Application of Numerical Methods for New Estimate of Rheology Constants in the 2D Computer Model of the Mantle Wedge Thermal Convection as a Possible Physical Mechanism of Hydrocarbons Transport

S.V. Gavrilov¹ and A. L. Kharitonov²

¹ Schmidt Institute of Physics of the Earth

Received: 6 December 2019 Accepted: 31 December 2019 Published: 15 January 2020

Abstract

For both Newtonian and non-Newtonian mantle rheology laws, the numerical model of the 2D dissipation-driven mantle wedge thermal convection is constructed for the case of subduction of the Black sea micro-plate under the Crimea peninsula with the account taken of the phase transitions in the mantle. The horizontal extent of the positive 2D heat flux anomaly zone localized in the rear of the Crimea mountains is shown to correspond to the model subduction velocity ~10 mm per year for the water content of one weight.

Index terms—2D thermal convection, Newtonian and non-newtonian rheology constants, phase transitions, hydrocarbons transport.

1 Introduction

Interaction of the lithospheric plates in the Crimea-Caucasus region leads to the thrusting of the Black Sea micro-plate under the Crimea peninsula [Nimetulayeva, 2004]. As a consequence, the seismic focal plane is formed along which the Crimea ascends as the result of seismic jerks. The velocities of vertical uplift of the Crimea mountains and sinking of the near-Crimean area of the Black Sea micro-plate equal to ~4 mm per year and ~10 mm per year, respectively. Mountainous Crimea is a folded fault region being a part of the Alps-Himalaya-Indonesia belt [Yudin, 2001].

In Ushakov et al., 1977 the subduction velocity of the Black Sea micro-plate under the Crimea peninsula is estimated of ~1 mm per year as the best fit to the observed sedimentary layer distribution. Other estimations are unknown to the knowledge of the authors. However the obtained estimate of ~1 mm per year appears to be an underestimate, being not correspondent to the vertical velocities of ~4 and ~10 mm per year of Mountainous Crimea and the Black Sea micro-plate.

According to Gavrilov, 2014; Terya, 2011; Terya et al., 2006 two types of dissipation driven small-scaled thermal convection in the mantle wedge are possible, viz. 3D finger-like convective jets, raising to volcanic chain, and 2D transversal Karig vortices, aligned perpendicularly to subduction. These two types of convection are shown to be spatially separated due to the pressure and temperature dependence of mantle effective viscosity, the Karig vortices, if any of them formed, being located behind the volcanic arc [Gavrilov, 2014]. Despite the firmly established localization of the seismic focal plane there is just a single definite conclusion concerning the velocity of subduction of the Black Sea micro-plate [Ushakov et al., 1977]. It is not completely clear if volcanism played a substantial role in forming Mountainous Crimea, or the mountains are of a purely thrust-and-fold origin. Nimetulayeva, 2004 indicates the contradictory statements on the Crimean volcanism to have been published, however in Fig. 2.4 in Nimetulayeva, 2004, the volcanic eruption in the Mountainous Crimea is depicted. The abovementioned picture is reproduced here in Fig. 1 with the convective vortices drawn additionally. It is worth assuming the two heat flux anomaly maxima observed in the south of the Crimea peninsula Smirnov,
2 II.

3 Algorithm and Computation Complexity

Thermo-mechanical model of the mantle wedge between the base of the overlying Scythian plate and the upper
surface of the Black Sea micro-plate subducting under the Scythian one with a velocity V at an angle ? is
obtained for the infinite Prandtl number fluid as the solution of non-dimensional 2D hydrodynamic equations in
the Boussinesq approximation for the stream-function ? and temperature T.) 660 ( ) 660 ( ) 410 ( ) 410 ( 2 2 2

Here ? is dynamic viscosity, ? and indices denote partial derivatives with respect to coordinates x (horizontal),
z (vertical) and time t , is the Laplace z x V ? ? , x z V ? ? . (3)

4 RT pV E

Following ??Trubitsyn & Trubitsyn, 2014 we assume the phase functions Where for "wet" olivine A=5.3×10
15 s -1 , m=2.5, the grain size h=10 -1 -10 mm, b * =5×10 -8 cm is the Burgers vector [Zharkov, 2003], E
* =240 kJ mol -1 is activation energy, V * =5×10 3 mm 3. mol -1 is activation volume, ? =300 GPa is
the shear modulus normalizing factor, R is the gas constant. At the chosen constants and the grain size h=1.6
mm, non-dimensional viscosity also denoted To check as to how the estimate of the velocity of subduction of
the Black Sea micro-plate is sensitive to the accepted linear rheological law here we make extra computations
for non-Newtonian rheology, in which case the viscosity formulae (5)-Where according to

It should be noted the constants in [7] vary considerably in the papers referred to by ??Trubitsyn, 2012] and
heretofore, we gave averaged values of constants. At C w =10 -3 on accounting for where the signs are changed
as z-axis is pointing upwards, ) ( ) (5 T z L

5 T z L

Equations (1)-(2) are solved for the isothermal horizontal and insolated vertical boundaries regarded no-slip impenetrable ones except for the "windows" for in-and outgoing subducting plate, where the plate velocity
is specified. Vertical boundary distant from subduction zone is assumed penetrable at right angle, the latter
boundary condition appears not too imposing in the case of very flat subduction. Q in (2) is non-zero in
the continental and oceanic crust 40 and 7 km thick. Initial vertical boundaries temperature is calculated for
the half-space cooling model for 10 9 yr and 10 8 yr for Scythian (continental) and Black Sea (oceanic) plates
respectively.
6 III.

7 Results and Discussion

Assuming the second (more remote from the trench) heat flux $q$ maximum in Fig. 1 appears above the convective flow, ascending to C 2 point in Fig. 1, and the convection cell dimension is equal to the two adjacent $q$ minima separation (i.e. the $q$ minima are located above the descending convective flows) we can estimate the convection cell dimension as $\sim 250$ km. To preliminarily access the mean velocity of subduction of the Black Sea micro-plate the coordinate

$x$ dependence of the growth rate $\gamma$ ? $\gamma(x)$ of transversal convective rolls for the constant viscosity fluid model can be allowed for. In such the model the averaged temperature and pressure viscosity dependence is accounted for in an averaged manner, the factor describing the temperature-and pressure viscosity dependence being equal to its mean value \[ Gerya, 2011]. \]

Analytical formulae in \[ Gavrilov, 2014 \] It should be noted the growth rates $\gamma$ ? $\gamma(x)$ are viscosity independent as convection is driven by viscous heat release (which is directly proportional to viscosity), while, on the other hand, the greater is the viscosity the more difficult is to arouse the convection. Fig. 2 clearly demonstrates the convective zone with $\gamma$ ? $\gamma(x) > 0$ amounts to $\gamma \sim 1 \times 10^7$ km.

250 km (i.e. the single convective cell of $\sim 250$ size is actually aroused) at $V=40.5$ mm per year, the latter value being a preliminary estimate of the mean subduction velocity. The $\gamma$ ? $\gamma(x)$ maximum is $7320$ km distant from the trench which is very close to the distance from the trench to the observed 2D heat flux anomaly ($\sim 400$ km, see Fig. 1).

To compute more accurate consistent model of small-scale convection in the mantle wedge between the overriding Scythian plate and subducting Black Sea micro-plate it is necessary from the computational point of view first to specify vanishing non-dimensional numbers $Ra$, $Di = 0$ in (1)-(2), i.e. to ignore convection and viscous dissipation. This approach is applied as convection with Ra and Di (4) passes through very vigorous stages, and the time steps in integrating (1)-(2) become too small making it difficult to model the thermal structure of the plates. Solving (1)-(2) by the finite element method in space on the grid $104^2 \times 104$ and the 3-rd order Runge-Kutta method in time one obtains for $Ra = 70$, $Di = 0$ and $V=45$ mm a year non-dimensional quasi steady-state $\gamma$ and $T$ shown in Figs. 3 where the streamlines are depicted with step 0.25 and the isotherms with an interval of 0.05. Subducting plate was considered rigid, while the viscosity at the zone of plates friction (at temperatures below 1200 K) was reduced by 2 orders of magnitude as compared to (5). The latter viscosity reduction at the plates contact zone accounts for lubrication effect by deposits partially entrained by the subducting plate. Such a lubrication prevents the overriding Scythian plate from gluing to the subducting one.

Thus the for the non-Newtonian mantle wedge rheology case, with the viscosity reduced by 3 orders of magnitude as compared to (7)-(9), the computation shows the convection in the mantle wedge to occur at $C w = 5 \times 10^{-1}$ weight % in the form of two micro vortices at $V=45$ mm per year. Convection of this type can provide abnormal 2D heat flux $q$ observed in the rear of the Mountainous Crimea and the upwelling of the mantle hydrocarbons to the Earth’s surface along the arrow \[ \text{c} \] (Yudin, 2003). Considerable velocity in convective vortices in Fig. 4 is due to the local viscous stresses increase resulting in the drop in viscosity in convective zone. In the case of Newtonian rheology the convection is aroused at the subduction velocity of over 10 2 mm×a −1, which appears unrealistic.

According to ??Zharkov, 2019, p.143], the water content in the mantle transition zone in the mantle wedge may amount to $-3$ wt. %. To investigate the role of water infused into the mantle wedge from the subducting slab the above computations were carried out for the mean water content of 1 wt. % and subduction velocity of 30, 20, and 10 mm per year. The results of the convection computation are shown in Figs. 5a and 5b for $V=30$ and $20$ mm per year respectively, where the streamlines corresponding to subducting Black Sea micro-plate are shown with the interval of 10, and the streamlines, corresponding to convective vortices with the interval of 10 6. The mean non-dimensional velocity in the left micro-vortex are $-15.2 \times 10^7$, $-7.1 \times 10^7$ and $-0.05 \times 10^7$ for the velocity of subduction of $V = 30, 20$, and 10 mm per year respectively. Thus, the convection may be considered to arise at the subduction velocity over $-10$ mm per year for the mean water content $C w = -1$ wt. %. Since the mean water content in the mantle wedge could hardly exceed $-1$ wt. % even at the water content in the mantle transition zone of 3 wt. %, the obtained subduction velocity of $-10$ mm per year may be regarded the minimum estimate of that of subduction of the Black Sea micro-plate.
It is worth noting, that in the case of Newtonian rheology, the mantle wedge dissipation-driven convection in the form of transversal rolls, as in Fig. 4, is characteristic of very small subduction angles, the convection of this type being absent already at subduction angle $\gamma = 30^\circ$ [Gavrilov & Abbott, 1999]. At the subduction angle under consideration here, $\gamma = 15^\circ$, the convective transversal rolls do not appear at $V < 10$ cm×yr$^{-1}$ for the Newtonian rheology case. Arrow (c) above the boundaries of the oppositely revolving convective vortices in Figs. 4, 5 indicate a possible direction of transport of non-organic mantle hydrocarbons to the Earth’s surface. Computations for Newtonian mantle rheology with the viscosity (5)-(6) shows the transversal rolls to be aroused at far greater distance from the trench than the observed 2D heat flux anomaly. the model constructed here favors the non-Newtonian mantle wedge rheology as better fitting in with the observed heat flux anomaly localization. It should be noted that numerous thermo-mechanical mantle models in the zones of subduction (see, e.g. Gerya et al., 2006; Gerya, 2011 and the vast number of references there) showed convection in the form of transversal rolls never to occur as the models with extremely small subduction angle and sufficiently great subduction velocity were not investigated.

### 8 Conclusions

The size of the cell of 2D mantle wedge dissipation-driven convection in the case of the realistic non-Newtonian rheology equals ~300 km at the subduction velocity 10 mm×yr$^{-1}$.

---

1 Application of Numerical Methods for New Estimate of Rheology Constants in the 2D Computer Model of the Mantle Wedge Thermal Convection as A Possible Physical Mechanism of Hydrocarbons Transport

2 © 2020 Global Journals
Figure 4:

Figure 5: T
Figure 8: