Impact of the geometry and the endothermic phase transition on the thermal mantle convection

Theses of the PhD Dissertation

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I. Introduction

There has been a long history of the research of mantle convection. A lot of studies have been written about mantle dynamics in the last decades (e.g. Schubert et al., 1975; Cserepes et al., 1988). However there are many fundamental problems in mantle convection, which have not been solved up to this day. This work aims at contributing to a better understanding of the impact of the geometry and the endothermic phase transition on the mantle dynamics.

Convection in the Earth's mantle

In general convection is one type of energy transport. If the thermal energy spreads by the moving of the material itself we call the phenomenon thermal convection. Due to the decay of the radioactive elements in the mantle and the heat flux from the Earth's core the temperature near the core mantle boundary (CMB) exceeds the 4000 K. The mean temperature of the surface is about 290 K. As a consequence a thermally unstable state occurs and the material of the mantle expands, its density decreases resulting buoyancy force. Due to the buoyancy force thermal plumes rise from the CMB to the surface. The mantle can flow on geological time scales due to the mechanism creep flow. Since this process is nearly adiabatic the plumes cool hardly but if they reach the lithosphere they lose their heat. The surface manifestation of mantle plumes are the so called hot spots (Morgan, 1971) e.g. Hawaii. The mantle plumes are the active part of the mantle upwellings but there exist other passive features as well.

The passive upwellings are located beneath the oceanic ridges, where new oceanic lithosphere is born. They form due to the pull of the oceanic slab (slab pull) at the subduction zones. Moving away from the ridges the oceanic slab is cooling and because of the cooling its density increases which result in a gravity instability. This leads to that in the subduction zones the cold (and old) oceanic lithosphere can sink into the lighter mantle. This process is the downwelling part of the mantle convection.

Sum up thermal convection requires thermal energy, gravity and fluid. As a consequence of the cooling of the Earth's core and the radioactive heat in the mantle we have thermal energy. Obviously the Earth has gravity field and as above mentioned the mantle can flow on geological time scale.

Endothermic phase transition and mantle avalanches

The phase transition in the Earth's mantle between 410 km and 660 km depth has been the topic of many studies (e.g. Christensen and Yuen, 1985; Nakagawa and Buffet, 2005; van Summeren et al., 2009). These days we are able to map the global structure as well as the circulation of the mantle with the help of seismic tomography (van der Hilst et al., 1997; Rawlinson et al., 2010). Using seismic tomography not only the cold subducting slabs (Gorbatov et al., 2003) but also the hot upwelling regions i.e. the mantle plumes can be revealed (Ji and Nataf, 1998; Montelli, 2004). In mantle convection theory these features carry the heat from the core-mantle boundary to the surface but there are other phenomena as well, e.g. episodic mantle overturns or avalanches (Peltier and Solheim, 1992; Machetel, 2003; Wolstencroft and Davies, 2011). These phenomena can occur due to the strong influence of the endothermic phase change at 660 km depth. This phase change is a transformation from ringwoodite to magnesiowustite and perovskite in the olivine mineral zone (Collier et al., 2001). It is known that this phase transition can hinder the mantle convection basically owing to the phase boundary distortion (Schubert et al., 1975; Christensen and Yuen, 1985).

In general, a phase boundary can influence the mantle flow in the following ways: in vertical boundary layers the phase boundary deviates from its equilibrium depth and the direction of distortion depends on the sign of the Clapeyron slope ($\gamma_d = dp/dT$, where p and T denote the pressure and temperature, respectively). Owing to the density contrast between the two phases the distortion of the boundary results in a buoyancy force which may facilitate or encumber the convection. An endothermic phase change has a negative sign, therefore it hinders convection. If the influence of the phase change is observable, two basic types of convection can exist: partially or intermittently layered convection at weak phase transition ($\gamma_d \leq -3$ MPa/K) and isolated convection at strong phase transition ($\gamma_d < -6$ MPa/K) (Tackley, 1995a, 1995b). In the case of intermittently layered convection rapid "flushing" events have been detected (Pysklywec and Mitrovica, 1997), these are called mantle avalanches as mentioned above. They can occur when a lot of cold material accumulates above the 660 km discontinuity and the boundary breaks up allowing a large amount of cold material to flow very rapidly to the lower mantle resulting in large mass and heat transfer. Obviously, at the same time hot material rises into the upper mantle due to the conservation of mass.

II. Scientific goals

This research work aims to model the impact of the geometry on the thermal mantle convection as well as to investigate the effect of the endothermic phase transition on the mantle dynamics. The model geometry has always an influence on the convection system but the question is how we can measure this influence. Therefore four type of geometries have been analysed, namely the Cartesian (rectangular box domain), the cylindrical, the cylindrical shell and the spherical-shell geometry.

The other question which on this work is focused is the occurrences and time characteristics of mantle avalanches. Using a series of numerical models with different Rayleigh numbers (the vigorousity of convection) and Clapeyron slopes the impact of the endothermic phase change has been modelled. Particular attention was paid to determine the periods of mantle avalanche events and to quantify the relationship between these periods and the Rayleigh number as well as the Clapeyron slope.

III. Methods

Doing research the governing equations (continuity, momentum, energy) of thermal convection were numerically solved (Batchelor, 1967). Studying the effect of the geometry finite element method was applied. To build the models in different geometries Comsol Multiphysics has been used (Zimmerman, 2006). Models which included endothermic phase transition have been calculated with the spectral and finite difference numerical code CMPH (Cserepes, 1992). All models were started from randomly perturbed conductive initial temperature distribution with isothermal horizontal and symmetrical vertical boundaries. Mechanical boundaries were symmetrical. The calculations have been run to reach a quasi-stationary solution and then the simulation was continued to observe the parameters characterizing the dynamics of the flow system.

IV. Theses

1. Using finite element method thermal mantle convection has been modelled in rectangular, cylindrical, cylindrical-shell and spherical-shell geometry. To solve the governing equations of thermal convection the Boussinesq approximation was applied (Chandrasekhar, 1961). I studied the mantle convection first time in Hungary in a cylindrical-shell, a cylindrical and in spherical-shell geometry. Twenty systematic model runs were carried out using a wide dynamic spectrum, the Rayleigh number (*Ra*) varied between: 10^4–10^7. Obviously, for a given *Ra*, *Nu*, v_{rms} and the mean temperature (T_{av}) of the convection cell depend on the geometry: the highest values were obtained in case of rectangular model domain, where the area of the hot bottom boundary of the model domain is equal to the top one. The significance of the cylindrical geometry is that for a given *rms* velocity the surface heat flow is the highest. In that sense the most effective heat transport occurs in cylindrical shape convection system. The cylindrical geometry proved to be a very efficient modelling tool since it requires the lowest finite element number therefore models run faster. Regarding to the cylindrical symmetry of mantle plumes the cylindrical geometry is a professional tool to be able to model individual mantle plumes (Herein et al., 2007).

2. Studying the impact of the geometry, it was found that relationships between surface heat flow (*Nu*) and *Ra* ($Nu \sim Ra^{1/3}$), and root-mean-square velocity (v_{rms}) and *Ra* ($v_{rms} \sim Ra^{2/3}$), originally derived from the thermal boundary layer theory (Turcotte and Oxburgh, 1967), are valid in all studied geometries. The non-dimensional mean temperature (T_{av}) was 0.5 in case of symmetric rectangular domain, and it was lower in cylindrical, in cylindrical shell and in spherical-shell domains. The lower T_{av} derives from the asymmetry of the flow regimes determined by these geometries. In case of cylindrical convection the surface of the hot upwelling plume in the centre is smaller than the surface of the cold downwelling flow along the rim. In case of cylindrical-shell and spherical-shell geometry the outer cold surface of the domain is larger than the inner heated surface resulting in low T_{av}. I have shown that among the investigated models the mean temperature depends on the *Ra* only in cylindrical geometry.

The results of three dimensional models were comparable with measured geophysical data, namely the global surface heat flow was estimated 20-70 mW/m^2 and global surface velocities were estimated 1–5 cm/year.

3. Studying the impact of the endothermic phase transition at 660 km, 64 three dimensional and 55 two dimensional models have been analysed. I have shown that the mantle flow is influenced only by two non-dimensional dynamical parameters i.e. the Rayleigh number (*Ra*) and the Clapeyron slope (γ). It has been established that the *Ra* effectively influences the dynamics of the phase transition. At higher *Ra* the hindering effect is stronger. At very strong γ the stable solution is a two-layered convection form, where there is no mass transfer between the upper and lower mantle. I constructed the classed map of mantle convection. Using this map three types of convection can be determined in the (Ra-γ system), namely one-layered, intermittently layered, two-layered. The boundary line between the different convective regimes can be well described with power laws. I determined these functions and my results harmonized well with other studies (e.g. Wolstencroft and Davies, 2011).

4. I developed a new detection routine for mantle avalanche events. In the case of intermittently layered convection mantle avalanches have been significantly detected by analysing the time series of vertical mass flux. Using Fourier analysis a new founding is that the nature of the avalanches is periodic (Herein et al., 2013).

5. I have shown first that the periodic behaviour of mantle avalanches is strongly dependent on Rayleigh number but essentially is independent of Clapeyron slope. As the *Ra* increases so decreases the time period (T_p) of avalanches. A new power law was proposed to describe the relationship between the *Ra* and T_p. The shape of these function was determined as: in two dimensions: T_p[Mév]=1,44·10^6·$Ra^{-0,57}$ and in three dimension T_p[Mév]=1,7·10^4·$Ra^{-0,331}$ (Herein et al., 2013).

6. Analysing the flood basalts Ernst and Buchan (2002, 2003) have shown that the generation rate of flood basalts follows a quasi-periodic pattern which means a 20-110 million years periodicity. For mantle like parameters (Ra~10^7, γ_d=-3 MPa/K) the time period of three dimensional mantle avalanches is about 55-100 Myr which is comparable with the geology. We can assume that the generating process of flood basalts is linked to the huge mantle avalanches.

V. Conclusions

Studying the impact of the geometry, it was found that relationships between surface heat flow (Nu) and Ra (Nu~$Ra^{1/3}$), and root-mean-square velocity (v_{rms}) and Ra (v_{rms}~$Ra^{2/3}$), originally derived from the thermal boundary layer theory, are valid in all studied geometries. Obviously, for a given Ra, Nu, v_{rms} and the mean temperature (T_{av}) of the convection cell depend on the geometry: the highest values were obtained in case of rectangular model domain, where the area of the hot bottom boundary of the model domain is equal to the top one. The significance of the cylindrical geometry is that for a given *rms* velocity the surface heat flow is the highest. In that sense the most effective heat transport occurs in cylindrical shape convection system. The T_{av} was 0.5 in case of symmetric rectangular domain, and it was lower in cylindrical, in cylindrical shell and in spherical-shell domains. The lower T_{av} derives from the asymmetry of the flow regimes determined by these geometries. In case of cylindrical convection the surface of the hot upwelling plume in the centre is smaller than the surface of the cold downwelling flow along the rim. In case of cylindrical-shell and spherical-shell geometry the outer cold surface of the domain is larger than the inner heated surface resulting in low T_{av}.

The other goal of the present study was to determine the transition between one-layered and two-layered convection and to analyse the dynamics of mantle avalanches using simple 2D and 3D numerical models. A series of numerical calculations have been carried out using different Rayleigh numbers (Ra) and Clapeyron slopes (γ). It has been established that the Rayleigh number effectively influences the dynamics of the phase transition. At higher Rayleigh numbers the hindering effect is stronger. Calculating the vertical mass flux at 660 km and analysing its time series three types of mantle flow were found. The first type is whole mantle convection, second one is the two-layered and the third one is the intermittently layered type.

The boundary line between the different types of convection can be described well with power laws in the *Ra-P* domain. In the case of intermittently layered convection mantle avalanches have been detected by analysing the time series of mass flux. Using Fourier analysis a new founding is that the nature of the avalanches is periodic. As a new result it was pointed out that the time period of avalanches (T_p) is dependent only on *Ra*. A new power law was proposed to describe the relationship between the Rayleigh number and the time period, T_p decreases with increasing *Ra*. For mantle like parameters (Ra~10^7, γ_d=-3 MPa/K) the time period of mantle avalanches is about 55-100 Myr, which can be compared to geological processes i.e. to the average time period of flood basalt activity, suggesting that the avalanches could be the generating mechanism of the flood basalts.

VI. Bibliography

Publications on which these theses are primarily based:

Herein, M., Galsa, A., Lenkey, L., 2013. Impact of the Rayleigh number and endothermic phase transition on the time behaviour of mantle avalanches. Journal of Geodynamics. 66, 103–113.

Herein, M., Galsa, A., Lenkey, L., Süle, B., 2008. A termikus földköpeny-konvekció numerikus modellezése különböző geometriák esetén. Magyar Geofizika. 49., 3., 111–124.

Other publications related to my doctoral work:

Herein, M., Galsa, A.. 2011. The effect of different geometries on the thermal mantle convection. Comsol Conference 2011. Stuttgart. Germany. http://www.comsol.com/papers/10915/

Galsa, A., Herein, M. 2011. Effect of disintegration of chemical layering on time-dependent behaviour of the mantle. 12th International Workshop on Modeling of Mantle Convection and Lithospheric Dynamics. Groß Dölln. Germany.

Herein, M., Galsa, A.. 2011. Impact of the Rayleigh number and endothermic phase transition on the mantle dynamics. 12th International Workshop on Modeling of Mantle Convection and Lithospheric Dynamics. Groß Dölln. Germany.

Herein M. 2011. The effect of different geometries on the thermal mantle convection. 6th Congress of Balkan Geophysical Society – BGS2011. Budapest. Hungary.

Herein, M., 2009. The effect of different 2D geometries on the numerical models of thermal convection in the Earth's mantle. 11th International Workshop on Modeling of Mantle Convection and Lithospheric Dynamics. Braunwald. Switzerland.

References

Batchelor, G. K., 1967. An Introduction to Fluid Dynamics. Cambridge University Press, Cambridge, England, 615 pp.

Chandrasekhar S., 1961: Hydrodynamic and hydromagnetic stability. Clarendon Press, Oxford.

Christensen, U. R., Yuen, D. A., 1985. Layered Convection Induced by Phase Transitions, J. Geophys. Res. 90, 10291–10300.

Collier J. D., Helffrich G. R., Wood B.J., 2001. Seismic discontinuities and subduction zones. Phys Earth Planet Inter. 127(1-4), 35-49.

Cserepes L., 1992. A földköpeny termikus konvekciójának háromdimenziós szerkezetéről. Doktori értekezés, ELTE Geofizika Tanszék, Budapest.

Cserepes, L., Rabinowicz, M., Rosemberg-Borot, C., 1988. Three-dimensional infinite Prandtl number convection in one and two layers with implications for the Earth's gravity field. J. Geophys. Res. 93, 12009–12025.

Ernst R.E, Buchan K.L., 2002. Maximum size and distribution in time and space of mantle plumes: evidence from large igneous provinces. J. Geodyn. 34, 309–342.

Ernst, R.E., Buchan, K.L., 2003. Recognizing mantle plumes in the geological record.
Annu. Rev. Earth Planet. Sci. 31, 469–523.

Gorbatov, A., Kennett, B.L.N., 2003. Joint bulk-sound and shear tomography for Western Pacific subduction zones. Earth Planet. Sci. Lett. 210, 3–4, 527-543.

Ji, Y., Nataf, H.C., 1998. Detection of mantle plumes in the lower mantle by diffraction tomography: Hawaii. Earth Planet. Sci. Lett. 159, 99–115.

Machetel, P., 2003. Global thermal and dynamical perturbations due to Cretaceous mantle avalanche. Comptes Rendus Geoscience. 335, 1, 91–97.

Montelli, R., Nolet, G., Dahlen, F.A., Masters, G., Engdahl, E.R. and Hung, S., 2004. Finite-Frequency Tomography Reveals a Variety of Plumes in the Mantle. Science. 303, 338–343.

Morgan W. J., 1971: Convection plumes in the lower mantle. Nature 230, 42–43.

Nakagawa, T., Buffett, B. A., 2005. Mass transport mechanism between the upper and lower mantle in numerical simulations of thermochemical mantle convection with multicomponent phase changes. Earth Planet. Sci. Lett. 230, 1–2, 11–27.

Peltier,W. R., Solheim, L. P., 1992. Mantle phase transitions and layered chaotic convection. Geophys. Res. Lett. 19, 321–324.

Pysklywec, R.N., Mitrovica, J.X, 1997. Mantle avalanches and the dynamic topography of continents. Earth Planet. Sci. Lett. 148, 3–4, 447-455.

Rawlinson, N., Pozgay, S., Fishwick, S., 2010. Seismic tomography: A window into deep Earth. 2010. Phys. Earth Planet. Int. 178, 3–4, 101–135.

Schubert, G., Yuen, D. A., Turcotte, D. L., 1975. Role of phase transitions in a dynamic mantle. Geophys. J. Roy. Astron. Soc., 42, 705–735.

Tackley, P.J., 1995a. Mantle dynamics: Influence of the transition zone, US National Report to the IUGG. 1991–1994, 275–282.

Tackley, P.J., 1995b. On the penetration of an endothermic phase transition by upwellings and downwellings. J. Geophys. Res., 100, 15477–15488.

Turcotte D. L., Oxburgh, E. R. 1967. Finite amplitude convective cells and continental drift. J. Fluid. Mech., 28, 29–42

van der Hilst, R.D.,Widiyantoro, S., Engdahl, E.R., 1997. Evidence for deep mantle circulation from global tomography. Nature. 386, 578–584.

van Summeren, J.R.G., van den Berg, A.P., van der Hilst, R.D., 2009. Upwellings from a deep mantle reservoir filtered at the 660km phase transition in thermo-chemical convection models and implications for intra-plate volcanism. Phys. Earth Planet. Int. 172, 3–4, 210–224.

Wolstencroft, M., Davies, J. H., 2011. Influence of the Ringwoodite-Perovskite transition on mantle convection in spherical geometry as a function of Clapeyron slope and Rayleigh number. Solid Earth, 2, 315–326.

Zimmerman W. B. J. 2006. Multiphysics modeling with finite element methods. World Scientific Publishing Company, pp. 432.