Constrain the nature of LLSVPs using observations of geoid and dynamic topography

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Abstract:
The structure of Earth's lowermost mantle is best characterized by African and Pacific large low shear velocity provinces, aka LLSVPs . These features are presumably very important for modulating long term evolution of Earth such as the main heat source for generating mantle plumes and surface volcanism. Using CitcomS I built up instantaneous thermal and thermal-chemical models and explored a range of density and viscosity for the whole mantle especially within LLSVPs by simultaneously comparing the predicted gravity and dynamic topography to their observational counterparts. Though a best fit with rational geoid highs for both LLSVPs is still on the way, influences of stratified viscosity and density anomaly under typical circumstances have been seen. Also, lateral viscosity variation(i.e. LVV) has large effects on surface observables together with some of those viscosity profiles, in contrast to earlier works suggesting little effect of LVV on gravity.

Contents

1.Introduction

Away from locations with higher-than-average seismic wave speeds in the lower mantle, underling current and past tectonic plate subduction zones, are regions beneath hotspot volcanism with much lower wave speeds. This kind of spatial correlation together with tomography for subducting has largely increased supporters of whole mantle convection. When decomposed to spherical harmonic results , tomography shows those speed lows are strongly dominated by degree 2 structure , it occurs in two almost antipodal large low shear velocity zones : one locates beneath the Pacific Ocean and the Atlantic Ocean and the western and southern part of the African continent overlie the other, they are LLSVPs.

The degree-2 geoid accounts for >50% of total geoid power, and these anomalies consist of two broad positive parts over the Pacific and Africa , correlating well with LLSVPs , similar for the dynamic topography (Fig 1)(Hoggard et al., 2016). Obviously they could become strong constraints for LLSVPs' structure.

Origin of LLSVPs has been heavily debated, from pure thermal to thermal-chemical. A numerical seismic suggested that these areas might be compositionally distinct from ambient mantle , for instance , joint inversion studies showed anti-correlation in LLSVPs for P,S, and bulk sound speeds (Su & Dziewonski, 1997), (Ishii, 1999)'s normal mode work indicated that density there might be higher than surroundings , not as low as that directly interpreted from Vs. At the beginning I just wanted to set thermal-chemical pile for LLSVPs directly basing density and viscosity profile from former studies and my target was to produce better geoid anomalies for those regions , but a close-to-observation shape for geoid highs both in Pacific and African LLSVPs was never reached , so new scaling (i.e. conversion factor between tomography and density) and viscosity profile for whole mantle are needed. As for dynamic topography , acceptable output appeared in the earlier part of this program , my attention focuses on geoid more.

2.Methods

2.1 Governing Equations

To establish 3-D spherical shell geometry thermal-chemical convection models , I use the finite element CitcomS. The mantle, assumed to be incompressible fluid including the effects of self- gravitation, is under Boussinesq approximation. Nondimensional governing equations for the conservation laws of the mass, momentum, energy, and composition are (Zhong & Liu, 2016):

$$\nabla \cdot \boldsymbol{u} = 0, \tag{1}$$

$$-\nabla p + \nabla \cdot \left[\eta \left(\nabla \boldsymbol{u} + \nabla^T \boldsymbol{u}\right)\right] + Ra\,(T - BC)\,\boldsymbol{e}_r = 0, \tag{2}$$

$$\frac{\partial T}{\partial t} + (\boldsymbol{u} \cdot \nabla)\,T = \nabla^2 T + \gamma, \tag{3}$$

$$\frac{\partial C}{\partial t} + (\boldsymbol{u} \cdot \nabla)\,C = 0, \tag{4}$$

where $\boldsymbol{u}$ is the velocity vector, p is the dynamic pressure,η is the viscosity, $\boldsymbol{e}_r$ is the unit vector of the radial direction, Ra is the Rayleigh number, T is the temperature, B is the buoyancy number, C is the composition field, t is the time, and γ is the internal heat production rate.

The Rayleigh number Ra in equation (2) controls convective vigor , providing the temperature contrast from surface to CMB, is defined as

$$Ra = \frac{\rho_0 g_0 \alpha_0 R^3 \Delta T}{\eta_0 \kappa_0} \tag{5}$$

Here the subscript 0 means reference values, ρ is the density, g is the gravitational acceleration, α is the thermal expansion coefficient, R is the radius of the Earth, ΔT is the temperature difference across the mantle, and κ is the thermal diffusion. Note that it is Earth's radius instead of mantle thickness that is used as the length scale to nondimensionalize the governing equations , so Ra here us about 10 times larger than defined by mantle thickness.

My thermal-chemical models only consider 2 compositions with different density. C measures mantle composition(actually is ratio of tracers :$\frac{N_{LLSVPs}}{N_{all}}$), 0 for regular mantle and 1 representing the LLSVPs, maybe denser or lighter. The buoyancy number B measures the relative strenghth between the compositional and pure thermal buyancy , defined as

$$B = \frac{\Delta \rho_c}{\alpha_0 \rho_0 \Delta T} \tag{6}$$

where $\Delta \rho_c$ is the intrinsic density difference between LLSVPs and ambient mantle materials, aka chemical density.

The detailed formulation and nondimensionalization of the equations together with calculations of geoid and dynamic topography can be found in CitcomS Benchmark(Zhong et al., 2008).

2.2 Initial, and Boundary Conditions

The top and bottom boundaries represent the surface and core-mantle boundary (CMB) and have dimensionless outer and inner radii r=1 and r=0.55, respectively. The models use free slip as well as isothermal boundary conditions at the top and bottom boundaries with fixed temperatures of 0 and 1, respectively. Initial temperature field is derived from high resolution tomography S40RTS using modified scaling from previous study. Reference temperature was chosen as 0.7 without adiabatic increasing , which contributes little to effective convection in my models:

$$\frac{\delta\rho}{\rho} = k\frac{\delta V_s}{V_s} \tag{7}$$

$$T = 0.7 + \frac{\frac{\delta\rho}{\rho}}{\alpha_0 \Delta T} \tag{8}$$

Where k is scaling ,δ means perturbation based on average,V_s represents shear wave velocity. Note that density anomaly here is seen as “pure thermal”.

Also, temperature for upper 200km is kept but negative buoyancy from density anomaly is removed(Actually these features provide little effect in my model).

As for initial viscosity , most of the time I only use 1-D profile modified from the same source of scaling(Simmons et al., 2010; Spasojevic et al., 2010) , but temperature- or composition-dependant viscosity (i.e. with lateral variation) is also under consideration. In terms of Conditions of transition zone I use (Billen, 2008)'s example, i.e. $\Delta\rho_{410} = 3.0\%$, $\gamma_{410} = 4.0MPa \cdot K^{-1}$,$\Delta\rho_{660} = 7.0\%$,$\gamma_{660} = 2.0MPa \cdot K^{-1}$, they represent density contrasts and Clapeyron slope across depth of 410km and 660km.

The only point we care is current state , hence all of my models are instantaneous , to be more specific , we merely need step 0(i.e. the first step) and timestep is fixed to 7.7748e-8s.

Parallel computing techniques are implemented in CitcomS, as mantle is divided into 12 caps and each of them is further distributed to multiple cores. Outputs for node set of 257x257x129(x,y,z respectively) with 3072 cores and 65x65x33 with 48 cores are almost the same , therefore most of the time I choose the latter one as parallel computing inputs.

To add compositional components in CitcomS , One must use tracers , as is stated before, only 2 flavors of tracers are needed , and I select initial temperature and depth as criteria for thermal-chemical piles. To realize this function , I modified tracer related codes and move temperature initialization in front of tracer setting up. With Paraview I am able to find the best T and depth range for largest LLSVPs and fewest unrelated scattering areas. For all the model with LLSVPs tracers, their depth is between 1800km to CMB(i.e. 2866km), temperature range could be different according to different scaling in the lowermost mantle, usually T is higher(Spasojevic et al., 2010) than 0.78(Fig 1d,1e).

3.Inputs and Results

3.1 Pure Thermal Benchmark

To validate the density/scaling and viscosity settings and their effects , I use Spasojevic et al., 2010's viscosity profile and scaling (except for tomogaphy , they use TX2005 , but there is only slightly differences between S40RTS and that, scaling here is 0 above 200km and 0.1 for rest) and successfully reproduced their results. Take one of their best fit (for geoid lows) for example, In `,3,4 , a shows viscosity input and geoid and dynamic topography from that paper(viscosity b in Supplementary Figure S6), b gives viscosity output and geoid and dynamic topography(denoted as **DT** below) of my model , respectively, they matches vey well(amplitude of geoid maybe a little smaller due to scaling implement), a,b share the same colorbar.

As for Simmons et al., 2010 , they did not test geoid output. Their scaling and simplified viscosity strcuture(red line) are shown in Fig 5a,6a, and the viscosity couterpart in my model are plotted in Fig 5b,6b. Fig 7 a,b provides the poor result of geoid and DT.

3.2 Use tracer to add composition dependent viscosity and chemical buoyancy

When setting up tracer as above (2.2), we got composition field (Fig 8). Based on the successful benchmark , I test composition dependent viscosity and chemical buoyancy directly. Fig 9 and 10 indicates that composition dependent viscosity has limited effect under such viscosity background when LLSVPs get lower lateral viscosity , but on the opposite direction, huge influences could be observed both for geoid and DT. The reaction of two long wavelength features is the same, i.e. become higher with lower viscosity and lower with higher viscosity , direction of which fits intuition and governing equations. As for the whole picture , it seems that when meeting higher viscosity, geoid anomalies are quite the opposite as tomography at depth from 200km to 600km(Fig 11). On the other hand, though sign of chemical buoyancy is consistent with its effect-- negative buoyancy ratio means lighter piles leading to higher anomalies , ambient mantle acts to the contrary , and in the other way , is totally different-- the shape change of different sign of geoid is very strange , not like LLSVPs , nor is any layer of tomography(Fig 12). Consider the DT, situations are similar to geoid.

3.3 Change viscosity and scaling for whole mantle

If we compare observed geoid in Fig 1c and outputs in section 3.2, none of the latter ones provide a positive geoid in African LLSVP and remain negative in east Pacific , when adding chemical density or lateral viscosity variation depending on LLSVPs tracers that are based previous study , clearly these two regions change in the same direction. Thus modification on the background viscosity and temperature is inevitable.

Considering the different results in benchmark of two papers, initially I tried to combine their viscosity , i.e. (Spasojevic et al., 2010) for upper mantle and (Simmons et al., 2010) for the rest(denoted as 1c), meanwhile retain scaling in the former paper. Contrast to output from (Spasojevic et al., 2010), we got better shape for sign around Africa and South America, but more high area in east Pacific is not what we expect. Then I used deeper lithosphere, that is let viscosity of top 300km as high as top 100km(denoted as c2), now low degree features turn too distinct, though positive parts to the south of Africa and around Iceland are close to observation. More changes for top 300km are implemented shown in FIg 13,14 , but the way two features are affected always keeps the same.

To describe my models in time-domain sequence, I test new scaling next. At first this work is more like grid search , preliminary outputs look more like repetition of old work-- LLSVPs act like twins(omit figures here). As a matter of fact, I have to decouple them . By examining tomography I realize that obvious sign difference between them can be found within depth from 200km to about 1200km. Concretely, almost the whole Pacific area has slow anomaly while key part of Africa is the other way(Fig 11). Currently I have two solutions to solve decouple, one way is to shrink scaling in this range , the other way is add compositional lateral viscosity or T dependent viscosity among these depth. Until now I have tried several models using the first scheme:

scaling simple20:

vtx=[200,1200,1800,2900]#This is depth layer,unit is km

vty=[0.2,0.05,0.1,0.15]#This is scaling,e.g.,0.2 for 0~200km scaling simple 21:

vtx=[200,1200,1800,2900]

vty=[0.2,0,0.1,0.15]

The outputs are in fig 15a,b , not as expected, positive regions even expand.

Other than models above, I tried to remove scaling or use reference viscosity of upper mantle , or set different scaling for different sign of share wave speed anomalies for lowermost mantle, Type of their results still stay similar with previous ones. (omit figures here)

Back to viscosity profile, basing output of a broad positive African high component, I turned to explore the effect of every layer(the division of layers follows 1c), geoid outputs lie in rest of fig15,16, see table 1 for comparison of each pairs . The scaling s22 is twice of s21. Unluckily none of them can reduce the geoid of East Pacific will remaining enough high at Africa(maybe s22_22c is acceptable generally speaking). The buoyancy ratio -0.2 for the last figure exceeds actual demand considering the result. Further work about this and the other decoupling solution is waiting to be done after the cluster being repaired.

Table 1 Comparison of different viscosity profile(and double scaling)

Pairs	different range	visc change	East Pacific LLSVP	African LLSVP	South America	North America	Indian Ocean
16c 14c 11c	0-100	1 1.2 1.5	higher	higher at east and Iceland		higher west lower east	higher
8c 12c 9c 10c 1c	0-100	1 1.2 1.5 2.5 3	higher	higher at east	lower	higher west lower east	higher then lower
9c 15c	410-660	0 1	A little higher	A little higher	higher	lower at both sides	lower
9c 11c	100-410	-2,-1	higher	higher	higher	lower at both sides	lower north higher south
14c 17c	410-660	0 1	higher	higher	lower	lower at both sides	lower
15c 18c	Around 660	1.3 2	lower	south Iceland lower	higher	lower west higher east	lower
18c 20c 19c	660-1950	2 2.3 3	lower	lower at south	higher	lower west higher east	lower at south
20c 21c	Around 2230	0.7 1.5	lower	lower at south	higher	lower at both sides	higher south lower northwest
s22 s20 (20c)	Double scaling		higher	higher at southwest	lower(change sign)	higher at both sides	A little lower at south

4.Effects of LVV

Initially to converge in a shorter period, my models are over-smoothed about the viscosity structure. That leads to distortion of real viscosity profile , among those models , LVV of thermal-chemical pile plays a role of more important than (Moucha et al., 2007) stated. Of course the scaling and background viscosity together with the way we set LVV is not exactly the same, but its effect cannot be ignored in this program. According to figure 9 we can assert that under (Spasojevic et al., 2010)'s settings LVV only works well in one direction. But on the contrary, for instance, using scaling s7:

vtx=[200,2900]

vty=[0,0.4]

and background viscosity from (Simmons et al., 2010) smoothed 5 times in fig 17, together with buoyancy ratio -0.5, LVV of 10 times (Fig 18)can produce enormous influences,even change the sign of whole geoid(Fig 18). Meanwhile I provide earlier best fit from that viscosity structure in Fig 18 as well.

5.Conclusion

Until now I Learned how to perform global geodynamic models with tomography input and variable viscosity, implemented compositional tracers to explore the density and viscosity of the LLSVPs And Benchmarked tomography model S40RTS in predicting geoid and dynamic topography. MoreoverI discovered that lateral viscosity variation (LVV) of the LLSVPs has large effects on surface observables, in contrast to earlier works suggesting little effect of LVV on gravity in ceartain situaion. However, I am still in the process of locating the bestfit LLSVP density and viscosity structures.

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