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Simulation of a Continent - Continent Collision Using the Mantle Convection Theory

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Summary

The application of a numerical model of mantle convection to regional geological problems is proposed. Considering the 2-dimensional flow in a limited region it is possible to achieve a spatial resolution of 5 - 10 km. The result of such models could be compared with regional geological data. It is expected that better interpretation of geological data can be obtained in this way. The Fennoscandian shield is a good testing object for such research.

1. Introduction

The theory of plate tectonics was developed by scientists in the late sixties (e.g. *Le Pichon et al.*, 1973). Its main assumption is that the lithosphere - the outer layer of the Earth - is divided into several plates. The relative motion of these plates is observed as the continental drift and gives rise to orogenesis. For many regions the geological processes have been interpretated on the basis of the plate tectonics (e.g. for Fennoscandia see, Fig. 1).

Plate tectonics is, however, a kinematical theory, i.e., it only postulates motion of the plates. It explains neither the origin of plate motions nor their changes in geological time. In the process of interpretation of geological data on the basis of plate tectonics one must assume the plate's motion. This assumption may be dynamically inconsistent, i.e., there were no forces that accomplish the assumed motion.

Dynamical inconsistences can be avoided if the mantle convection theory is used (e.g. *Czechowski*, 1986). This theory is based on the physical equations and it provides a physical background for plate tectonics. In the present paper we discuss the possibility of using an approach of mantle convection theory to regional geological problems in Fennoscandia.

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2. *Problem of resolution*

Theoretical investigations of the mantle convection are usually based on numerical solution of fluid equations. Most problems arise in solving the Navier-Stokes equation. For a large Prandtl number it is an elliptic differential equation. Using the finite difference method (FDM) we seek an approximate solution at selected points, the so-called grid points. The easiest way of choosing these points is to space them evenly on the considered region. The discretization of an elliptic equation leads to a large system of algebraic equations; at least one equation for every grid point. A similar situation occurs if the finite element method (FEM) is used. *Baumgardner* (1988) used a 3-dimensional FEM global model. The whole mantle was divided into 81920 elements. The solution of a system of 130 662 equations is required to obtain the velocity field. Even a powerful computer may have some problems in handling such a system. The spatial resolution of the model is about 600 km. It is far too low for any regional problem. Thus, the global models are not useful for the interpretation of regional geological structures and therefore we are forced to reduce the region of simulation. However, there are some limitations in doing so. The system of equations requires that we specify temperature (or its gradient) and velocity (or stresses) on the boundaries. It can be done with a reasonable confidence for the whole mantle, since temperatures at the core surface or Earth's surface may be assumed to be constant. More problems arise for mechanical boundary conditions. Free of stress as well as rigid boundary conditions can be used depending on the situation.

On the other hand it is not possible to specify any reasonable conditions for any boundary cutting flow lines unless the velocity and temperature distributions are known. The conclusion of the above discussion is that the model should take at least one whole convection cell.

Another possibility of increasing the resolution of the model is offered by 2-dimensional models. They may be a reasonable model of the reality if geological structures have a plane of symmetry. Many Precambrian structures of the Baltic Shield appear NW-trending e.g. *Havskov* and *Medhus*, 1991. This means that the vertical plane along NE-direction may be treated as an approximate plane of symmetry. The Fennoscandian Shield is a good testing object also because a diversity of geological processes were recognized over there.

3. *Structures that can be modelled*

Let us consider what class of structures can be modelled using the 2-dimensional model of mantle convection. First of all the main features of mantle convection: moving plates, subduction zones and spreading centres. The model can give the place and time of their origin, their duration and intensity as well as distributions of stress, temperature and heat flow. The modelled subduction zone can be easily compared with geological data, providing a valuable test of the model. The data about spreading centers are poorly represented on continents. In fact the numerical models might be the most direct source of information about spreading centers in the past.

Many processes in the spreading zones can also be modelled, including the collisions of terranes. Having the stress distribution calculated from the model, one can calculate the deformation of the terranes as well as sediments between them. Comparing stresses and strength of the rocks it is possible to calculate the faulting in the lithosphere. The changes of vertical stresses lead to vertical motion. On the basis of the temperature, heat flow and stress distributions, one can infer some general informations about volcanic activity. The paleomagnetic data about polar wander can be compared with calculated plate motion.

Seismic methods also give valuable data for comparison. These are: remnants of the subducted plates and the deep faults that indicate the large stresses in the past (e.g. *Babel*, 1990).

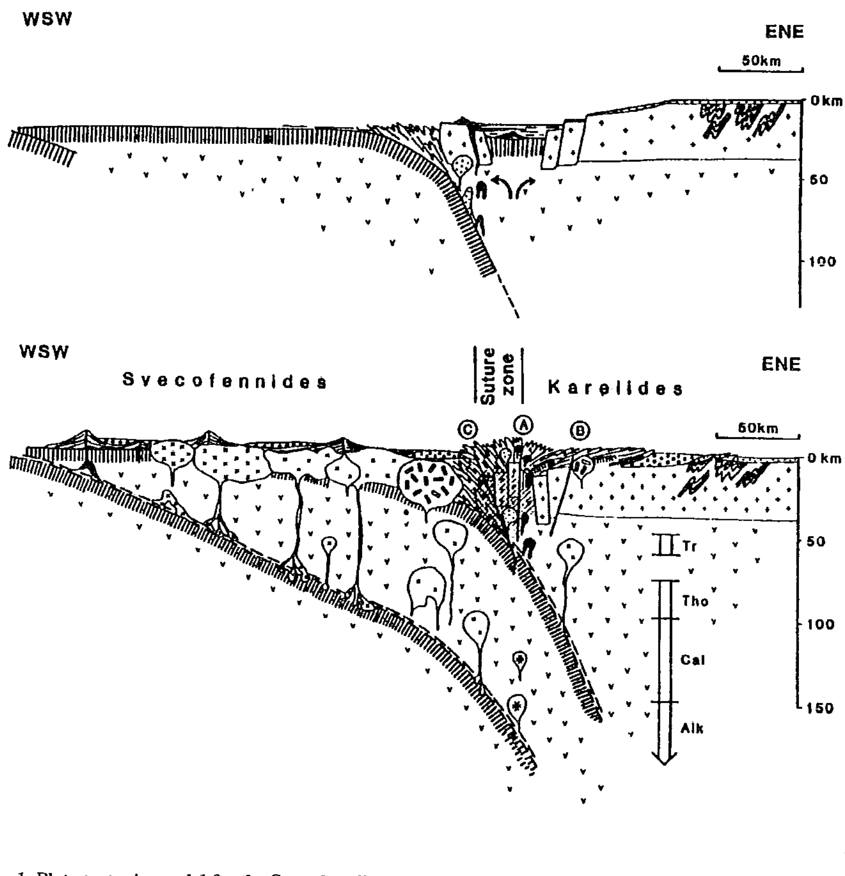

Fig. 1. Plate tectonic model for the Svecokarelian cycle of the Baltic shield c. 1920 Ma (above) and c. 1880 Ma ago (below), approximately to scale. After Gaal (1986).

4. *Objectives*

The main objective of the present analysis is to consider the possibility of applying the convection theory to simulate some geodynamical processes. This involves the following questions: a) could the known geological history of a given region be modelled by the convection equations? b) what values of the equations' parameters should be used (initial and boundary condition, rheological properties of the mantle's rocks, parameters of gravitational differentiation, etc.). c) what limits on the value of the parameters of the equations are imposed by the known geological history of the region? d) is the present interpretation of geological structures right?

For example: Five major orogenic cycles were distinguished in North Europe (*Gaal*, 1986). These cycles were interpreted according to the plate tectonics as changes in motion of the lithospheric plates (Fig. 1). In my research I would attempt:

- To find such values of convection parameters (initial and boundary conditions and other parameters of the equations) that reproduce the changes in motion of the plates. If the given system of equations is unable to do so, a more general system should be used (e.g., including gravitational differentiation) or some parameters changed. The objectives a) and b) will be achieved if geological history of the region is reproduced by the equations with enough accuracy.
- To obtain information about initial conditions in the mantle and mantle's properties in the past. It can be done by repeating simulation of the convection with different values of parameters of the equations.
- In some cases, reinterpretation of the geological data could be done.

Let us indicate now some limitations of the proposed models. Some features cannot be modelled by the 2-dimensional model. These include: hotspots, transform faults and rotation of the plates. Also, the length of the modelled region of the mantle could not be greater than 4000 km because of the resolution requirement and limitation of the computer power. The model fails if the modelled continent moves out beyond this considered region.

The drift history of Fennoscandia from Archean is described by *Pesonen et al.* (1989). The displacement of Fennoscandia is too large to be afforded by a single model spanning 2000 Ma. The past should be divided into shorter periods and separate models should be used for every period. No such problem arises if a subduction zone is modelled. The plates can move rapidly during the process but the subducted plates serve as an anchor preventing the motion of the whole system of the plates in respect to the mantle.

The resolution of the proposed model is limited. Even for the 2-dimensional model, it may be difficult to achieve a resolution better than 5 km. This limitation could be relaxed using the "second order" models, i.e., models of even smaller region, that use the results of the main model as boundary conditions.

5. *Sample model*

Most numerical models are aimed at the investigation of the general properties of the mantle convection (e.g. *Jarvis*, 1984, *Christensen*, 1984, 1987, *Bercovici et al.*, 1989). Contrary to that deductive approach, the present model is aimed at simulation of the actual geodynamical processes. Therefore a special attention is given to make the model more realistic, e.g. the two-component fluid with gravitational differentiation is considered, properties of the mantle rocks might be temperature and pressure dependent and physical quantities accessible in direct observations are computed.

The model presented below is based on the Navier-Stokes equations, the heat transfer equation and equation of diffusion of the lighter component of mantle material. Thus, it is a double-diffusive convection model introduced to investigations of mantle convection by *Czechowski* (1979, 1980, 1984).

In the case of incompressible, two-dimensional flow at high Prandtl number, the stream function S can be introduced by the following formulae:

$$u = \frac{\partial S}{\partial y} \qquad v = -\frac{\partial S}{\partial x} \tag{1}$$

where u and v are the horizontal and vertical components of the velocity vector, respectively. The Navier-Stokes equations can now be reduced to one equation of the fourth degree:

$$\frac{\partial^2}{\partial x \partial y}\left(4\eta \frac{\partial^2 S}{\partial x \partial y}\right) + \left(\frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial x^2}\right)\left[\eta \left(\frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial x^2}\right) S\right] = \frac{\partial g \rho}{\partial x} \tag{2}$$

where η, ρ and g are the viscosity, density and gravity, respectively. The heat transfer equation is:

$$\frac{\partial T}{\partial t} + \mathbf{v} . \operatorname{grad} T = \kappa \Delta T + Q \tag{3}$$

where Δ is the Laplacian, T is the temperature, κ is the coefficient of temperature diffusivity, and Q is the radiogenic heat production rate divided by specific heat and density. The distribution of the lighter component of the mantle material is described by the equation:

$$\frac{\partial Z}{\partial t} + \mathbf{v} . \operatorname{grad} Z = c \, \Delta Z \tag{4}$$

where Z is a fraction of the lighter component ($0 \leq Z \leq 1$) and c denotes the coefficient of diffusion. The density ρ is given by the equation of state:

$$\rho(T,Z) = \rho_o - \rho_o \alpha\, T - e\, Z$$

where α is the coefficient of thermal expansion and e is a constant.

After transformation to dimensionless form we obtain the following equations (viscosity is assumed to be constant):

$$\Delta\Delta\, S = R_T \frac{\partial T}{\partial x} + R_z \frac{\partial Z}{\partial x} \tag{5}$$

$$\frac{\partial T}{\partial t} + \mathbf{v}.\,\mathrm{grad}\, T = \Delta T + 1 \tag{6}$$

$$\frac{\partial Z}{\partial T} + \mathbf{v}.\,\mathrm{grad}\, Z = C\,\Delta Z \tag{7}$$

where thickness d of the fluid layer is a new unit of length and d^2/κ is a new time unit. The Rayleigh number for internal heating is denoted by R_T. The other dimensionless numbers R_Z and $C=c/\kappa$ are specific for double-diffusive convection (see e.g. *Czechowski*, 1979, 1984).

A sample calculation is presented below. The dimensionless numbers are: $R_T=10^5$, $R_Z=10^6$, $C=10^{-4}$ Equations (5, 6, 7) are solved in the rectangular region ($0 \leq x \leq 2$, $0 \leq y \leq 1$). The free of stress boundary conditions are assumed. The upper boundary is assumed to be isothermic ($T=0$), the lateral ones are adiabatic and dimensionless heat flow (equal to 0.33) is specified at the lower boundary - see Table 1.

The collision of two small continents (terranes) is simulated. It is assumed that continents are built of low-density material. The initial distributions of temperature T and fraction of the lighter component Z are shown in Figure 2. The motion of the continents is sketched in Figure 3 (the low-density continental material is contoured). Streamlines and isotherms are drawn in Figures 4 and 5 (they correspond to Figures 3e and 3d). Other physical quantities are also calculated (but not presented here): stresses, surface deformation (topography) and gravitational anomalies.

Table 1. Parameters of the presented model.

Dimensionless numbers $R_T = \frac{g\, \alpha\, \rho_0\, d^5\, Q}{\eta\, \kappa^2} = 10^5$ $R_z = \frac{g\, e\, d^3}{\eta\, \kappa} = 10^6$ $C = \frac{c}{\kappa} = 10^{-4}$ The values of material parameters are limited only by values of these dimensionless number
Boundary conditions upper y=1: isothermic (T=0), free os stress lateral x=0 or x=2: adiabatic ($\partial T/\partial x = 0$), free of stress lower y=0: heat flow $\partial T/\partial y = 0.33$, free of stress
Initial conditions: see Fig. 2.

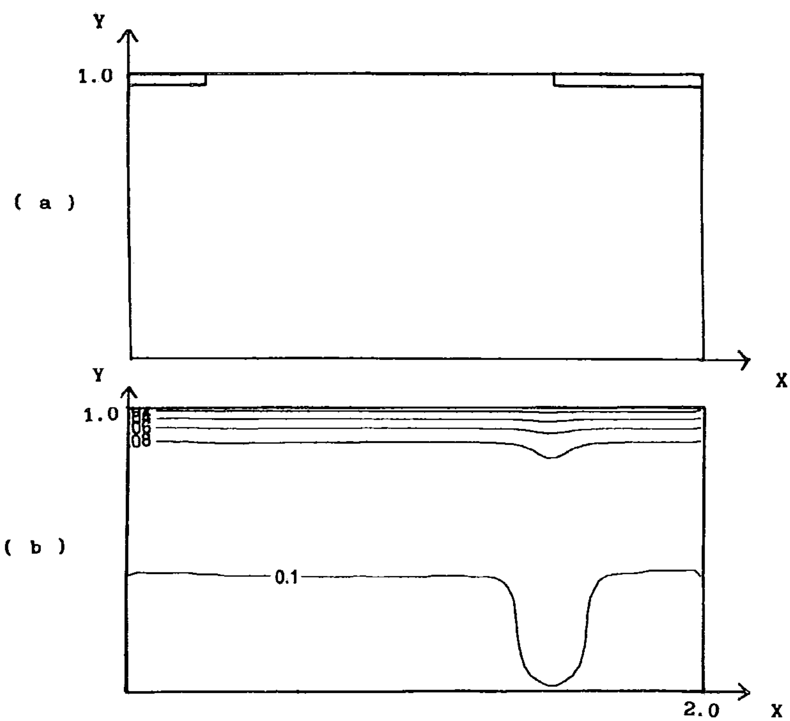

Fig. 2. Initial distribution of Z (a) and temperature (b) chosen for presented model.

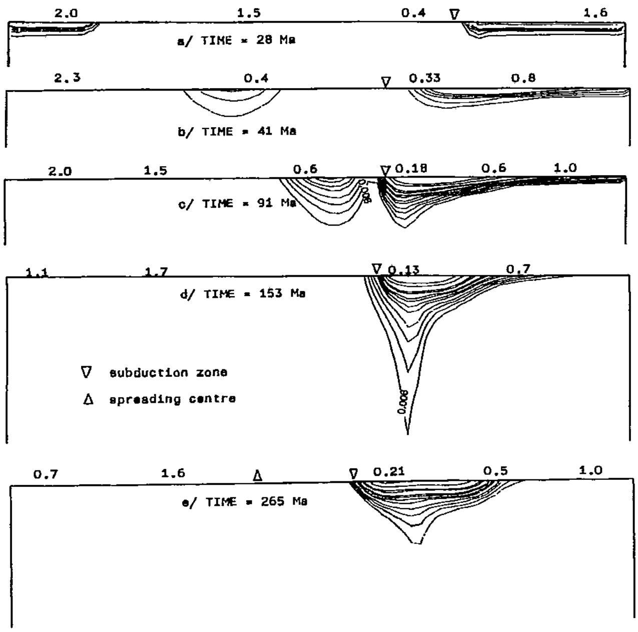

Fig. 3. Five consecutive stages of the collision of two small continents (distribution of Z is contoured). The dimensional time is calculated under the assumption that length of the region is 1400 km (thus depth d=700 km) and $\kappa = 10^{-6}\,m^2/s$. Another scaling is also possible. Subduction zones (∇) and spreading zones (Δ) are indicated. Dimensionless heat flow (numbers) is given in chosen points on the surface. The vertical scale is the same as horizontal. See text for discussion.

Let us consider 5 consecutive stages of the process outlined in Figures 3, 4 and 5.

A) It is an initial period. Low velocity of convection is observed.

B) Very intensive convection. Subduction zone (i.e. descending convection current) originates close to the margin of the right continent. This situation is common in the Pacific (e.g., the Peru-Chile Trench).

C) The continents collide. Large deformation of the continents and deposits between them is observed.

D) The continents are merged. A large amount of low-density material is subducted. Therefore, the velocity of convection decreases.

E) The convection pattern changes significantly. The region of intensive convection moves out of the continent. The isostatical uplift of the continent is observed. This can be interpreted as the final stage of orogenesis. Let us note also the origin of a convection cell with opposite sense of motion (in the left-hand side of Figure 5) and the origin of a spreading center near the continent.

Some conclusions concerning the model can be drawn:

- The deformations of the continents observed before collision are too large. The rigidity of continents should be increased in the model.
- The velocity of convection is too low. The Rayleigh number should be increased.

An interesting feature is the origin of the spreading centre in the last stage (Fig. 3e). The existence of spreading centre in the past could not be easily verified from geological data from continents. Therefore more numerical models should be performed for verification of the existence of the spreading centre. If it is confirmed it should be included in interpretation of the geological data.

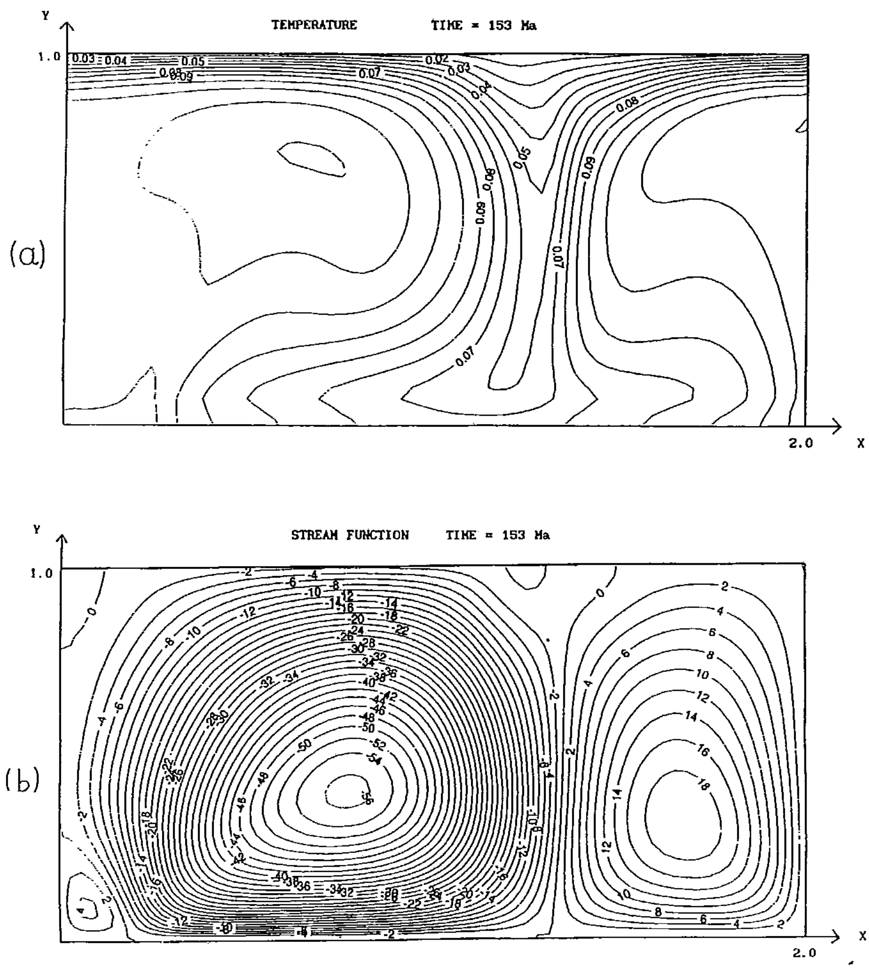

Fig. 4. Isotherms (a) and stream function (b) 153 Ma after the beginning of convection (see Figure 4d for corresponding Z).

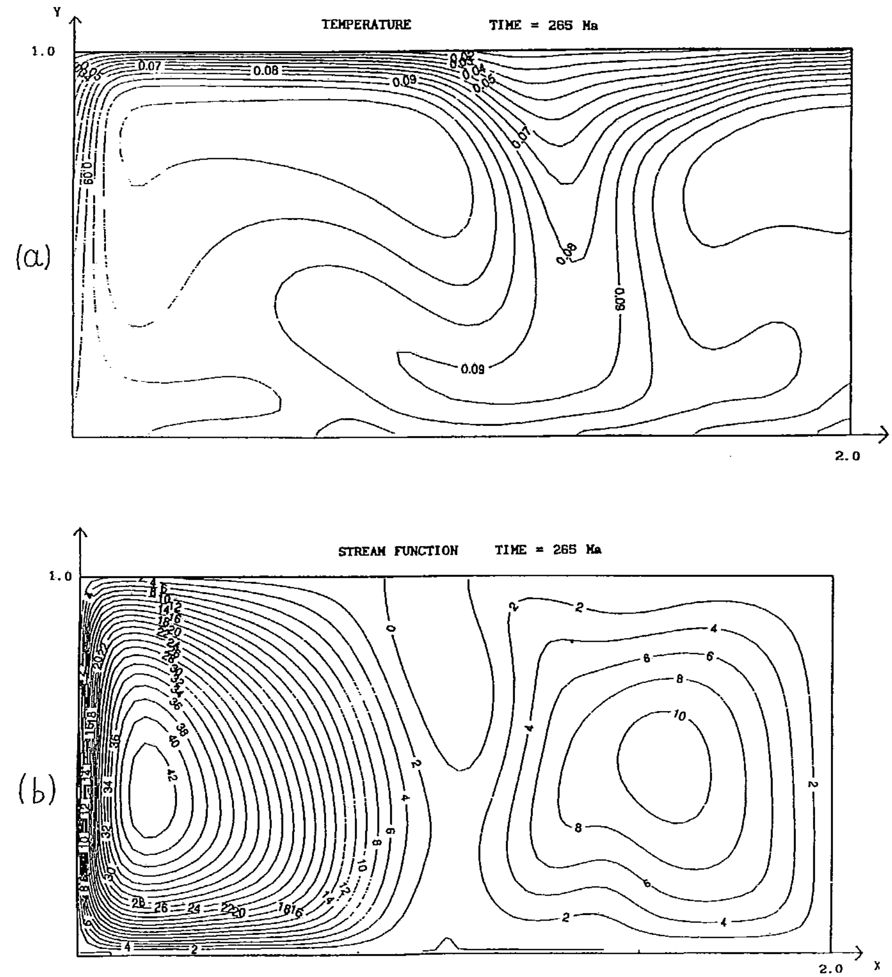

Fig. 5. Isotherms (a) and stream function (b) 265 Ma after the beginning of convection (see Figure 3e for corresponding Z).

6. *Conclusions*

The above discussion indicates that:

1) The resolution of the present mantle convection models enables one to use them for interpretation of regional structures that are a result of subduction or large deformations in the past.
2) Numerical models can be a valuable source of information about the past spreading centres and other structures poorly recognized from geological data. It seems worthful to consider if the geological data from Fennoscandia indicate the existence of ancient spreading centres close to the ancient continent.

3) Success in reproducing geological processes by a given model indicates that mantle parameters are properly chosen. In that way the hypothesis concerning the properties of the early mantle can be verified.

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