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Numerické modelování plášťového klínu

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Charles University in Prague
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Summary of Doctoral Thesis

Numerical Modelling of Mantle Wedge

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Contents

Abstract

Numerical modelling of subduction zones is a method widely used to infer more information about the temperature state of subducting plates and adjacent mantle wedges. Two types of models, dynamic and kinematic, are in use, however, in both types, the decoupling of the subducting plate from the overriding lithosphere in shallow depths is achieved by imposing some additional assumptions on the geometry of the subducting slab. In kinematic models, the geometry of the subducting slab is prescribed not only in a shallow portion but in the whole computational domain. Therefore, the slab geometry is not the outcome of the modelling and the models, particularly kinematic ones, are not self-consistent.

In the presented work, this main weakness of the steady-state kinematic models is addressed. The model of a generic subduction zone, in which the interface between the subducting slab and the mantle wedge is not prescribed a priori, has been developed. The key idea of the modelling consists in the fact that the flow field may be described by the stream function and contour lines of the stream function, stream lines, separate distinct parts of the fluid in the steady state. Therefore, a viscosity depending on the stream function can be defined and the stream function can be employed to distinguish between different parts of the model whose positions are not set in advance. Particularly, the stream function-dependent viscosity is used to allow the decrease in the viscosity of an uppermost part of the subducting slab, which is evidently weakened due to high water content, and its position is then calculated together with the temperature and velocity fields.

This study shows that the resulting non-linear problem converges and calculated results may be correlated with the observations. Pure decrease in the viscosity of the oceanic crust leads to plate-like behaviour and plate decoupling and, moreover, it has been shown that the viscosity decrease directly controls the dip angle: higher decrease of the viscosity in the weakening zone leads to shallower dip angle. This result may explain traditionally poor correlation between the dip angle and other slab properties such as convergence rate, thermal parameter or age.

The developed numerical model has been applied to another two phenomena related to subduction. Firstly, the model of the forearc wedge was constructed and it demonstrated that a backward flow occurs in the cold tip of the wedge if the viscosity decrease is assumed there. Such a backward flow would explain an exhumation of metamorphosed rocks from depths of about 80 km to lower crustal levels. The decrease of viscosity in the cold nose of the wedge is likely since its extensive serpentinization has been indicated by various independent observations. The presented model of the exhumation thus confirmed that the presence of weak serpentinites plays a decisive role in the exhumation of heavy eclogites, which would be hard to explain otherwise, but in contrast to other models, no density difference between a serpentinite-eclogite melange and surrounding peridotites is required as the exhumation occurs due to weakening in the strength of serpentinites.

Secondly, the model of the backarc wedge focused to surface heat flow was constructed. It has been recently pointed out that an increase in surface heat flow is a common feature of all backarcs and, particularly, at those, where no recent extension has been measured, the source of high surface heat flow still remains contentious. The presented model demon-

strated that the pattern of the surface heat flow increase can be reproduced if temperature- and pressure- dependent viscosity is used and it is stable under various thermal boundary conditions applied at the bottom of the model as well as for different slab parameters including age or convergence rate. The physical reason of the elevation is the flow induced by the traction from the subducting slab and it was shown that a low viscosity layer beneath the continental plate resulting from pressure-dependence of viscosity is also required.

The new method for calculation steady-state temperature and velocity field showed that there are likely two flow eddies in the mantle wedge. The small-scale circulation is located in the serpentinized forearc wedge and results in the exhumation of metamorphosed rocks, whereas the large-scale circulation in backarc is the reason of uniformly hot backarc and results in elevated surface heat flow over large backarc regions.

1 Introduction

Subduction zones are one of the most studied processes in geophysics since they play a key role in the plate tectonics theory. Although a lot of effort has been made to understand the nature of subduction zones and our understanding of the processes shaping the Earth's surface has advanced, some fundamentals have not been explained yet in detail.

The basic feature of subduction zones is so-called dip angle, under which the subducting lithospheric plates sink beneath the overriding lithosphere. The actual values for different subduction zones are determined from the slope of the Wadati-Benioff zones: the dip angles between 30° and 90° are observed and, moreover, the dip angles at shallow depths are small and increase with the increasing depths in almost all subduction zones. However, the correlation of the observed dip angles to other properties of the lithosphere such as the age of the subducting slab or the convergence rate has not been found (Jarrad, 1986; Cruciani et al., 2005).

The difference in the observed subduction dip angles is sometimes referred as a difference between eastward and westward dipping (Doglioni et al., 1999), which is remarkable particularly in Pacific, where west-oriented subduction zones (e.g. Tonga-Kermadec, Mariana, New Hebrides) are steeper and deeper (down to 670 km), whereas east-directed subduction zones (North Chile, Peru) are considerably less steep and shallow. Although the relation between the average deep dip and the direction of subduction might be explained by the global westward motion of the lithosphere with respect to the underlying mantle (Ricard et al., 1991), King (2001) emphasized that it is not easy to separate the effect of dip direction from other factors mainly because many of eastward dipping subducting plates are being overridden by continental plates. The fact that subducting plates, the downwelling currents, are oblique and one-sided is the important difference between the mantle convection and classical thermal convection and therefore, self-consistent mechanisms of subduction zone generation have been sought (Tackley, 2000).

Besides the dip angle, there are a lot of other observations that may be used to gain an insight into the nature of subduction zones. The most important findings have been revealed by the seismic tomography, which allows the most direct observation of a flow in the deep interior. In almost all major subduction zones, the tomographic inversions have revealed $100-200$ km thick plates of increased seismic velocities. Some of them sink into the lower mantle although they do not seem to reach the mantle core boundary. The increase in P-wave velocity is up to +6% (Zhao et al., 1994). Simultaneously it was revealed that the overlying regions usually exhibit decrease in P-wave velocity up to −6%. These low velocity zones are visible beneath the active volcanoes and extend to depths of $150-200$ km in the mantle wedge. The similar patterns may be observed also in seismic attenuation: most of slabs and forearcs exhibit a high Q factor, while mantle wedges beneath the volcanic front exhibit a low Q factor (Abers et al., 2006), which is in a good agreement with the older findings, since low Q factors in backarcs is a phenomenon known from the beginning of the plate tectonics (Barazangi and Isacks, 1971).

The results of seismic tomography are used to infer some more information about temperatures and material properties of the lithosphere. Both the seismic velocities and the attenuation factor Q may be related to the viscosity and the seismic tomography results are interpreted as clear evidence of a substantial viscosity decrease (two to four orders) in the mantle wedge beneath backarcs (Karato, 2003).

In many subduction zones, the anisotropy of shear waves has been observed, e.g. beneath Chile, Japan, and Kamchatka. Moreover, it has been reported that the anisotropic zone under Japan is located in the mantle wedge above the surface of the subducting slab and corresponds to the low-Q zone obtained from the seismic tomography. Detailed studies have revealed a complex anisotropy structure under Japan where the fast direction changes from the trench-parallel (close to the trench) to subduction parallel far away from the trench (Nakajima and Hasegawa, 2004).

The complex anisotropy structure in subducting regions cannot be easily explained and, particularly, the trench-parallel fast direction is still a puzzling question. At least three different explanations were proposed and currently the lattice preferred orientation seems to be the most likely reason at least at some subduction zones (Kneller and van Keken, 2007).

An important quantity, which needs to be used to constrain numerical models of the mantle wedge, is surface heat flow since it is a direct measurable manifestation of the temperature state of the lithosphere. The thermal state of the oceanic lithosphere reaching the trench is important because it controls the depths of the deepest seismicity occurring in a particular subduction zone. The measurements in forearc clearly showed that surface heat flow is low, typically 30 – 40 mWm^{-2} (Ziagos et al., 1985). Unlike forearcs, backarc regions are usually much hotter and values about 70 – 80 mWm^{-2} are reported. The extent of anomalously high surface heat flow zone in backarcs may vary but usually is hundreds of kilometres and, moreover, elevated surface heat flow occurs also in backarcs where no recent extension is reported (Hyndman et al., 2005). Between the forearc and the backarc very high heat flow values are observed since a volcanic front sits there. The transition between the cold forearc and the hot backarc is sharp: a considerable increase in surface heat flow is observed in a narrow zone maximally 50 km in width. An excellent example of this remarkable feature is the Cascadia subduction zone. The high surface heat flow zone extends there up to 550 km and the anomalously high surface heat flow above this subduction zone is there even more evident because the backarc is adjacent to a cold cratonic lithosphere, where the average measured surface heat flow is as low as 42 mWm^{-2} . Although the increase in surface heat flow seems to be an important feature of all backarcs, not too much attention has been paid to it in subduction zone modelling and if so, then models were not successful in reproducing such a pattern in surface heat flow (Currie et al., 2004).

Another important constraint on the subduction models stems from the serpentinization of the mantle wedge forearcs, which has been reported from many subduction zones, including Mariana, Cascadia, and central Japan, and it is generally accepted that extensive serpentinization is a common feature of most, if not all, forearcs (Hyndman and Peacock, 2003). Serpentinization greatly impacts the rheology: it was demonstrated that 10% serpentinized dunite (peridotite) has strength equal to that of the pure serpentinite (Escartin et al., 2001). Serpentinites, which have a low density about 2.7 gcm^{-3}, are also expected to play a key role in the exhumation of heavy eclogites (3.5 gcm^{-3}). Several possible mechanisms of their exhumation have been proposed (Platt, 1993) but currently the most preferred one is the exhumation channel along the interface of the subducting slab and the mantle wedge, in which the exhumation is driven by buoyancy (Schwartz et al., 2001).

The above mentioned observations form a basic frame for mantle wedge modelling, although also other additional observations such as geoid anomalies or a dynamic topography may constrain subduction models.

2 Numerical modelling

Numerical modelling of mantle convection is based on our understanding that the driving force is buoyancy. Although King (2001) pointed out that the subduction zones are the most important feature of the mantle convection, self consistent generation of plate tectonics with asymmetric downwellings has not been successful yet. Different numerical models try to bypass this issue in various ways. Dynamic models usually prescribe a fault at the plate contact up to a certain depth (Čížková et al., 2007) and kinematic models prescribe the velocity of the whole slab (Kneller and van Keken, 2007). The kinematic models include a complex, if not realistic, rheology and allow handling various non-linear effects like shear heating or phase transitions, however, are usually limited to the steady state. Nevertheless, the number of kinematic steady-state models has increased during the last decade; the attraction of kinematic models consists in the fact that the input of the model is well known – plate velocity, age, and geometry of the subducting plate. The fixed geometry is, however, the most significant weakness of the current steady-state models, since kinematically prescribed slabs behave rigidly as kinematic models are not able to account their internal deformation; the use of kinematic models is limited to shallow portions of the mantle.

The kinematic steady-state models are used in order to infer more information about the temperature of the oceanic crust and the overlying sedimentary layer and, particularly, to gain a better understanding whether the melting of sediments and/or the oceanic crust is possible beneath the volcanic front (van Keken et al., 2002). Recently, it has been used to explain the anisotropy pattern in the forearc (Kneller and van Keken, 2007), but these models failed completely in the simulation of hot backarcs (Currie et al., 2004) and also the exhumation are not modelled in these models.

3 Goals

The main goal of this thesis is to formulate a steady-state model of the mantle wedge, which would include the contact between the subducting slab and the overlying lithosphere in a self-consistent way, i.e. without any a priori information about its position. The current steady-state models use the geometry of this contact as an input since the geometry of the Wadati-Benioff zones is know relatively well. In that way, a part of the flow (solution) is imposed to the results a priory. In this work, the opposite approach is suggested: if the contact was the outcome from the simulation, a comparison of the calculated dip angles with the observed would offer an excellent criterion of how the calculated flow solution is close to the reality. Thus, the known shapes of the subducting plates might be used to validate the models a posteriori.

Furthermore, it would be of interest to use a mantle wedge model with the self-consistent contact generation to explain some unresolved questions, particularly, the hot backarc mystery or to exhumation of metamorphosed rocks. Such a model might also help to improve the understanding of how the dip angle is related to other parameters of the subducting slab.

4 Method

We modelled the subduction zone as a flow of an incompressible fluid in a 2-D domain and since only the steady state is sought, the standard set of equation reduces to

$$-\nabla p + \nabla \cdot \boldsymbol{D} + \rho \boldsymbol{g} = 0, \tag{1}$$

$$\nabla \cdot \boldsymbol{v} = 0, \tag{2}$$

$$\rho c_p \boldsymbol{v} \cdot \nabla T = \nabla \cdot (k \nabla T) + \boldsymbol{D} : \boldsymbol{v} + Q, \tag{3}$$

where p is the pressure, $\boldsymbol{v}$ is the velocity, ρ is the density, $\boldsymbol{g}$ is the gravity acceleration, c_p is the specific heat, k is the thermal conductivity, and $\boldsymbol{D}$ is the deviatoric part of the stress tensor given by the viscosity η and the strain rate $\dot{\boldsymbol{e}}$:

$$\boldsymbol{D} = 2\eta \dot{\boldsymbol{e}}, \quad \dot{\boldsymbol{e}} = \frac{1}{2}\left(\nabla \boldsymbol{v} + (\nabla \boldsymbol{v})^T\right). \tag{4}$$

Since equations (1) – (3) are solved in a rectangular computational domain schematically depicted in Figure 1, advantage of the stream function formulation may be taken. The stream function ψ is defined by equations

$$v_1 = \frac{\partial \psi}{\partial x_2}, \qquad v_2 = -\frac{\partial \psi}{\partial x_1}, \tag{5}$$

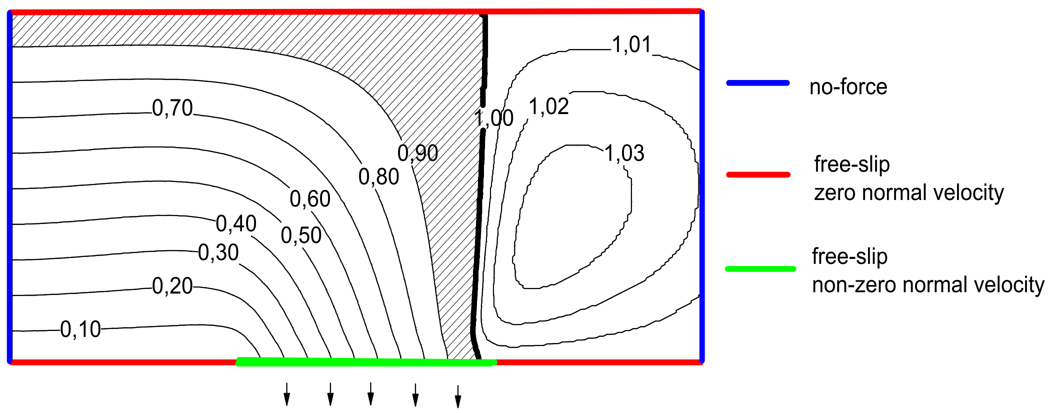

Figure 1: Scheme of the rectangular domain 300 × 100 km showing the flow pattern developed in the case of a constant viscosity. The stream function is scaled by the value ψ_B so as the slab-wedge interface is marked with the contour line $\psi = 1$.

and then equations (1) – (3) can be solved using the Picard iterations (Cuvelier et al., 1986) even in the case of non-linear viscosity. We employ the following iterative scheme

$$T^0 \to \psi^1 \to T^1 \to \psi^2 \to \cdots \to T^n \to \psi^{n+1} \to T^{n+1} \to \psi^{n+2} \to \cdots \tag{6}$$

The Picard iterative process usually converges without a need for an accurate initial guess even in the case of strongly non-linear equations, however, it may converge slowly in some cases.

We solve the equations for the stream function and temperature in the iterative scheme (6) numerically using the Finite element method with a newly developed program. The program is written in C++ and tested against standard mantle convection benchmarks (Blankenbach et al., 1989).

5 Results

The key point of the presented modelling consists in the way, how the subducting plate can be defined without prescribing its position a priori. In Figure 1, the subducting plate is modelled as a prescribed inflow coming from the left side of the domain, whereas the right side of the domain is opened and material can freely move across this boundary. Since the stream function is given by equation (5), its value in the left bottom corner may be set to zero. The value in the left upper corner is then given and may be denoted as ψ_B. The stream line ψ_B thus bounds the material coming through the left boundary (subducting plate) from the rest (overriding lithosphere). This leads to a definition of a non-linear viscosity of the Arrhenius type

$$\eta = \eta_{\max} f(\psi) \exp\left(-\frac{\ln(K_t)T}{\Delta T}\right), \tag{7}$$

where $f(\psi)$ is a piece-wise function defined as

$$f(\psi) = \begin{cases} w, & \psi \in \langle (1-\delta_w)\psi_B, \psi_B \rangle, \quad 0 < \delta_w < 1 \\ 1, & \text{elsewhere} \end{cases} \tag{8}$$

Thus, we can impose a zone of weakness with the viscosity $\eta = w\eta_{\max}$ at the top of the subducting plate but the geometry of the plate is not set in advance.

We carried out a parametric study changing the viscosity reduction w for different slab velocities. Although the viscosity given by equation (7) is a long way from what might be a realistic viscosity, the subducting plate is decoupled from the overriding one and the plate-li behaviour occurs if the weakening w is sufficient, i.e. if the viscosity of the topmost part of the subducting plate is by about several orders of magnitude less than the viscosity of the overriding plate. Moreover, it may be easily seen that the dip angle depends on the weakening factor w as well: higher weakening results in a less steep dip angle of subducting plates, see Figure 2.

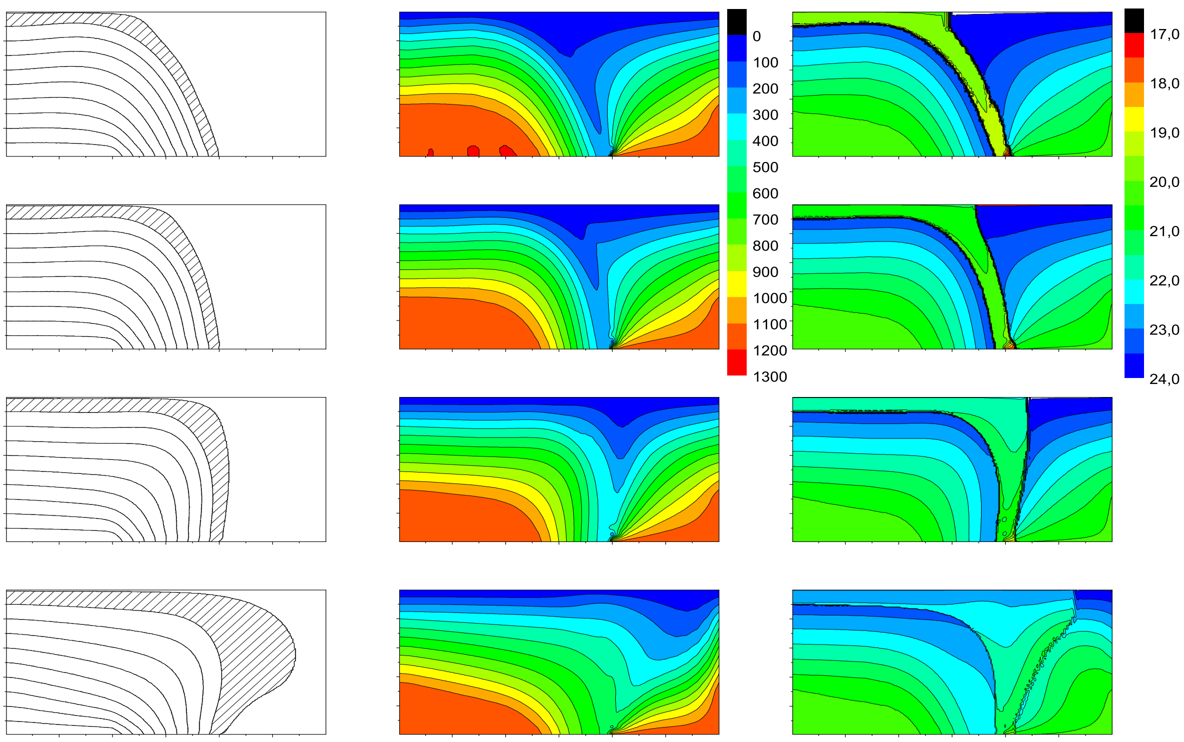

Figure 2: Stream lines (left), temperature (middle), and viscosity in log scale in the case of velocity $v_0 = 5$ cm/year. Reference viscosity η_0=10^{24} Pas and $K_t = 10^3$. The weakening parameter w changes from top to bottom: 10^{-4}, 10^{-3}, 10^{-2}, and 10^{-1}. The position of the weakening zone is hatched.

Furthermore, we created more complex model of the forearc wedge using the pseudo-plastic viscosity, and the zone of weakening is assumed not only in the uppermost part of the subducting slab but also in a cold portion of the mantle wedge limited by the antigorite stability field, which is supposed to be serpentinized. The results showed that in such a case the backward flow may be developed in the cold nose of the wedge if the weakening in the oceanic crust and the cold nose of the wedge are of the same order, i.e. if the serpentinization of these domains is roughly the same. Such a backward flow would explain the exhumation of metamorphosed rocks from depth of about 80 km to lover crustal levels and it was also shown that isothermal decompression may be easily explained if the temperature contour lines coincide with stream lines of the exhumation circulation.

The developed method was also employed to the model of backarc wedge in order to explain high values of surface heat flow observed in most backarcs. It was shown that the pattern of heat flow is very sensitive to the thermal boundary condition applied at the bottom the mantle wedge, however, the exact boundary condition, which should be applied there, is unknown, particularly, because behaviour of the subducted slabs around 660 km discontinuity may be very different; some slab easily penetrates to the lower mantle but some exhibit flattening around the discontinuity, which would significantly cool down the base of the backarc. This is why we sought for a viscosity capable to reproduce the heat flow pattern independently on the actual thermal boundary condition and we concluded that both strong temperature- and pressure-dependent viscosity resulting in a low viscosity layer beneath the continental crust is our preferred solution. This viscosity produces the stable pattern of surface heat flow also other properties of the subducting slab such as age or convergence rate.

6 Conclusions

The main goal of this work was to develop a numerical model of a subducting lithospheric plate which would include a contact between the subducting plate and the overriding one without need for a geometric description of this contact. The self-consistent generation of subduction zones is one of the most important questions of plate tectonics (King, 2001), however, it has been mostly ignored in mantle wedge models. We have shown a way how the contact can be incorporated into the steady-state wedge models although its position is not set in advance. Consequently, the described principle has been implemented in a numerical model of the mantle wedge and it has been demonstrated that a weak oceanic crust acts as a lubricant and the viscosity weakening magnitude primarily controls the shape of the subducting slab in shallow depths.

The developed numerical model has been used to model two different effects connected with subduction zones. In the model of a generic forearc, a serpentinized tip of the wedge has been modelled as a low viscosity zone. This model demonstrated that exhumation of rocks may occur in the wedge if serpentinite rocks are weak enough. Moreover, the model showed that nearly isothermal exhumation may uplift the rocks from depths of about 80 km to a lower crustal level at temperatures close to 700°C, which is consistent with some observations.

The presented model has also been employed to model the flow in backarc regions.

Since almost all backarcs exhibit an increase in surface heat flow (Hyndman et al., 2005), a rheology, which reproduces this feature under a wide range of possible thermal conditions, has been sought. This topic is currently widely discussed because numerical models used so far have not successfully modelled this feature (Currie et al., 2004; Currie and Hyndman, 2006). It has been found that a purely temperature-dependent rheology is not able to reproduce the observed pattern in surface heat flow, however, a temperature- and pressure-dependent viscosity is able to fit the increase in surface heat flow if the pressure-dependency is strong enough. In such a case, an almost uniformly hot backarc is formed under a wide range of slab properties including various dip angles and convergence rates. The overall idea of the flow in the mantle wedge is schematically summarized in Figure 3.

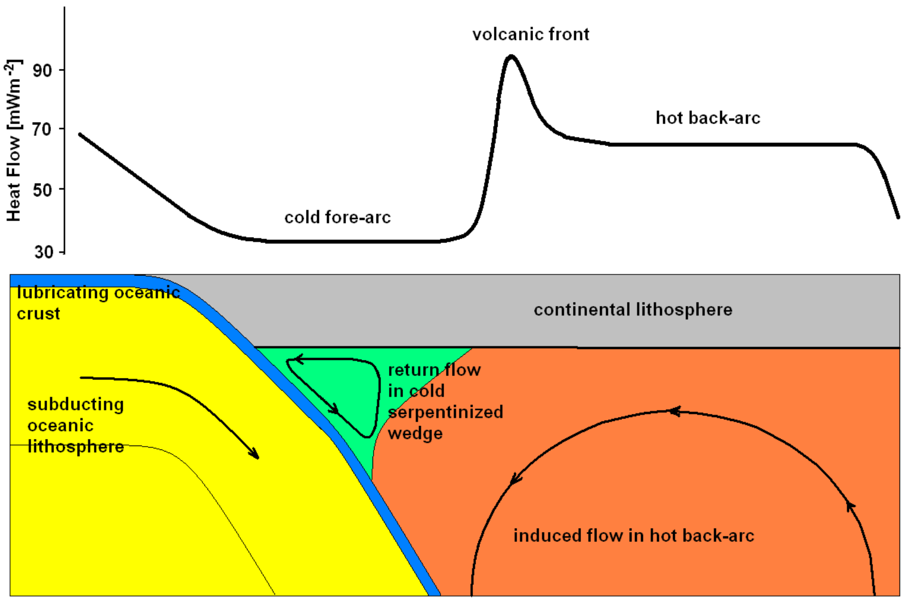

Figure 3: Schematic picture of possible flow in the mantle wedge shows the corner flow induced in the serpentinized forearc and the large-scale flow in backarc, which considerably affects surface heat flow.

The presented work has shown that a self-consistent inclusion of the plate-wedge boundary is possible in steady-state models and, moreover, it is a must-have feature of subduction models. In a simple steady-state model it has been demonstrated that inclusion of this contact may results in effects so far unforeseen by "classical" numerical models.

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