{crust}}$ is the crustal density, $c_b$ is the specific heat of basalt, $\Delta T_1$ is the temperature contrast between lava and the surface, $E_{lk}$ is the latent heat of crystallization, $l_r$ is the ridge length, and $s$ is the spreading rate. Provided that half-space cooling is a good approximation to the thermal evolution of plates,

$$Q_{\text{cond}} = 2k\Delta T_2 \left( \frac{A_{\text{oc}}c_b}{\pi K} \right) \sqrt{s} \sim c_2 \sqrt{s},$$  \hspace{1cm} (18)

where $A_{\text{oc}}$ is the area of the ocean basins only, which we take to be $0.6 \times A$ as on Earth. We can now solve the quadratic in $s$:

$$Q^2 = c_1 s^2 + c_2 s.$$ \hspace{1cm} (19)

Finally, we obtain an expression for $Mo$:

$$Mo = \frac{Q_{\text{magma}}}{Q_{\text{cond}}} = \left( \frac{\rho_{\text{crust}}(c_b\Delta T_1 + E_{lk})Z_{\text{crust}}l_r}{2k\Delta T_2 \sqrt{A_r}/(\sqrt{\pi K})} \right) \sqrt{s}. \hspace{1cm} (20)$$

Here, $l_r$ is the ridge length and $s$ is the spreading rate. We assume a latent heat of crystallization $E_{lk} = 550$ kJ kg$^{-1}$, a specific heat of basalt $c_b = 0.84$ kJ kg$^{-1}$ K$^{-1}$, crustal density $\rho_{\text{crust}}$ of 2860 kg m$^{-3}$ (Carlson & Herrick 1990), base lithosphere temperature of 1300 °C, and lava temperature of 1100 °C and surface temperature of 0 °C giving $\Delta T_1 = 1100$ K and $\Delta T_2 = 1300$ K. This gives $4.2 \times 10^{18}$ J in melt km$^{-3}$ plate made. As an illustration, for Earth (mid-ocean ridge crust production 21 km$^2$ yr$^{-1}$), $Q_{\text{magma}}$ is 2.8 TW. The total oceanic heat flux is 32 TW, so today’s Earth has a $Mo \sim 0.10$.

Therefore, given the one-to-one relationship between $Q$ and $T_p$, we can solve for spreading rate (Figure 12). As $Mo \rightarrow 0$, $s \rightarrow Q^2$ (Sleep & Zahnle 2001). Note that the characteristic age at subduction $\tau = A/(2l_r s)$. As a consequence, the Moore number does not vary with different possible scalings of ridge length (equivalently, plate size) with increased planet mass. As planet mass increases, we hold plate area (rather than the number of plates) constant to produce Figure 12. If one instead holds the number of plates constant, $l_r$ falls and $s$ increases, but, because $\tau$ is unchanged, our subsequent buoyancy and rate of volcanism calculations (Sections 4.4 and 5) are not affected. For Earth, Equation (18) gives $s \sim 5$ cm yr$^{-1}$, a good match to present-day observations (minimum <1 cm yr$^{-1}$ in the Arctic Ocean, maximum 15 cm yr$^{-1}$ at the East Pacific Rise, mean $s \sim 4$ cm yr$^{-1}$).

Reaching $Mo \sim 1$ requires temperatures near or beyond the limit of validity of our melting models. Coincidentally, $Mo = 1$ plots close to $Z_{\text{crust}}/Z_{\text{lith}} = 1$ on a mass–time graph. We conclude that heat-pipe cooling is not dominant for Earth-like planets $\gtrsim 2$ Gyr old.

4.3. Phase Transitions Within Crust

Basalt, which is less dense than mantle rock, undergoes a high-pressure exothermic phase transition to eclogite, which is more dense than mantle rock (Bucher & Frey 2002). Except during subduction, the pressures at the base of Earth’s basaltic crust are too low to make eclogite. However, the pressures at the base of the crust on massive Earth-like planets are far greater. If the crust of a massive Earth-like planet includes an eclogite layer at its base, this may delaminate and founder, being refreshed by hotter mantle (Vlaar et al. 1994).

We tracked temperature and pressure at the base of the crust for planets in plate tectonics mode, and compared these with the phase boundaries for eclogite plotted in Figure 9.9 of Bucher & Frey (2002). We assumed uniform thermal conductivity within the thermal boundary layer. We found that eclogite is not stable for $M < 25 M_\oplus$. As planet mass increases, the ratio of crustal to lithospheric thickness increases, while mantle temperature also rises. Consequently, the temperature at the base of the crust rises, inhibiting the exothermic eclogite-forming reaction.

4.4. A Continental Throttle?

Continental crust may sequester radiogenic elements, inhibiting plate tectonics and melting by imposing more rapid mantle cooling. The limit is a fully differentiated planet, in which successive melting events have distilled nearly all radiogenic elements into a thin shell near the surface. Independent of this effect, too great an area of nonsubductible, insulating continents may itself be enough to choke off plate tectonics—a limit of 50% of total area has been suggested (Lenardic et al. 2005). Which limit is more restrictive to plate tectonics? On Earth, continents contain 26%–77% of the radiogenic complement of Bulk Silicate Earth (Korenaga 2008), and cover ~40% of the planet’s surface area. If the threshold value for a significant nonsubductible-cover effect on mantle dynamics is 50% (Lenardic et al. 2005), this limit will be passed before complete differentiation occurs. However, all radiogenic elements would be sequestered in continental crust before continental coverage.
reached 100%. We expect that the thickness contrast between continental and oceanic crust will scale as the inverse of gravity. This is because crustal thickness variations are limited by crustal flow (and brittle failure down gravitational-potential-energy gradients). If in addition the radiogenic-element content of continental crust does not vary, then we can relate the two limits by expressing the fraction of planet surface area covered by continents as

\[ f_{\text{area}} = \frac{V_{\text{cont}}}{A Z_{\text{crust}}} = \frac{f_{\text{radio}} M}{M^{1/2} M^{-1/2}} = f_{\text{radio}} M, \tag{21} \]

using the approximation \( R \propto M^{-0.25} \). This implies that continental coverage will be the more severe limit for massive planets as well. A massive planet will enshroud itself with nonsubductible crust before it sequesters a substantial fraction of its radiogenic elements into crust.

Provided that crustal flow limits continental thickness, a representative calculation shows that continents will spread out to coat the surface of an Earth-like planet \( > 3 M_{\oplus} \), in much less than the age of the Earth (Figure 13); this is because continental production rate scales roughly as planet mass, but planet area increases only as the square root of mass. To produce this figure, we set net continental growth to zero for the first 1 Gyr of each planet’s evolution (guided by the age of the oldest surviving continental blocks on Earth). From 1 Gyr forward, we set continental growth to be proportional to crustal production rate, with a proportionality constant picked to obtain 40% coverage on Earth today.

4.5. Will Trenches Jam?

Subduction will cease if the relative buoyancy of crust, less dense than mantle, exceeds that of the colder and denser lithospheric mantle. Provided that thermal conductivity and crustal density are constant, the subduction condition is

\[ \Delta \rho \cong -\rho_{\text{ lith}} + \frac{1}{Z_{\text{ lith}}} (\rho_{\text{ lith}} (1 + 2 \Delta T_3) (Z_{\text{ lith}} - Z_{\text{ crust}}) \]

\[ + (\rho_{\text{ crust}} Z_{\text{ crust}})) < 0, \tag{22} \]

where

\[ \Delta T_3 = \frac{1}{2} \left( 1 - \frac{Z_{\text{ crust}}}{Z_{\text{ lith}}} \right) \Delta T_2 \tag{23} \]

and \( \Delta \rho \) is the density difference favoring subduction, \( \rho_{\text{ lith}} \) is the reference density of mantle underlying the plate, \( Z_{\text{ lith}} \) is the lithospheric thickness, \( \Delta T_3 \) is the average cooling of mantle lithosphere, all evaluated at subduction. Hotter—that is, bigger or younger—planets must recycle plate faster, so a plate has less time to cool. In addition, higher potential temperatures produce a thicker crust. Both factors tend to produce positively buoyant plate, which is harder to subduct. This effect is more severe for massive planets because of their greater gravity.

Once subduction is initiated the basalt-to-eclogite transition can sustain subduction. However, it is not clear that subduction initiation is possible if plate is positively buoyant everywhere, as seems likely for early Earth (Davies 1992; Sleep 2000). The geological record is neither mute nor decisive. All but the last Gyr of Earth’s tectonic history is disputed, but evidence is accumulating that subduction first occurred at least 2.7 Gya (1.8 Ga after formation), and perhaps earlier than 3.2 Gya (1.3 Ga after formation; Condie & Pease 2008). Taking buoyancy stress per unit length of trench to be the appropriate metric for buoyancy, we can relate Archean observations to high-mass planets (Figure 14). For example, the buoyancy stress that had to be overcome on Earth after 1.8 Ga is the same as that on a 16 \( M_{\oplus} \) planet after 4.5 Ga. Here we have assumed that all plate reaches the subduction zone at a characteristic age, \( \tau \), that the temperature distribution within the plate is described by half-space cooling (so \( Z_{\text{ lith}} = 2.32 \kappa^{0.5} \tau^{0.5} \)), and that \( \kappa \) and \( \rho_{\text{ crust}} \) (2860 kg m\(^{-3}\); Carlson & Herrick 1990) are constant. This gives a negative (subduction-favoring) buoyancy stress of 38 MPa at the characteristic age of subduction on the present Earth. The much more sophisticated model of Afonso et al. (2007) yields 21 MPa, so our estimate probably understates forces retarding subduction. However, the base of a thick, water-rich crust may be at temperatures/pressures permitting amphibolite-grade metamorphism, producing dense crust. (In addition, the crust-mantle density contrast declines with increasing melt fraction as the olivine content of the crust increases). For this reason, we also plot results for a constant crustal density of 3000 kg m\(^{-3}\), intermediate between the densities of amphibolite (3000–3300 kg m\(^{-3}\); Cloos 1993) and unmetamorphosed crust. Whether or not amphibolitization is considered, our assessment is that plate buoyancy raises a severe
Figure 14. Buoyancy stresses as a function of thermal evolution and planet mass. Buoyancy stress is the product of density contrast, gravity, and lithospheric thickness. Positive values denote plate denser than underlying mantle, favoring subduction; negative values denote plate more dense than underlying mantle, retarding subduction. Solid lines connect buoyancy values for planets of different masses 2.5 Gyr, 5 Gyr, 7.5 Gyr, and 10 Gyr after planet formation, for constant crustal density of 2860 kg m\(^{-3}\). Dash-dotted lines are for a crustal density of 3000 kg m\(^{-3}\), as might be the case for partial amphibolitization. Dotted lines are possible lower limits to plate tectonics based on Earth’s (disputed) geological record; arguably, subduction must be possible on planets whose buoyancy forces plot above these lines. The Earth symbol is the model calculation for present-day conditions on Earth.

5. RATE OF VOLCANISM AND IMPLICATIONS FOR DEGASSING

5.1. Degassing Rate

In plate tectonics mode, for “Earth-like” planets with oceans and some land, we calculate the rate of volcanism by multiplying spreading rate (Section 4.3), mid-ocean ridge length, crustal thickness (Section 3), and crustal density, then dividing by planet mass (Figure 15). Our model gives \(1.2 \times 10^{-11}\) yr\(^{-1}\) by mass for Earth, observations give \(1.1 \times 10^{-11}\) yr\(^{-1}\) (Best & Christiansen 2001). The discrepancy is mainly due to our model’s higher-than-observed spreading rate (Section 4.3). For comparison, Earth’s total observed present-day rate of volcanism is \(1.7 \times 10^{-11}\) yr\(^{-1}\) by mass, and \(3.1 \times 10^{-11}\) yr\(^{-1}\) by volume (Best & Christiansen 2001). This includes arc and ocean-island volcanoes, which are not modeled in this paper. Rate per unit mass increases monotonically with increasing mass, for all times. Per unit mass, rates of volcanism vary only by a factor of 3 on planets <3 Gyr old and >1 \(M_\oplus\), but a stronger mass dependence develops for older planets (Figure 15). Melting in plate tectonic mode ceases when potential temperature falls below the zero-pressure solidus, but this only occurs for small (0.25 \(M_\oplus\)) planets \(\geq 10\) Gya (Figure 5(b)).

In plate tectonic mode, the flux of mantle into the melting zone balances spreading rate. To calculate the rate of volcanism on a planet in stagnant lid mode (Figure 16), we must first find the flux of material into the upper boundary layer as a function of \(Ra\). We define a near-surface convective velocity such that all heat flow in excess of the conductive heat flow is advected

\[
Nu - 1 = \frac{u \Delta T_{\text{conv}} \rho c}{2} = \frac{u \rho c d}{2k} \frac{T_m - T_c}{T_m - T_s},
\]

where

\[
u = 2(Nu - 1) \left( \frac{k}{\rho c d} \right) \left( \frac{T_m - T_s}{T_m - T_c} \right),
\]

and

\[
R = \frac{A_{up}}{M_{\text{planet}}} \left( \frac{\rho_{\text{crust}} Z_{\text{crust}} g}{P_f - P_o} \right),
\]

where \(R\) is the rate of melt generation per unit mass, \(Z_{\text{crust}}\) is obtained from our models in Section 3, and the bracketed term is the mean melt fraction. This sets an upper limit to the rate of volcanism (Figure 16) because it assumes that all melt generated reaches the surface, and that all ascending mantle parcels reach \(P_o\). The first assumption is probably safe because of the large forces driving magma ascent on massive planets, and the short absolute distances they must ascend. With these assumptions, we find that the rate of volcanism on stagnant lid planets initially exceeds that on their plate tectonic counterparts but this contrast soon reverses as the stagnant lid thickens. The predicted shutdown of nonplume melting on stagnant lid planets shows remarkably weak dependency on mass and melting model, as explained in Section 3.3. We consider the rate of crust production...
to be a good proxy for the rate of degassing. But because volatiles are incompatible, they partition almost quantitatively into even small fractions of melt. Therefore, a more accurate statement is that degassing should be proportional to the flux of mantle processed through melting zones (Papuc & Davies 2008). We had great difficulty in determining this processing flux because of the “solidus rollover” problem (Section 6.2). (Because of volatile incompatibility, order-unity differences in the volatile concentrations of planetary mantles should not make much of a difference to our melting curves. Wet parcels of ascending mantle soon “dry out.”) In addition to lavas that are extruded at the surface, magmas that crystallize below the surface as intrusions—such as the sheeted dykes and gabbros of Earth’s oceanic crust—are assumed to degas fully and are referred to as “volcanism.”

The implications for greenhouse-gas release of our results depend on the water and CO₂ contents of extrasolar planet mantles. These will depend on the mantle’s oxidation state (Elkins-Tanton & Seager 2008b), the range of semimajor axes from which the growing planet draws material, and the extent of volatile loss on the planetesimals which collide to form the planet. The water and CO₂ contents of terrestrial magmas are our only empirical guide. At mid-ocean ridges, these range from 0.1%–1.5% for H₂O, and 50–400 ppm for CO₂ (Oppenheimer 2003). Taking the upper-limit values (which is appropriate, given that additional volatiles are almost certainly present in
Figure 16. Rate of volcanism on massive Earth-like planets undergoing stagnant lid convection, normalized to calculated rate on a plate-tectonic Earth, for MB88 (top) and K03 (bottom) melting models. Dark gray shaded regions correspond to mantle temperatures too high for a reliable crustal thickness calculation. Contours are at 0, 0.5, 1, 2, 5, and 10 times Earth’s rate.

an unmeasured fluid phase), assuming that all mantle fluxing through the melting zone is completely degassed, and ignoring overburden pressure, our model yields $6 \times 10^{13}$ mol a$^{-1}$ for H$_2$O and $7 \times 10^{11}$ mol a$^{-1}$ for CO$_2$. This is within the range of uncertainty of observational estimates (Oppenheimer 2003). Because our model is not “tuned” to observed rates of volcanism, but only to crustal thickness, this lends some credence to our results for other Earth-like planets.

5.2. Overburden Pressure

The rate of degassing from seafloor volcanoes will also be regulated by the thickness of the volatile overburden. A volatile envelope can have two effects.

1. Through a greenhouse effect, a volatile envelope can raise surface temperatures, and increase partial melting. This is shown for our thermal-equilibrium model in Figure 2. Here, we show the internal temperature needed to drive convection when the surface temperature is 647 K, the critical point of water (q.v. 273 K for the baseline model). In thermal equilibrium, the reduced mantle-surface temperature difference demands more vigorous convection to drive the same heat flux across the upper boundary layer. The increase in mantle temperature is 50–55 K (Figure 2), which has a significant feedback effect on melting (Figure 3). Such high surface temperatures are classically considered to be encountered only for brief intervals on the path to a runaway greenhouse (Ingersoll 1969), but if this catastrophe is suppressed for massive Earths (Pierrehumbert 2007), massive Earths will experience these temperatures for geologically significant intervals. The sign of this feedback is positive; higher mantle temperatures increase crustal thickness, and the associated degassing would enhance the greenhouse effect. We do not consider still higher temperatures, relevant for close-in rocky exoplanets (Gaidos et al. 2007), because plate tectonics is thought to require liquid water.

2. Through overburden pressure, a volatile envelope can suppress degassing (and melting for sufficiently thick volatile layers). Water degassing is readily suppressed by 0.1–0.2 GPa of overburden (Papale 1997), although joint-solubility effects allow some water to degas at higher pressures in association with other gases (Papale 1999). CO$_2$, an important regulator of climate on the known terrestrial planets, has a solubility of 0.5% GPa$^{-1}$. Therefore, the overburden pressure provided by 100 km of ocean on a 1 Earth-mass planet is enough to suppress CO$_2$ degassing from a magma containing 0.5 wt % CO$_2$. A planet with a massive ocean cannot degas. However, it can regas, provided that hydrous/carbonated minerals pass the line of arcs at subduction zones. This suggests a steady state ocean mass over geodynamic time.

Much more pressure is needed to shut down melting than is needed to shut down degassing (Figure 17). However, numer-
tical simulations of water delivery during late-stage accretion (Raymond et al. 2004, 2006), assuming (following Raymond et al. 2006) that volatiles are partitioned between surface and mantle reservoirs in the same proportions as on Earth. We treat the effect of the volatile overburden on melting as being equivalent to that of a stagnant lid with the same basal pressure.

Figure 17. Crustal thickness as a function of planet mass and ocean mass for planets with plate tectonics, after 4.5 Gyr. K03 melting model. Solid lines are contours of crustal thickness at 1 km intervals. Small fluctuations in the contours are interpolation artifacts. Black circles correspond to simulated planets are contours of crustal thickness at 1 km intervals. Small fluctuations in the contours are interpolation artifacts. Black circles correspond to simulated planets with plate tectonics, after 4.5 Gyr. K03 melting model. Solid lines are contours of crustal thickness at 1 km intervals. Small fluctuations in the contours are interpolation artifacts. Black circles correspond to simulated planets.

5.3. Melt-Residue Density Inversion: Decoupling Melting from Mantle Degassing?

Melts are more compressible than mantle minerals, so at sufficiently high pressures melt will be denser than its residue; for example, mid-ocean ridge basalt becomes denser than garnet at 12.5–19.5 GPa (Agee 1998). If the sinking rate exceeds mantle velocities, these denser melts may accumulate at the base of the mantle (Ohtani & Maeda 2001). Meanwhile, the residue will continue to rise to shallow pressures, where it will eventually generate melt less dense than itself. That melt will segregate, ascend, and form a crust. However, because atmosphere-forming volatiles are highly incompatible, they will partition into the early stage (sinking) melt and erupted melts will be volatile-poor. Generating melt at sufficiently high pressures for the density inversion to come into play requires very high potential temperatures. In our modeling, these are not encountered for planets in plate tectonic mode (except during the first 1 Gyr, which is a transient associated with cooling from our high initial temperature; initial conditions are thus very important). But the density crossover is encountered for \( >5 \) \( M_\oplus \) and \(< 3 \) Gyr in stagnant lid mode. We speculate that in these planets, melting is decoupled from mantle degassing.

6. DISCUSSION AND CONCLUSIONS

6.1. Summary of Results

1. Modest effect of planet mass on temperature and crustal thickness. Scaling analysis predicts \( T_m \) should only be weakly dependent on planet mass (Stevenson 2003). Because of the exponential dependence of viscosity on temperature, modest variation in \( T_m \) can accommodate the range of heat flows generated by planets of varying masses. Our more detailed study confirms this, and although the non-linearity of mantle melting leads to greater variations in crustal thickness, these are still of order unity (Section 3.2; Section 3.3; Figure 5). However, planet mass can determine which mode of mantle convection the planet is in (Section 4), which in turn determines whether melting is possible at all (Section 3.3).

2. Inhibition of plate tectonics on massive Earths. Plate buoyancy is an increasingly severe problem for plate tectonics as planet mass increases (Section 4.5). Because early Earth faced the same challenge, geologic fieldwork may determine the threshold beyond which plate tectonics shuts down (Section 4.5). Middle-aged super-Earths may suffer from continental spread, which could choke off plate tectonics (Section 4.4). Shutdown of plate tectonics could place a planet in stagnant lid mode.

3. Shutdown of melting on old, stagnant lid planets. All our melting models predict that stagnant lid planets older than Earth cease melting and volcanic activity (Sections 3.3–5, but see caveats in Section 6.2). Therefore, observed volcanism on rocky planets >8 Gya would provide some support for plate tectonics—if and only if tidal heating could be shown to be small. A candidate planetary system has been identified around \( \tau \) Ceti (Marcy 2002), a 10 Gya star at 3.65 pc, and may provide an early test of this prediction.

4. Implications for the stability of atmospheres, climate, and habitability. The atmospheres of Venus, Earth, and Mars were produced by the release of gases dissolved in partial melts, as well as temperature-dependent exchange of volatiles between the atmosphere and surface rocks. Planets lacking dynamos and on close orbits around their parent stars may experience high rates of atmospheric erosion due to stellar winds and coronal mass ejections (Khodachenko et al. 2007), and their atmospheres would persist on main-sequence timescales only if maintained by mantle melting. Under more benign conditions, crust formation may establish the long-term carbon dioxide content of Earth-like atmospheres; \( CO_2 \) released in volcanism is sequestered as carbonates produced during the low-temperature weathering of that crust (Walker et al. 1981). Volcanism may underpin the long-term habitability that the fossil record teaches us is a prerequisite for advanced life (Butterfield 2007).

6.2. Overview of Approximations and Model Limitations

In this paper, we assume whole-mantle convection. Layered mantle convection can alter the volcanic history of a planet by
introducing long-term sensitivity to initial thermal conditions. For a phase boundary to form a barrier to flow its Clapeyron slope must be strongly endothermic. Historically, the $sp \rightarrow pv$ transition was thought to have this character but this is now known not to be the case. Deeper phase transitions are either exothermic ($pv \rightarrow ppv$) or very gradual (Seager et al. 2007).

In spite of these arguments against layered mantle convection, barriers to flow are possible if stable deep mantle layers arise during or shortly after fractional crystallization of the primordial magma ocean. Although CBM pressures reach $14 \text{ Mbar}$ for $10 M_\oplus$ and $40 \text{ Mbar}$ for $25 M_\oplus$, we have not considered metalized silicates (Umemoto et al. 2006), nor the possibility that lower-mantle convection is extremely sluggish (even isoviscous; Fowler 1983) due to low homologous temperatures, nor pressure-dependent viscosity (Papuc & Davies 2008). Our parameterized treatment of mantle convection assumes the solid state and is inappropriate for very high temperatures, when the greater part of the lithosphere is underlain by a magma ocean. For almost all cases, however, the transition to a magma ocean takes place at temperatures beyond the range of validity of our melting models, so magma ocean development is not the limiting consideration in interpreting our results.

Our model does not consider tidal heating, which may be important for Earth-like planets on close eccentric orbits about low-mass stars (Jackson et al. 2008), nor does it take into account the energetics of the core (Nimmo 2007). Because the magnitude of core cooling is set by mantle cooling, core energetics only dominate mantle thermal evolution in Earth-like planets as $t \rightarrow \infty$ and $H \rightarrow 0$. Surface temperature is assumed to be constant, which is likely to be a good approximation except for close-in exoplanets with thin atmospheres in a 1:1 spin-orbit resonance (Ganesan et al. 2008).

All our melting models show “solidus rollover” at high $P$—that is, $T_p \rightarrow T_{pv}$ as a consequence, plots of $X$ versus $P$ at high $T_p$ have a long, thin high-pressure tail, and the pressure of first melting diverges at finite $T_p$. Although solidus rollover is a real effect, resulting from the greater compressibility of silicate melts versus solids (Ghiorsos 2004), infinite pressures of first melting are unphysical. In particular, phase transitions near $14 \text{ GPa}$ introduce unmodeled kinks of the solidus. To sidestep the solidus rollover problem, we truncate our melting integration at $8 \text{ GPa}$, and do not plot model output where model melting will only occur above mantle upwellings. Also, the observable crustal thickness may be everywhere greater than the integral of melting fraction from the surface to great depth, because crust generated in previous melting events is located directly underneath “fresh” crust. This situation is described in the context of Io by Moore (2001). On stagnant lid planets, volcanism may be episodic (as on Mars; Wilson et al. 2001) and absent for long periods. This means that an observed lack of compounds with a short photochemical lifetime would not preclude a high level of volcanic activity averaged over a sufficiently long period ($\gtrsim 10^{-8}$ yr). Volcanism is not the only possible source of degassing. Metamorphic decarbonation (Bickle 1996), and the episodic release of deep-seated volatiles as on the Moon (Gorenstein & Bjorkholm 1973), could permit (low) rates of degassing on nonvolcanic worlds.

By assuming that all melt reaches the surface, we have ignored the distinction between extrusion and intrusion. However, extrusion can alter the reflectance properties of the planet without sustaining an atmosphere—consider the Moon—and it may eventually be possible to discriminate between the two possible fates for melt.

6.3. Comparison with Solar System Data

6.3.1. Thermal Evolution, with an Emphasis on Earth

Four decades since plate tectonics became widely accepted, geologists have not determined the detailed thermal history of the Earth, neither have we even produced a model that satisfactorily accounts for the few data points in hand. The model of Korenaga (2006, taking a parameterized approach) may be an exception, but this model assumes that present-day observed averages are valid for the past, and is probably not portable to other Earth-like planets. Complicating the picture are two sharp-edged lower mantle anomalies mapped by seismic tomography under Africa and the S. Pacific, which are likely distinct in composition and radiogenic-element density from the rest of the mantle and which may be persistent, ancient features that have interfered in mantle convection since more than 2.5 Gyr ago. Their origin is unknown (Garnero & McNamara 2008). Geoneutrino detectors will break some of these degeneracies before 2020, and continued field mapping of ancient tectonic features will sharpen the history of past dynamics of plate deformation (Condie & Pease 2008). But using simple models and making changes along one dimension only—the approach taken here—is still a meaningful approach because the more complex models introduce many more free parameters, and it is not clear how these free parameters vary with mass. By contrast, our approach involves only one “tuning” parameter, the offset $T_m - T_p$.

The situation for the other terrestrial planets—single plate planets with stagnant lithospheres—is in many ways better. Parameterized cooling fits all the observations. This is not just because of a lack of data: stagnant lid planets seem to be truly simpler, and the relevant fluid physics is probably better understood than the “viscoelastoplastic plus damage” phenomenology needed to accommodate the observed geological motions of the Earth’s plates. On Earth, mantle heat loss is largely by conduction aided by hydrothermal convection at mid-ocean ridges, but mantle heat loss on stagnant lid planets should be less sensitive to the details of surface deformation.

The degree to which the mantle cools over geological time depends on the activation energy for deformation of mantle rock, which is known only imprecisely (Karato 2008). We take...
There is geological and isotopic evidence for episodic continental growth (Condie & Benn 2006). Durable continents may require photosynthetic life both in the oceans and on land (Lee et al. 2008). None of these mechanisms may take over. Plumes rising from the CMB, or from a compositional interface within the mantle, can have temperatures up to several hundred degrees greater than that of passively upwelling mantle. This requires a more detailed treatment of thermal evolution than we have taken in this paper, and could be the basis of a more detailed study.

In particular, Mars’ continuing—although fitful and low-rate—volcanic activity (Borg & Drake 2005) indicates that volcanic activity can continue on planets in stagnant-lid mode for longer than our simple models predict, perhaps as the result of plumes in a compositionally layered mantle (Wenzel et al. 2004) or a thick, thermally insulating crust (Schumacher & Breuer 2007). On Venus, mantle fluxing by sinking delaminated lithosphere has been proposed as a mechanism that would allow volcanism to continue through to the present day (Elkins-Tanton et al. 2007), although there is no robust evidence of ongoing volcanism. Continued solar system exploration is needed if we are to fully exploit nearby data points to understand the geodynamic window for life.

Many of the ideas discussed here are drawn from the conversation of Dave Stevenson, whose support for the early stages of this project was invaluable. We thank Nick Butterfield, Rhea Workman, Brook Peterson, Norm Sleep, and Itay Halevy for their productive suggestions. We acknowledge support from the NASA Astrobiology Institute. E.K. acknowledges support from the Berkeley Fellowship and a Caltech Summer Undergraduate Research Fellowship.

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