DATA REPOSITORY

MODEL SETUP

Isostasy and boundary conditions

Gravity body forces incorporated in the models provide differential buoyancy forces internally within the modeled lithosphere. Several different approaches have been tested for characterizing the base of the lithosphere. Generally, a simplified external boundary condition is applied to the bottom of the lithosphere which is characterized by a solid-fluid coupling problem. The Winkler foundation is the most popular simplification of the problem assuming a perfectly fluid buoyant asthenosphere. However, we found that this approach leads to erroneous results since it does not recognize the fact that there are viscous drag forces at the base of the lithosphere, nor does it recognize that the asthenosphere has a finite thickness. We therefore tested a hybrid solid-fluid setup (Winkler foundation plus drag forces) boundary condition at the bottom of the lithosphere first presented in Regenauer-Lieb et al. (2001) and further detailed in Regenauer-Lieb, (2006). We also used a more sophisticated evolutionary model the BEM –FEM model (Morra and Regenauer-Lieb, 2006), which also considers induced mantle flow feedback in addition to viscous drag, in which case the thickness of the asthenosphere can be considered.

Model simulations have been conducted with all of these three isostasy boundary conditions. We found that the uplift of the lithospheric and asthenospheric mantle dome can be enhanced significantly for cases of asthenosphere with a low viscosity and high differential buoyancy. Buoyancy also has a significant effect on the dominant wavelength of fastest growth (Fletcher and Hallet, 1983), thus affecting the style of deformation. In the extreme end-member case of high buoyancy and low viscosity the entire model is governed by the asthenospheric dome and uplift produces a classical mid-ocean ridge very different than the results presented here.

The case presented in the main text does not consider asthenospheric uplift due to the following reasons. Compared with the normal mantle, heat flow values from the Galicia margin are relatively low (<60 mW/m^2, Louden et al., 1997). For this reason, mantle viscosity is high and differential buoyancy less unimportant. Hence, we avoided using asthenosphere buoyancy as an additional booster for mantle doming. In the model results presented in this paper, the bottom of the lithosphere is held at a common, frictionless stratum and the top boundary of the crust is an open boundary with a Lagrangian surface. This produces conservative values for exhumation of the mantle dome and associated topography. Most significantly, our choices allow us to focus on the physical behavior of a simpler system.

The side boundaries of the numerical box are also considered to be frictionless (free of surface tractions). However, the vertical motion on the left side of the box is constrained to be equal to the right side of the box. This symmetric condition introduces a periodic boundary, and with it an artificial wavelength corresponding to the width of the model box. We compared this periodic boundary condition setup with a solution including an infinite flexural half space. In that solution the flexural wave is allowed to decay exponentially outside of the model domain. The results of this analysis is that periodic boundary conditions with lateral box size smaller than 100 km capture artificially the wavelength of maximum growth, while in solutions where the box size is larger than 100 km this is not the case. Mantle doming can again be enhanced significantly by imposing a wavelength smaller than 100 km. This analysis has informed our choice of the 200 km box length. Unlike the results for buoyancy driven uplift discussed above, the style of deformation remains similar. We present results where the mantle uplift is generated through the rheological evolution inside the lithosphere alone and do not enhance it through a pre-existing wavelength. We conclude from this analysis that for a heterogeneous lithosphere with a pre-existing wavelength before onset of stretching, structures similar to our results would develop but at lower beta factor.

Limitations on excessive shear stress

In order to avoid excessive shear stress, deviatoric stresses larger than the pressure are not allowed. This condition is implemented in a Drucker-Prager yield criterion which, unlike the classical Mohr-Coulomb criterion, is thermodynamically self-consistent. It follows the principle of maximum dissipation, converting all the plastic deformation to heat. Without energy, coupling this formulation is resilient to the formation of shear localization. In our formulation, shear zones in the brittle crust only form through energy feedback effects.

Geotherms and perturbations

We use initial conditions following a steady state isotherm (Turcotte and Schubert, 2001, equation 4-31). Since we do not include erosion in our simple model, the question of erosion of radiogenic heat production is not addressed. Note that the assumed exponential decay of radiogenic heat producing elements would be self-preserving upon erosion. The total crustal radiogenic heat production is 3μWm^{-3}, corresponding to a typical value of heat production for a granite of 10^{-9} Wkg^{-1}. In the notation in Turcotte and Schubert (2001), the constants used for initial conditions are:

h_r	10 km	Thickness of heat producing layer
k	2.8 Wm^{-1}K^{-1}	Crustal conductivity
qm	0.02 Wm^{-2}	Mantle heat flow
q_0	0.05 Wm^{-2}	Surface heat flow
T_0	280 K	Surface temperature

This steady state isotherm is initially perturbed by 70 K amplitude white noise perturbations on 4% of the nodes.

***TABLE DR1:* Other parameters in numerical models**

Parameter	Name	Value	Units
χ	Shear heating efficiency	1*	-
κ	Thermal diffusivity	Q = 0.7 x 10^{-6} F = 0.7 x 10^{-6} O = 0.8 x 10^{-6}	m^2s^{-1}
α_{th}	Thermal expansion	3 x 10^{-5}	K^{-1}
c_P	Specific heat	Q = 800 F = 800 O = 1000	$Jkg^{-1}K^{-1}$
ρ	Density	Q = 2800 F = 2800 O = 3300	kgm^{-3}
ν	Poisson ratio	0.25	-
E	Youngs modulus	4.5 x 10^{10}	Pa
A	Material constant - pre-exponential parameter	Q† = 1.3 x 10^{-34} F§ = 7.9 x 10^{-26} O# = 3.6 x 10^{-16}	$Pa^{-n}s^{-1}$
N	Power-law exponent	Q† = 4 F§ = 3.1 O= 3.5	-
H	Activation enthalpy	Q† = 135 F§ = 163 O# = 480	$kJmol^{-1}$
B	Thickness of radiogenic layer	10	km
Qs	Surface heat flow	50	mWm^{-2}
Q_m	Mantle heat flow	20	mWm^{-2}

Note: Q = Quartz; F = Feldspar; O = Olivine. *Chrysochoos & Belmahjoub (1992), †Hirth et al. (2001), §Shelton & Tullis (1981), #Hirth & Kohlstedt (2003)

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