ICTP Trieste 2024 Workshop on the lithosphere

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Practical investigation of isostasy in the lithosphere

The aim of this practical is to investigate the role of the crust and lithospheric mantle in determining the elevation of the continents, in the context of simple models of isostasy.

1. Introduction

Isostasy exerts a fundamental control on the elevation of the continents, determined by the density structure of the lithosphere and asthenosphere (Watts 2001). The largest density contrast in the continental lithosphere is at the Moho, and so it is widely assumed that crustal thickness is the principal factor determining surface heights, as originally proposed by George Airy (Airy1855). In simple Airy Isostasy, flotational equilibrium is assumed to occur at the base of the thickest crust, defined as the depth of compensation (Fig. 1a). In this case, variations in elevation (ΔH, increase is positive) of the Earth's surface above sea level are determined by both variations in crustal thickness (ΔC, increase is positive) and the densities of the crust (ρ_c) and mantle (ρ_m):

$$\Delta H = \Delta C/\alpha' \qquad (1),$$

where $\alpha' = \rho_m/(\rho_m - \rho_c)$. For typical mantle and crustal densities (Ludwig et al. 1970, Christensen and Mooney 1995), this indicates that α' is in the range $5 - 8$, corresponding to a crust - mantle density contrast in the range 400 – 600 kgm^{-3}. We can correct for water depth by multiplying the right-hand side of Equation (1) by a factor $\rho_m /(\rho_m - \rho_w)$, where ρ_w is the density of water.

With the development of plate tectonic theory, it has become clear that the crust and the top few tens to hundreds of kilometres of the underlying mantle comprise a relatively 'cool' lithosphere that in the oceans, at least, rests on a hotter and weaker asthenosphere. Here, we are defining the base of the lithosphere in terms of the thermal structure of the outer part of the Earth, effectively marking a change from a conductive to convective cooling regime – we call this the conductive lithosphere. Thus, implicit in the theory of plate tectonics is the concept of at least *two* regional density contrasts in the outer relatively 'cold' and 'strong' part of the Earth, between the crust and mantle, and between the lithospheric and asthenospheric mantle; and both crust and lithosphere are likely to show significant lateral variations in thickness. This way, the concept of Airy isostasy in the continents can been logically extended to include the whole lithosphere, referred to here as Whole Lithosphere Isostasy (WLI), as has been done so successfully in the oceans (Fig. 1b, Parsons and Sclater 1977, Parsons and McKenzie 1978). However, in the presence of significant flexural strength of the lithosphere, this isostatic balance will be regional (i.e 100s km scale) rather than local (Watts 2001). See Lamb et al. (2020) for more details.

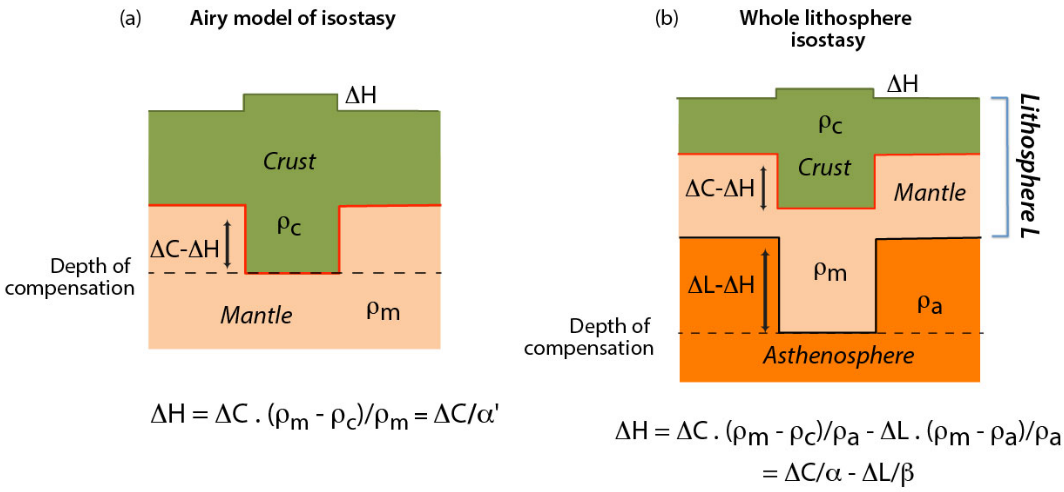

Figure 1. Models of local isostasy. (a) Simple Airy isostasy in which the crust is in flotational equilibrium with the underlying lithospheric mantle, with a depth of compensation at the base of the crust. In this case, a change in surface elevation ΔH is directly proportional to the change ΔC in underlying crustal thickness. (b) Whole lithosphere isostasy in which the lithosphere is in flotational equilibrium with the underlying asthenosphere, with a depth of compensation at the base of the lithosphere. In this case, a change in surface elevation is linearly related to both the change in underlying crustal and lithospheric ΔL thickness - the factors α and β define this relationship.

2. Whole Lithosphere Isostasy (WLI)

Priestley and McKenzie (2013) mapped out the thickness of the conductive lithosphere in the continents from inversions of a broad spectrum of seismic surface waves, although their methodology cannot resolve lithospheric thickness much less than about 50 km. An updated version of their lithospheric model was made available in 2016 (http://ds.iris.edu/ds/products/emc-cam2016/), which we use in this practical (referred to as Priestley et al., 2018), although an even more recent version (Priestley et al., 2024) has now been released. The base of the conductive lithosphere here is defined by the depth at which the conductive geotherm intersects the convective geotherm, using a calibration between S-wave velocity and pressure and temperature based on mantle xenoliths and a plate cooling model for oceanic lithosphere - see Priestley and McKenzie (2006, 2013) for a full description of their methodology. This is more-or-less an isotherm, between 1350 and 1400°C, depending on the precise conductive and convective geotherms (Priestley and McKenzie 2013). The resolution of the model is about 250 km horizontally, with a vertical uncertainty of ~30 km, but the locus of gradients of lithospheric thickness is more precisely determined, although flattened by the moving window method of averaging (Priestley and

McKenzie 2013).

If we assume a simple three layer crust, lithospheric mantle and asthenosphere structure, with a depth of compensation in the asthenosphere (Fig. 1b), then for WLI, the factors controlling changes in surface elevation above sea level (ΔH) will include, in addition to those of simple Airy isostasy (Equation 1), changes in lithospheric thickness (ΔL, increase is positive), and the density of the asthenospheric mantle (ρ_a), where ρ_m and ρ_a are now the *average* densities of the lithospheric mantle and asthenosphere:

$$\Delta H = \Delta C/\alpha - \Delta L/\beta \qquad (2),$$

where $\alpha = \rho_a/(\rho_m - \rho_c)$, and $\beta = \rho_a/(\rho_m - \rho_a)$, and water depth is allowed for by multiplying the right-hand side of Equation (2) by a factor $\rho_a/(\rho_a - \rho_w)$. Note that we would anticipate the local uncompressed density of the lithospheric mantle to decrease with depth as the temperature increases, although perturbed by depletion effects (Crosby et al. 2010, Naliboff et al. 2012). The effect of rock compressibility has a very small effect on predicted surface elevations, because it essentially applies equally to all lithospheric columns, and the isostatic balance is determined by the dimensionless density ratios α and β, and not the densities themselves. However, the total range in density will be small and <3% of the actual density given typical coefficients of expansion, compression, and lithospheric mantle temperatures (McKenzie et al. 2005); the critical parameters in Equation (2) are the average density *contrasts* between the lithospheric mantle and crust ($\rho_m - \rho_c$) and asthenospheric mantle ($\rho_m - \rho_a$). For negatively buoyant mantle lithosphere, an increase/decrease in lithospheric thickness has the opposite effect on elevation to an increase/decrease in crustal thickness.

3. Practical Exercise

This practical explores the implications of WLI for the elevations, lithospheric structure, and densities of the continents.

You are provided with a series of Excel spreadsheets tabulating topography, crustal thickness and lithospheric thickness, for three continental-scale profiles in Canada, Europe, and Antarctica. These profiles have been chosen to cross major steps in lithospheric thickness, so that the effect of the lithosphere on surface elevations will be most apparent. The lithospheric model comes from Priestley et al. (2018), and the crustal data from CRUST1.0 in Laske et al. (2013) for Canada and Europe, and Shen et al. (2018) for Antarctica. Elevations are taken from Etopo1 (2011). Data from North America and Europe have been regridded on to 2° x 2° grid, whereas the Antarctica data has been regridded onto a 50 km x 50 km grid.

The spreadsheets contain the appropriate formulas for simple Airy Isostasy and Whole Lithosphere Isostasy (WLI) in terms of the parameters α', α and β defined above. The elevations are calculated through an isostatic balance with respect to either a reference crustal thickness for zero elevation for Airy Isostasy, or a reference lithospheric structure for WLI. The aim is to determine the predicted topography along the profiles, given choices of the parameters α', α and β, and the reference crustal or lithospheric column. A mantle density of 3.3 g/cc is assumed for the Airy Model, and an asthenospheric density of 3.25 g/cc is assumed for WLI. Thus, the critical parameters are the crust-mantle, and lithospheric mantle- asthenosphere average density contrasts, defined by α', α and β. This is done by filling in trial values in the 'yellow' cells, and then pulling down each column to determine the calculated topography, which should automatically plot in the graphs. Note that for Antarctica, it is also necessary to calculate the ice 'unloaded' bedrock elevation, choosing an appropriate density for ice, and then carrying out a simple isostatic 'backstripping'. For the purposes of the practical, you can ignore the effects of lithospheric flexure, although it is worth thinking about what this might be.

For each profile, experiment with choices of parameters to obtain the best 'visual' fit between the observed and predicted topography for each profile. Address the following questions.

(1) Which model is a better description of isostasy in the Earth along the selected profiles? In making your decision, consider whether the required density contrasts are likely to be realistic.
(2) It is likely that there are errors in the input parameters of crustal and lithospheric thickness used in the profiles. Calculate what the errors in crustal thickness along the profile must be to achieve perfect fits for Whole Lithosphere isostasy. Are these errors plausible?
(3) Summarise your principal conclusions about the density contrasts between crust and mantle, and mantle and asthenosphere, based on WLI.

Advanced questions

(4) Assuming the errors in the WLI models along the profiles are due to the average crustal and lithospheric density contrasts along the profiles, what would they each

need to be for a perfect fit? Likewise, calculate the errors in lithospheric thickness, if all the misfit is due to these.

(5) Given the likely errors in all the relevant parameters, do you think it is possible to distinguish between WLI and some other model of vertical force balance, such as that due to dynamic processes?

4. References

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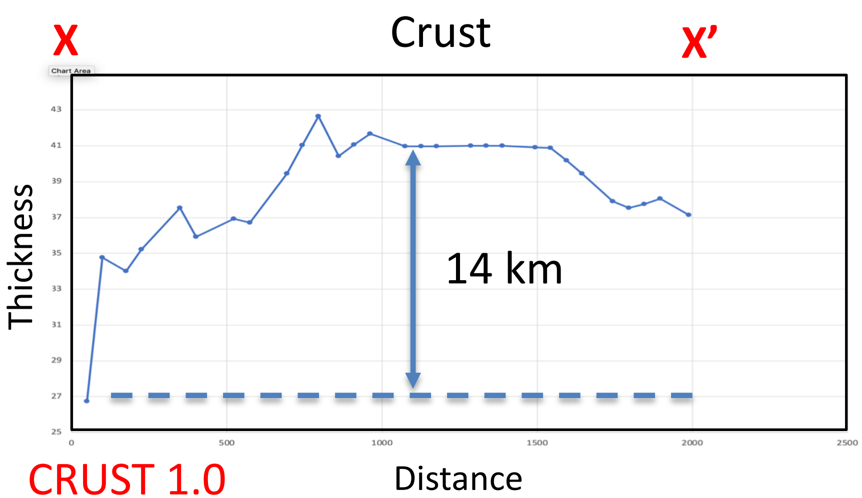
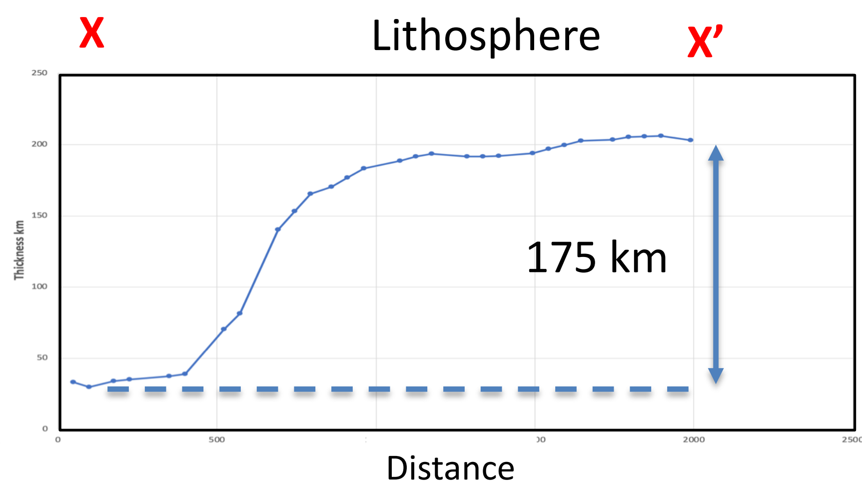
Canadian Transect



CRUST 1.0



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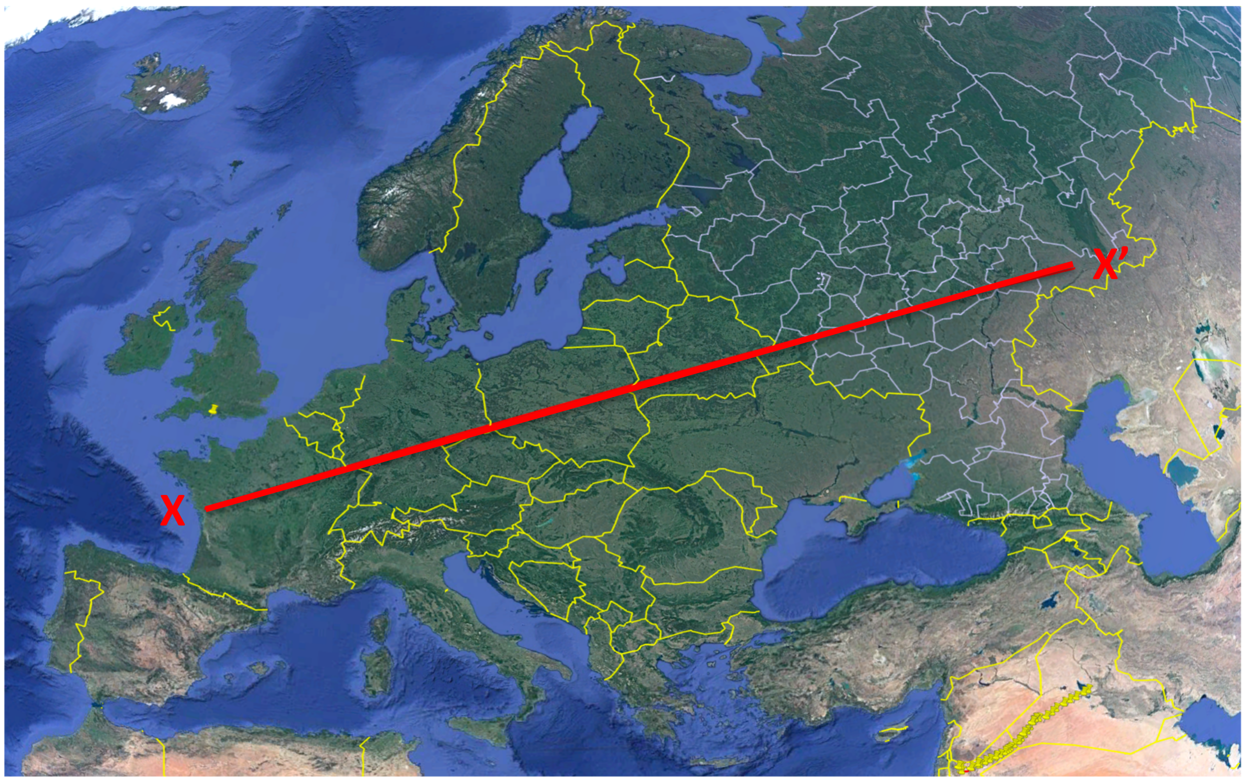

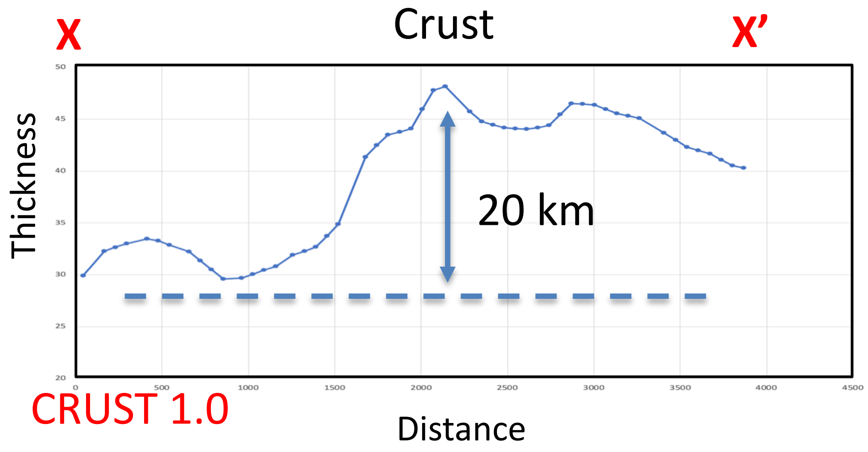

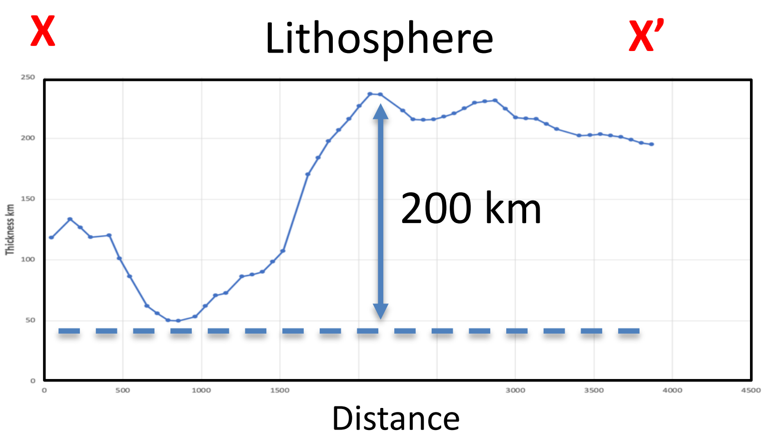

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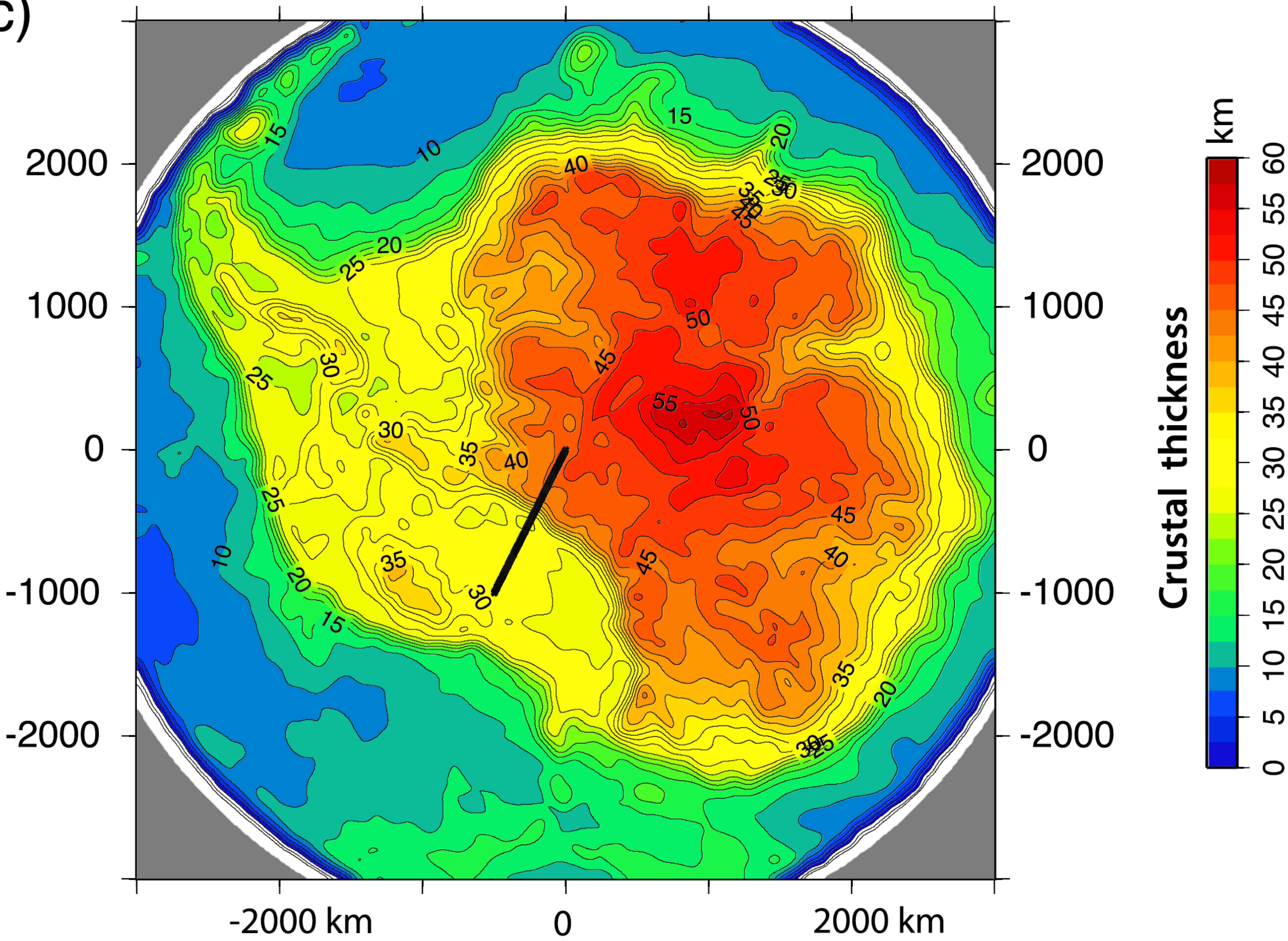

2000
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2000 km
Crustal thickness
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