Uplift of Beta Regio: Three-dimensional models

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Received 4 March 2004; revised 4 June 2004; accepted 21 June 2004; published 25 August 2004.

[1] Three-dimensional models of the uplift of Beta Regio caused by a mantle plume satisfy constraints on gravity, topography, rheology, and the uplift rate substantially better than two-dimensional models. In particular, the uplift time of Beta Regio is reduced to an acceptable 800 million years. Three-dimensional models give the plume formation depth around 3000 km, which approximately corresponds to the core-mantle boundary. The results depend only weakly on the initial lithospheric thickness (at the time of global resurfacing), including a very thin initial lithosphere. This implies that the thick present-day lithosphere (~400 km) suggested by our models can be reconciled with a thin lithosphere (100–200 km) inferred from the melt generation rates and the flexural rigidity models. *INDEX TERMS:* 3210 Mathematical Geophysics: Modeling; 8147 Tectonophysics: Planetary interiors (5430, 5724); 8121 Tectonophysics: Dynamics, convection currents and mantle plumes; 6295 Planetology: Solar System Objects: Venus; *KEYWORDS:* Beta, modeling, Venus

Citation: Vezolainen, A. V., V. S. Solomatov, A. T. Basilevsky, and J. W. Head (2004), Uplift of Beta Regio: Three-dimensional models, *J. Geophys. Res.*, *109*, E08007, doi:10.1029/2004JE002259.

1. Introduction

[2] Beta Regio is one of equatorial highlands on Venus which is believed to be formed by a hot plume [*McGill et al.*, 1981; *Senske et al.*, 1991, 1992; *Smrekar et al.*, 1997; *Phillips and Hansen*, 1994; *Stofan et al.*, 1995]. In the past, the main constraints on the models of Beta Regio were gravity and topography data [*Kiefer and Hager*, 1991, 1992; *Moresi and Parsons*, 1995; *Nimmo and McKenzie*, 1996; *Moore and Schubert*, 1997]. *Solomatov and Moresi* [1996] showed that the inferred results depend strongly on the assumed rheology of the mantle. For example, the same gravity and topography profiles can be obtained with the lithospheric thickness from 100 to more than 1000 kilometers depending on the viscosity parameters. The results are particularly sensitive to changes in the regime of mantle convection. At small viscosity contrasts between the lithosphere and the mantle, the plumes can easily penetrate the weak lithosphere. At the viscosity contrasts larger than 10^4–10^5, the lithosphere becomes stiff (stagnant lid regime) and the plumes can penetrate only the lower part of the lithosphere. *Solomatov and Moresi* [1996] showed that stagnant lid convection is the regime expected for Venus and the interpretation of gravity and topography data can be improved using laboratory constraints on the viscosity of major mantle minerals such as olivine.

[3] However, several important issues remain unsolved. First, even with the rheological constraints imposed on the models, the situation was still ambiguous; a range of solutions with different Rayleigh numbers could satisfy the observations equally well. Second, the plume formation depth corresponded to mid-mantle region, which did not have a clear physical interpretation. Third, the models were steady-state while the interaction between the plume and the lithosphere is a time-dependent process. *Vezolainen et al.* [2003] addressed these issues using an additional constraint: geomorphological estimates of the uplift time of Beta Regio. It turned out that it was difficult to obtain a fast uplift of Beta Regio suggested by the new constraints; it takes a long time to heat up a ~400 km thick Venusian lithosphere. As one of the possible solutions, *Vezolainen et al.* [2003] proposed that the lithosphere has to be nearly as weak as on Earth. In this case the uplift is facilitated by the lithospheric flow. Although *Vezolainen et al.*'s [2003] model satisfies constraints on gravity and topography anomalies as well as the uplift rate, it is inconsistent with the laboratory constraints on the rheology of mantle minerals [*Karato and Wu*, 1993] and with the high strength of the Venusian crust [*Mackwell et al.*, 1998]. In addition, a weak lithosphere seems to be inconsistent with the models of degassing history of Venus [*Franck and Bounama*, 2003]. Therefore it is interesting to explore models other than those involving lithospheric

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Table 1. Estimates of Absolute Ages of the Craters of Beta Regio Based on Results of *Basilevsky and Head* [2002] and *Basilevsky et al.* [2003][a]

Name	Lat, °	Lon, °	Diameter, km	Dark-Halo Type[b]	Age, *T*	Relations with Beta[c]
Balch	29.9	282.9	40	NH	>0.5	cut by *rt*
Raisa	27.5	280.3	13.5	FH	>0.5	superposed on *pl*1, flooded by *pl*2
Tako	25.1	285.3	10.5	FH	>0.3	superposed on *rt*
Sanger	33.8	288.6	84	CH	<0.5	crater ejecta outflow cut by *rt*
Olga	26.1	283.8	15.5	CH	<0.5	superposed on *rt*1, cut by *rt*2

[a]Absolute ages are in fractions of the planet mean surface age *T*.
[b]NH, no dark halo; FH, faint dark halo; CH, clear dark halo.
[c]Beta volcanic units and tectonic structures: *rt*, rift-associated faults; *rt*1, early rift-associated faults; *rt*2, late rift-associated faults; *pl*1, early rift-associated volcanics; *pl*2, late rift-associated volcanics.

flow. *Moore et al.* [1998, 1999] showed that small-scale instabilities developed within the three-dimensional plume head can increase the uplift rate. Fast lithospheric thinning can probably be achieved by small-scale convection alone, without any plume [*Reese et al.*, 1999]. Also, a large temperature difference between the core and the mantle can generate a super-plume [e.g., *Thompson and Tackley*, 1998; *Ke and Solomatov*, 2004] the effect of which on the uplift is yet to be studied. Here we investigate the uplift of Beta Regio assuming the same model of plume formation as the one considered by *Vezolainen et al.* [2003]. The only difference is that instead of two-dimensional plumes we consider three-dimensional (3D) plumes. The motivation to explore 3D plumes is based upon studies of early axisymmetric models [e.g., *Kiefer and Hager*, 1992] which showed that 3D plumes can increase the topography by as much as a factor of 2. Thus we expect that 3D plumes might increase the uplift rate and the plume formation depth by a similar factor.

2. Timing of Beta Regio Uplift

[4] Several constraints can be imposed on the timing of uplift of Beta Regio [*Vezolainen et al.*, 2003]. First, extensive rifting clearly associated with Beta uplift occurred after the emplacement of regional plains. No traces of old, preregional plains rifting are seen within Devana Chasma [*Basilevsky and Head*, 2000b], the axial rift of Beta Regio uplift. Second, the wrinkle-ridge network is not concentric to the uplift in Beta Regio [*Basilevsky*, 1996], as it is concentric to the Sif and Gula topographic rise [*Basilevsky*, 1994; *Banerdt et al.*, 1997]. This fact implies that the uplift occurred after the emplacement of wrinkle-ridges. Time of the emplacement of regional plains and their deformation by the wrinkle ridge network is close to the mean surface age *T* [*Basilevsky and Head*, 1998; *Basilevsky et al.*, 1999; *Basilevsky and Head*, 2000a]. The best estimate of *T* based on impact crater statistics is ∼750 m.y., but any age between 300 m.y. and 1 b.y. is considered as acceptable [*McKinnon et al.*, 1997]. Another bound on the Beta uplift age is imposed by impact craters. As it was shown by *Herrick and Phillips* [1994], *Basilevsky and Head* [2002], and *Basilevsky et al.* [2003] the degree of preservation of the radar-dark deposits associated with impact craters can be used for absolute dating of these craters. Such estimates for the craters of Beta Regio are given in Table 1. They and the mentioned relations of the Beta uplift with regional plains and deforming then wrinkle ridges, suggest that the uplift, accompanied by rifting and associated volcanism, did not start yet at time *T*, started at some time before 0.5 *T* (see crater Raisa in Table 1) and continued after 0.5 *T* (Sanger, Olga).

3. Model

[5] The finite element code CITCOM [*Moresi and Solomatov*, 1995] is used to solve the equations of thermal convection in Boussinesq approximation with an infinite Prandtl number in a three-dimensional box with a fixed temperature contrast ΔT between the lower and upper boundaries. All boundaries are free-slip and the side boundaries are thermally insulated. The number of finite elements in $0.5 \times 0.5 \times 1$ box is $33 \times 33 \times 65$ (the height of the box is unity). The problem is symmetric so that only one quarter of the plume is calculated.

3.1. Viscosity

[6] We assume that mantle viscosity is controlled by diffusion creep in olivine (Newtonian viscosity). The viscosity is an Arrhenius function of temperature,

$$\eta = b \exp\left(\frac{Q}{RT}\right), \tag{1}$$

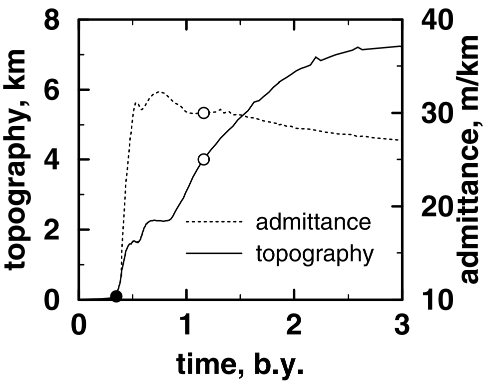

Figure 1. The topography and admittance as functions of time for a three-dimensional model with the Rayleigh number $Ra_1 = 3 \cdot 10^7$ and with an Arrhenius viscosity ($\Delta\eta = 10^8$ and $\theta = 10^3$). The uplift begins after the initial transient period (about 350 million years), during which the plume forms and travels through the mantle. The beginning of uplift is formally defined as the time when the topography reaches 100 m (solid circle). The present-day time (open circles) is defined as the time when the model satisfies the observed admittance (30 m/km) as well as the topography of Beta Regio (4 km). The oscillations after the initial fast uplift are due to interactions of the cold downwellings with the hot plume.

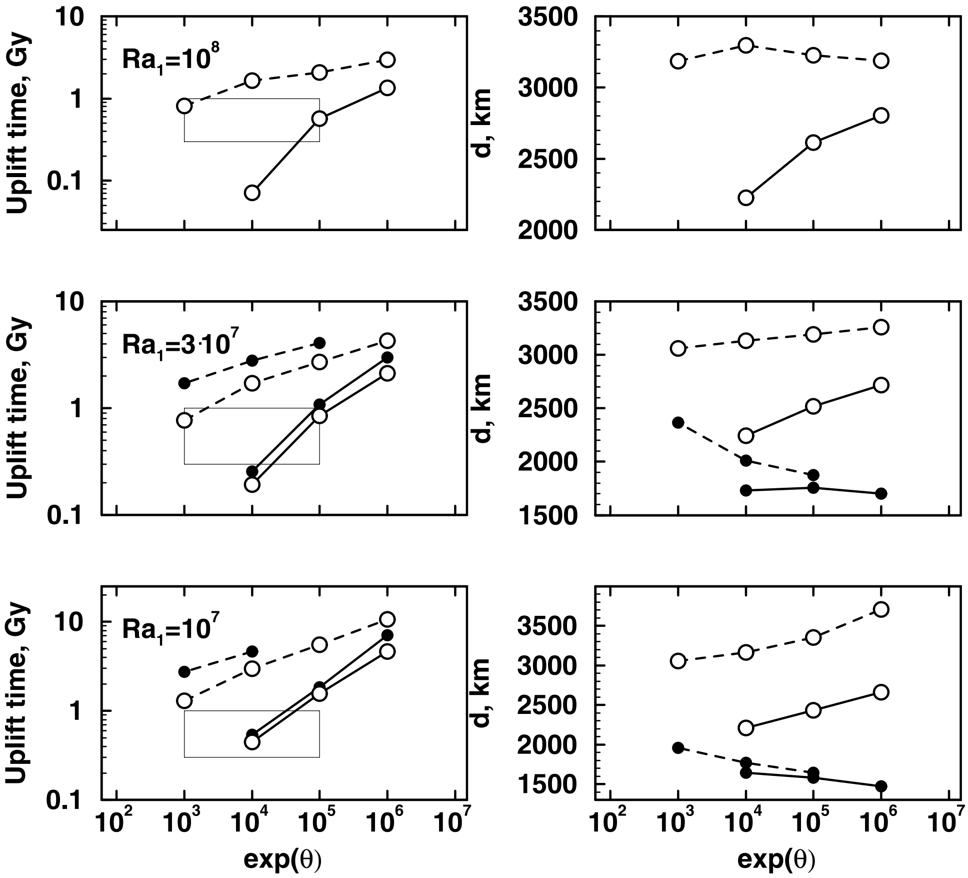

Figure 2. (left) Three-dimensional model (open circles) versus two-dimensional (solid circles) models for three different Rayleigh numbers: 10^8, $3 \cdot 10^7$, and 10^7. Arrhenius viscosity is shown with dashed lines. Exponential viscosity is shown with solid lines. (right) The corresponding plume formation depth *d*. The total viscosity contrast across the layer is 10^8 in all cases with Arrhenius viscosity. The box shows the parameter range which satisfies both the rheological constraints and the uplift time of Beta Regio [*Vezolainen et al.*, 2003]. All models give the correct values of present-day geoid and topography.

where b is a constant, $Q = E^* + PV^*$ is the activation enthalpy, V^* is the activation volume, P is the hydrostatic pressure, E^* is the activation energy, and R is the gas constant. For large viscosity contrasts and small values of PV^*, equation (1) can be approximated by an exponential function (Frank-Kamenetskii approximation)

$$\eta = \eta_0 \exp(-\gamma T), \quad (2)$$

where η_0 is the viscosity at the upper boundary,

$$\gamma = \theta \Delta T^{-1} \quad (3)$$

is a constant, T_i is the interior temperature and θ is the Frank-Kamenetskii parameter.

[7] The exponential viscosity is described with the help of one parameter, θ, while the Arrhenius viscosity is described with the help of two parameters, for example, θ and the total viscosity contrast $\Delta\eta$ across the layer,

$$\Delta\eta = \exp\left(\frac{Q}{RT_1} - \frac{Q}{RT_0}\right). \quad (4)$$

Note that although our models do not explicitly take into account pressure-dependent viscosity, its effect (for both exponential and Arrhenius viscosity) can approximately be described with the help of effective Frank-Kamenetskii parameter,

$$\theta = \frac{\Delta TE}{RT_i^2} - \frac{P_i V T_0}{RT_i^2}, \quad (5)$$

where $P_i = \rho g \delta$ is the pressure at the bottom of the thermal boundary layer of thickness δ [*Solomatov and Moresi*, 2000].

[8] With the viscosity parameters for diffusion creep [*Karato and Wu*, 1993] and assuming that the lid thickness can be as large as 450 km [*Solomatov and Moresi*, 1996], we obtain that the acceptable range of exp(θ) is 10^3 to 10^5. This parameter controls the width of the weak part of the lithosphere (which is inversely proportional to θ). It also controls the lithospheric flow in the lithospheric thinning and the surface uplift.

[9] The range of $\Delta\eta$ is 10^8 to 10^{11}. This parameter controls the surface mobility. At $\Delta\eta > 10^4$–10^5 the planetary surface is immobile and the exact value of $\Delta\eta$ becomes

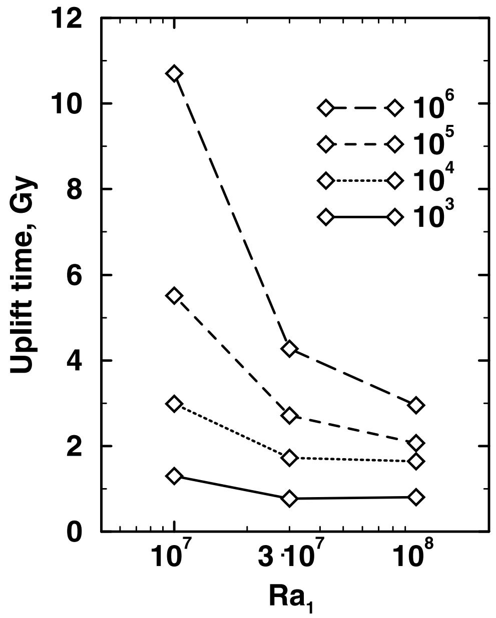

Figure 3. The dependence of the uplift time on the Rayleigh number for three-dimensional models with Arrhenius viscosity with $\Delta\eta = 10^8$ and $\exp(\theta) = 10^3, 10^4, 10^5$ and 10^6.

unimportant [*Solomatov*, 1995; *Kameyama and Ogawa*, 2000].

3.2. Rayleigh Number

[10] The Rayleigh number is defined as

$$Ra_1 = \frac{\alpha g \rho \Delta T d^3}{\kappa \eta_1}, \tag{6}$$

where ρ is the density, g is the acceleration due to gravity, α is the thermal expansion, and κ is the thermal diffusivity, η_1 is the viscosity at the lower boundary and d is the thickness of the convective layer.

3.3. Parameters

[11] The physical parameters for Beta Regio are as follows. The density is $\rho = 3300$ kg m^{-3}, the acceleration due to gravity is $g = 8.9$ m s^{-1}, the coefficient of thermal expansion is $\alpha = 3 \cdot 10^{-5}$ K^{-1}, the coefficient of thermal diffusivity is $\kappa = 8.1 \cdot 10^{-7}$ m^2 s^{-1}, the surface temperature is 733 K, and the temperature contrast across the mantle is $\Delta T = 1100$ K [*Solomatov and Moresi*, 1996].

[12] We assume that initial temperature distribution is linear near the surface (this defines the initial lithospheric thickness) and constant through the rest of the mantle. A very thin boundary layer is imposed at the core-mantle boundary. To initiate the formation of a single plume we add a small (0.5%) harmonic perturbation to the temperature field. It should be noted that the temperature distribution in the Venusian mantle could be nonuniform at the time when the uplift started. Strong inhomogeneities could affect plume formation, its propagation through the mantle and the rate of lithospheric thinning beneath Beta Regio. This question may require further investigation.

3.4. Topography, Geoid, and Uplift Time

[13] The results of our nondimensional calculations can be related to the observational data as follows. Nondimensional topography and geoid anomalies caused by plumes are related to the dimensional ones as [*Solomatov and Moresi*, 1996]

$$h_s(t) = \frac{\alpha \Delta T d}{Ra_1} h_s'(t'), \tag{7}$$

$$N(t) = \frac{2\pi G \rho \alpha \Delta T d^2}{g Ra_1} N'(t'), \tag{8}$$

where G is the gravitational constant and t' is the nondimensional time which is related to the dimensional time t as

$$t = \frac{d^2}{\kappa} t'. \tag{9}$$

Equations (7) and (8) give the equation for the admittance

$$\frac{N}{h_s} = \frac{2\pi G \rho d N'}{g h_s'}. \tag{10}$$

Topography and geoid anomalies (7) and (8) are calculated as peak-to-peak values. The geoid to topography ratio (10) is calculated as $\lambda/2 = d$ wavelength admittance.

[14] The scaling factor d (the plume formation depth) and the uplift time t are calculated iteratively from equations (7),

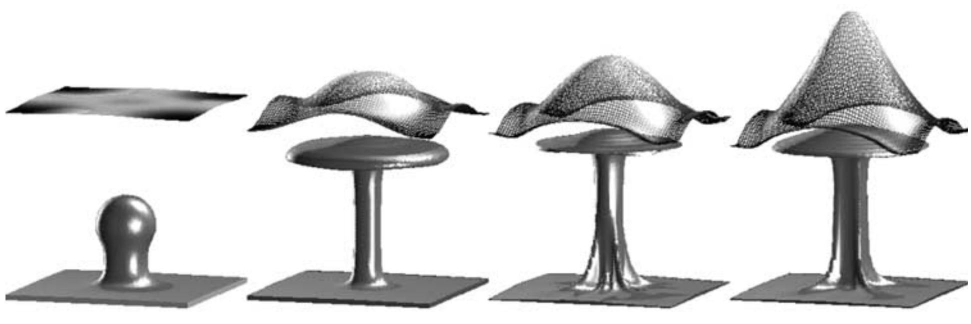

Figure 4. The best fit model of the uplift of Beta Regio. The snapshots corresponds to $t = 0$, 100, 500 and 800 m.y. (left to right). The time $t = 0$ corresponds to the moment when topography reaches 100 m. The plume is visualized with the help of an isotherm $T \sim 1700$ K. The mesh shows the model topography.

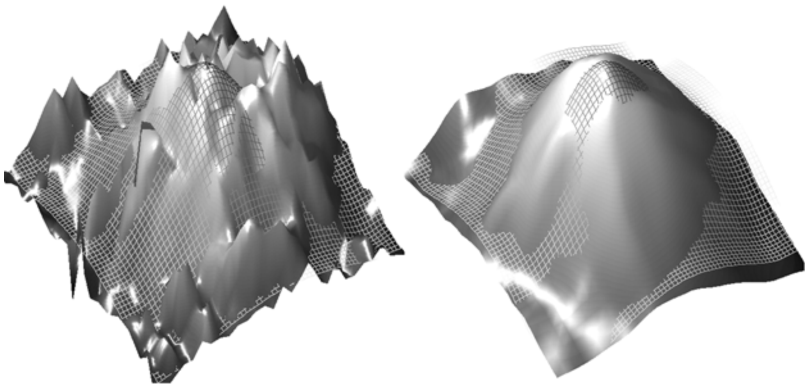

Figure 5. The best fit model topography and geoid (mesh) superimposed on 3060 × 3060 km region of 1 × 1 degree resolution map of Beta Regio (view from southeast).

(9), and (10) using the requirement that the model topography and geoid reach their observed values. First, assuming some value of d as a first approximation, from equation (7) we find the nondimensional time t' when the dimensional topography reaches its observed value h = 4 km. Second, using the nondimensional admittance N'/h_s' at time t' and the observed dimensional admittance N/h_s = 30 m km^{-1} we find the second iteration of d from equation (10). After several such iterations we obtain the values of t' (nondimensional) and d (dimensional) such that both topography and admittance satisfy their observed values. Finally, the dimensional time t is obtained from equation (9). Note that if the topography and admittance are satisfied, the geoid will also be approximately satisfied [*Solomatov and Moresi*, 1996]. An example of such solution is shown in Figure 1.

[15] Note that a rapid uplift occurs only when the plume starts interacting with the lithosphere. Therefore the definition of the uplift time should exclude the transient period during which the plume develops and travels through the mantle (Figure 1). During this transient period, the topography does not exceed 100–500 m, depending on the rheology, the Rayleigh number, and the amplitude of initial perturbations [*Vezolainen et al.*, 2003]. We define the uplift time as the time interval between the moment when the topography reaches 100 m and the moment when it reaches the observed value of 4 km. Changing the "cut off" topography from 100 m to 500 m affects the calculated age of Beta Regio by less than 10%.

4. Results

[16] The uplift time for Beta Regio as a function of Frank-Kamenetskii parameter θ for different viscosity laws and Rayleigh numbers is shown in Figure 2.

[17] The uplift is faster in three-dimensional geometry. This happens because a three-dimensional plume generates a more focused heat source as well as a more concentrated force on the lid than a two-dimensional one.

[18] The effect of 3D geometry on the uplift rate is larger for the Arrhenius viscosity than for the exponential viscosity. This is most likely due to the fact that for $\exp(\theta) < 10^5$ the lid becomes increasingly mobile in the case of exponential viscosity while it remains stagnant in the case of Arrhenius viscosity. This implies that the uplift is purely thermal for the Arrhenius viscosity and it becomes partially dynamic for the exponential viscosity. Thus these two cases can respond differently to the change from 2D to 3D geometry.

[19] In general, larger Rayleigh number implies more vigorous convection, hence a larger force at the base of lithosphere. Also, smaller Frank-Kamenetskii parameter implies a smaller resistance of the lithosphere. Both factors accelerate the uplift rate of Beta Regio (Figures 2 and 3).

[20] Although the uplift rate increases with the Rayleigh number (Figure 3) this effect becomes less pronounced as the Rayleigh numbers approaches 10^8. Moreover, for the

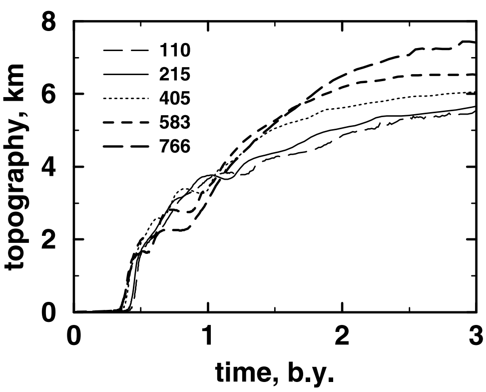

Figure 6. Topography of Beta Regio as a function of time for different initial lithospheric thicknesses. Initial mantle temperature is 1659 K. All models satisfy the admittance at the time when the topography reaches 4 km.

Table 2. Uplift Time of Beta Regio, Present-Day Lithospheric Thickness at the Center of Beta Regio, and the Plume Formation Depth d for Several Initial Lithospheric Thicknesses[a]

	Initial Lid/Mantle Ratio				
	0.0312	0.0625	0.1250	0.1875	0.25
Plume depth, km	3518	3439	3237	3108	3060
Initial lid, km	110	215	405	583	766
Present lid, km	276	287	305	361	390
Uplift time, m.y.	923	842	745	758	813

[a]Initial mantle temperature is 1659 K. The horizontally averaged steady-state lid thickness is about 0.2 d km.

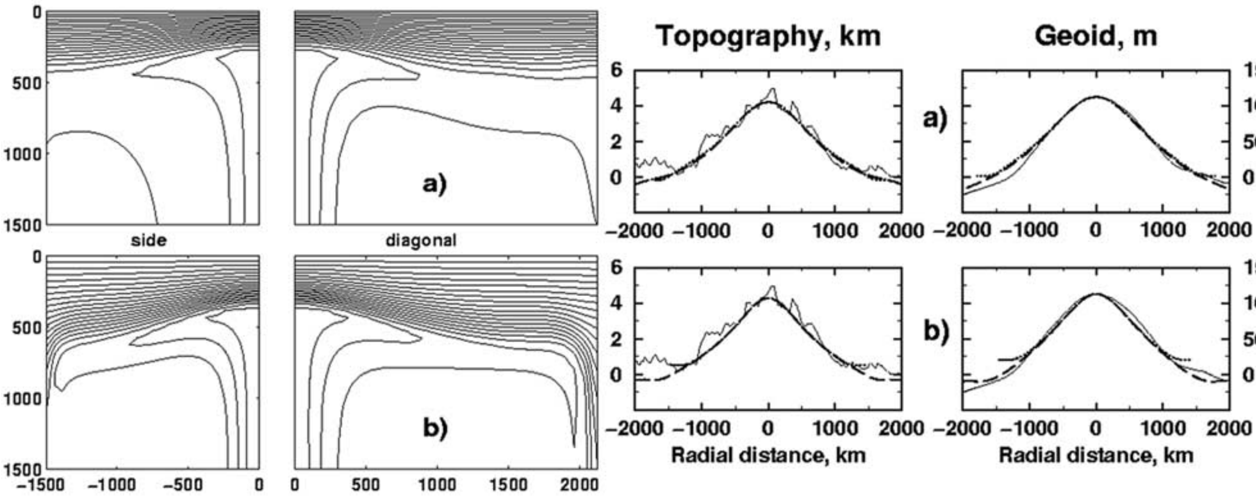

Figure 7. (left) Temperature contours and (right) topography and geoid profiles across the upper side (dotted lines) and the diagonal (dashed lines) of the $d \times d \times d$ region superimposed on the corresponding Magellan profiles from −86.62°E 11.77°N to −53.39°E 37.13°N (solid lines). Initial mantle temperature is 1659 K. Initial lid thickness is (a) 90 km and (b) 725 km. The calculated plume formation depth d is (a) 3518 km and (b) 3060 km.

Arrhenius viscosity with $\exp(\theta) = 10^3$ and 10^4, the increase in the Rayleigh number from $3 \cdot 10^7$ to 10^8 practically does not affect the uplift rate. This probably happens because at high Rayleigh numbers the convective flow becomes time-dependent, and multiple instabilities develop near the bottom of the lid resulting in a broader upwelling and a slower uplift. This situation is somewhat similar to 2D cases described by *Vezolainen et al.* [2003]. Furthermore, in 2D geometry and at high Rayleigh numbers the topography loses its bell-like shape and actually never reaches 4 km [*Vezolainen et al.*, 2003]. In 3D geometry this transition probably occurs at higher Rayleigh numbers. In either case, the results obtained so far suggest that further increase in the Rayleigh number might not necessarily increase the uplift rate.

4.1. Best Fit Model

[21] A model with Arrhenius viscosity law with $e^\theta = 10^3$ and $\Delta\eta = 10^8$ gives ~800 m.y. uplift time for Beta Regio. This is in good agreement with the geomorphological constraints (0.3–1 b.y.). Despite the cubic geometry of the numerical domain, topography and geoid profiles show reasonable cylindrical symmetry and are in adequate agreement with the Magellan profiles (Figures 4–5).

[22] The best fit model gives the plume formation depth of 3060 km which is very close to the whole mantle thickness, 2900 km [*Phillips and Malin*, 1983]. The two-dimensional models [*Solomatov and Moresi*, 1996; *Vezolainen et al.*, 2003] gave plume formation depths of about half of this value.

4.2. Effect of Initial Lithospheric Thickness

[23] To investigate how the initial lithospheric thickness (at the time of plume formation) affects the uplift rate we performed the calculations for a range of initial lithospheric thickness from 110 to 766 km. The upper bound corresponds approximately to the thermal boundary layer formed by conductive cooling since planetary formation. The lower bound corresponds to the thermal boundary layer formed by conductive cooling during the time it takes the plume to reach the lithosphere. The results are shown in Figure 6. For all the values of the initial lithospheric thickness our models give reasonable uplift rates (Table 2) as well as topography and geoid (Figure 7). The fastest uplift is achieved for the initial lithospheric thickness which is close to its equilibrium value. This happens because topography anomaly is caused by variations in the lithospheric thickness. To produce the observed topography, the lithosphere needs some additional time to thicken (or to thin) back to its steady-state thickness. Therefore an initially nonequilibrium lithosphere (too thin or too thick) slows down the uplift. The lithospheric thickness for the best fit model (determined from the velocity profile [*Solomatov and Moresi*, 2000]) reaches about 300 km at the center of Beta Regio (Table 2) while the average lithospheric thickness is about 400–500 km.

[24] The result that the uplift rate only weakly depend on the initial lithospheric thickness suggests a possible way to reconcile a thick lithosphere constrained by gravity, topography and rheology data and a thin lithosphere inferred from the estimates of melt generation rates [*Nimmo and McKenzie*, 1998] and from flexural models [*Simons et al.*, 1997; *Barnett et al.*, 2000]: the lithosphere could have been thin at the time of global resurfacing and has thickened due to conductive cooling. The flexural models probably give the elastic thickness at the time of loading when the lithosphere was thin (see *Watts and Zhong*'s [2000] analysis of the competition between strengthening caused by thermal cooling and weakening caused by stress relaxation).

4.3. Effect of Initial Mantle Temperature

[25] The studies of basaltic composition of surface rocks suggest the upper mantle temperature of about

1550 K at the time of resurfacing [*McKenzie et al.*, 1992] and not higher than 1750 K at the present time [*Nimmo and McKenzie*, 1997]. The effect of initial mantle temperature on Beta Regio uplift rate is shown in Figure 8 and Table 3. Slightly faster uplift rates are observed at lower initial mantle temperatures, while the average steady-state mantle temperature for the best fit model is ~1700 K. A higher initial mantle temperature implies a smaller temperature contrast in the bottom boundary layer and a weaker plume. This explains why the uplift is slower at higher temperatures.

4.4. Steady-State Topography

[26] The best fit model steady-state topography, 5.7 km, is somewhat higher than the present-day topography of Beta Regio (4 to 4.5 km). This may imply that Beta Regio is still growing. In principle, this may also indicate that the uplift ceased and Beta Regio started to subside. However, the latter possibility is not supported by photogeologic observations [*Senske et al.*, 1992; *Basilevsky*, 1996; *Ivanov and Head*, 2001] which show no evidence for such subsidence so the hypothesis of the continuing uplift of Beta Regio seems to be correct.

5. Conclusion

[27] Three-dimensional models of Beta Regio satisfy observational and rheological constraints substantially better than two-dimensional models. The uplift rate, ~800 m.y., is consistent with geomorphological constraints. The parameters of the Arrhenius viscosity, $e^{\theta} = 10^3$ and $\Delta\eta = 10^8$, are in reasonable agreement with the rheology of olivine in the diffusion creep regime. The plume formation depth is ~3060 km which can be identified with the core-mantle boundary. The lithospheric thickness in the central part of Beta Regio is about 300 km. The initial lithospheric thickness does not affect the results much. This implies that a very thin lithosphere at the time of global resurfacing and a thick present-day lithosphere is a possible way to reconcile our estimates with the estimates based on melt generation rates and flexural models.

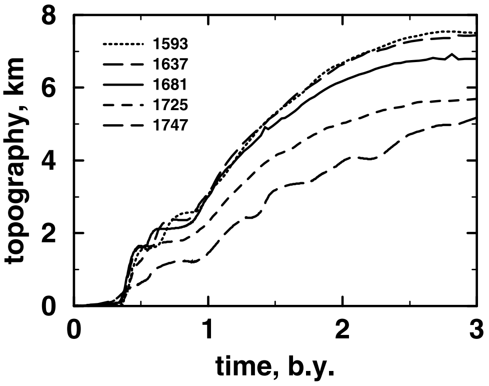

Figure 8. Topography uplift of Beta Regio for different initial mantle temperatures. Temperature contract across the mantle is fixed at 1100 K. Surface temperature is 735 K. All models satisfy the admittance at the time when the topography reaches 4 km.

Table 3. Uplift Time of Beta Regio and Plume Formation Depth d for Different Initial Mantle Temperatures[a]

	Initial Temperature (Nondimensional)				
	0.78	0.82	0.86	0.90	0.92
Initial temperature, K	1593	1637	1681	1725	1747
Plume depth, km	3059	3062	3038	3093	3270
Uplift time, m.y.	831	801	862	1193	1770

[a]Initial lid thickness is ~0.25d.

[28] **Acknowledgments.** This work was supported by NASA grant NAG5-13123. Numerical simulations were done with the help of finite element code CITCOM developed by Louis Moresi. We thank the Associate Editor Francis Nimmo and the anonymous reviewers for their thoughtful comments.

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