Secular Evolution of the Plate Tectonics System in Thermo-chemical Convection Models

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Introduction

Today plate tectonics governs the thermal and compositional evolution of the Earth's mantle, but its role in the long-term evolution of the mantle composition is still unclear. In the opposite direction, the influence of the thermal and chemical evolution of the mantle on the operation of plate tectonics has been studied to some extent, but is far from completely understood.

In this work, we combine previous numerical models of mantle melting and depletion and subduction/plate tectonics to study the mantle evolution by means of numerical modeling of the plate tectonic cycle through the Earth's history. We adress the following questions:

- To what extent does the thermal and chemical evolution of the mantle influence the operation of plate tectonics, both at the production side (ridges) and the subduction side (trenches)?
- Vice versa, to what extent does the operation of plate tectonics influence the thermal and chemical evolution of the mantle.
- How important is the onset timing of plate tectonics in this?

Numerical Model

We use a finite element code based on the commercial package SEPRAN (Segal and Praagman, 2002) to solve for conservation of energy, momentum and mass:

$$\frac{\mathrm{d}T}{\mathrm{d}t} - Di(T+T_0)w = \nabla^2 T - \frac{\Delta S}{c_\mathrm{p}}\frac{\mathrm{d}F}{\mathrm{d}t}(T+T_0) + \frac{Di}{Ra}\Phi + R_\mathrm{H}H \qquad (1)$$

$$\nabla\left[\eta(p,T,\tau,F)\left(\nabla\vec{u} + \nabla\vec{u}^{T}\right)\right] - \nabla\Delta p = \left(RaT + RbF\right)\hat{z} \qquad (2)$$

$$\nabla\cdot\vec{u} = 0 \qquad (3)$$

Convection is driven by temperature differences through the Rayleigh number *Ra*. Additionally, Composition (degree of depletion *F*), described by a set of active particle tracers, interacts through the compositional Rayleigh number *Rb*.

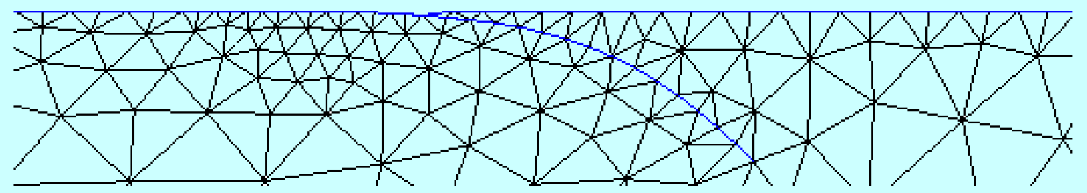
The evolution of the composition field is described by:

$$\frac{\mathrm{d}F}{\mathrm{d}t} = S(P,T,F) \qquad (4)$$

We assume that all melt that is produced is instantaneously transported to the surface, producing a basaltic crust which transforms into eclogite upon reaching a depth of 30 km.

Subduction zones

Subduction zones are incorporated using free slip faults which have a fixed location:



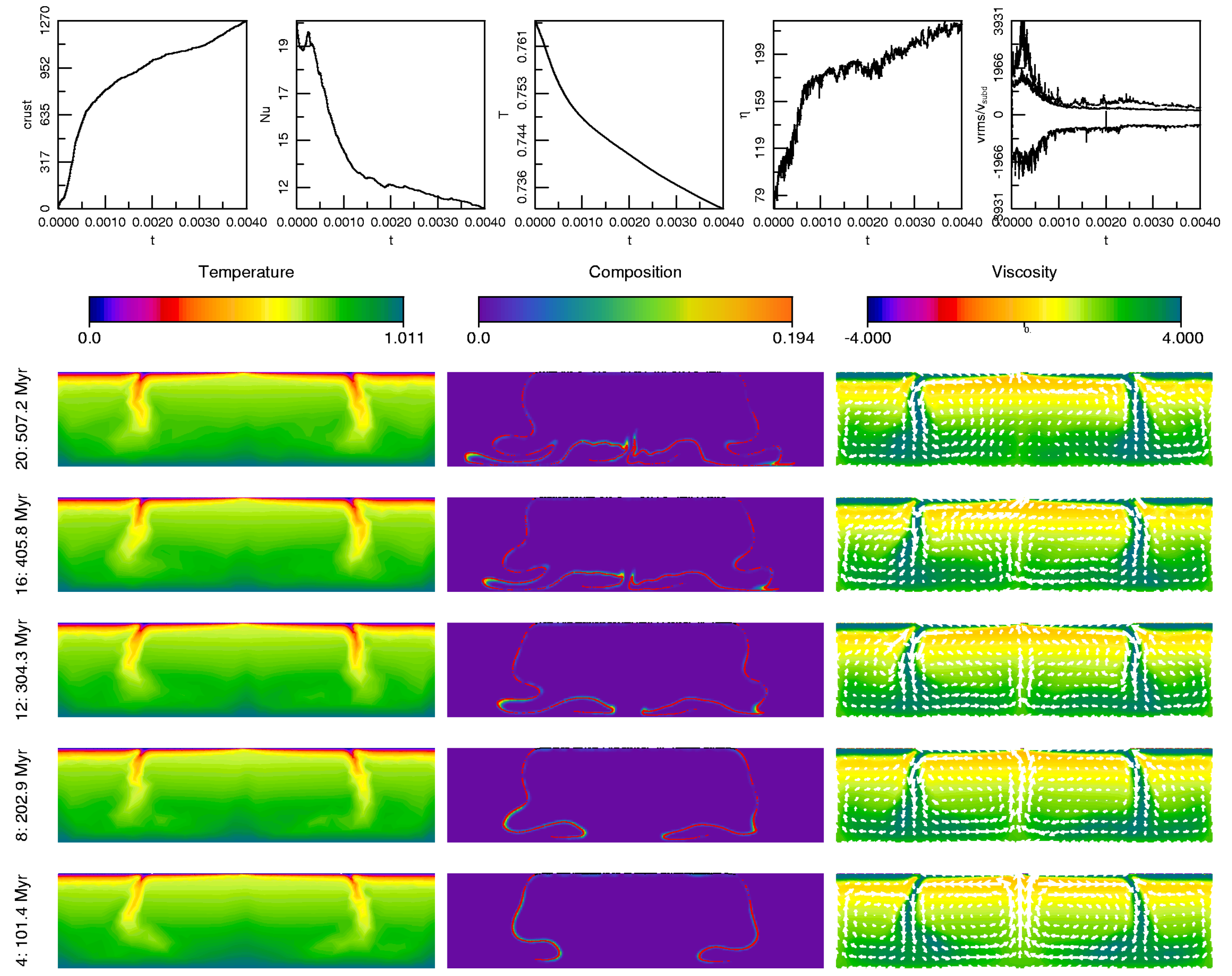


Figure 1: T_{pot} = 1350°C

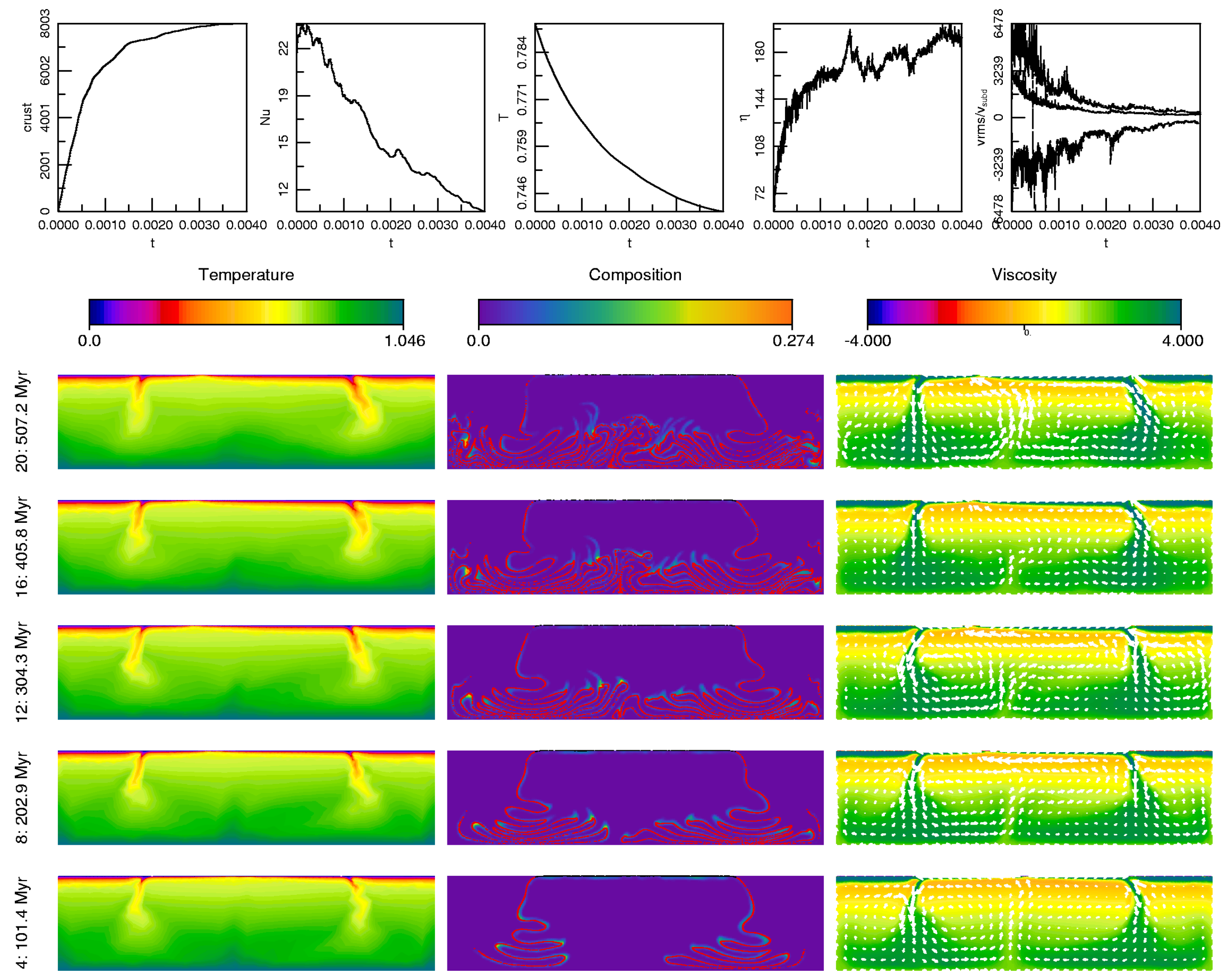


Figure 2: T_{pot} = 1400°C

Mid-Ocean Ridges

MOR's are formed self-consistently by localized shallow upwelling of fertile mantle material. The code includes partial melting and an approximate melt segregation mechanism. This results in partial melting taking place in the upwelling, producing a basaltic crust and a depleted Harzburgitic residue. Continuous removal of the lithosphere from the ridge by the subduction system results in continuous upwelling, partial melting and crust production.

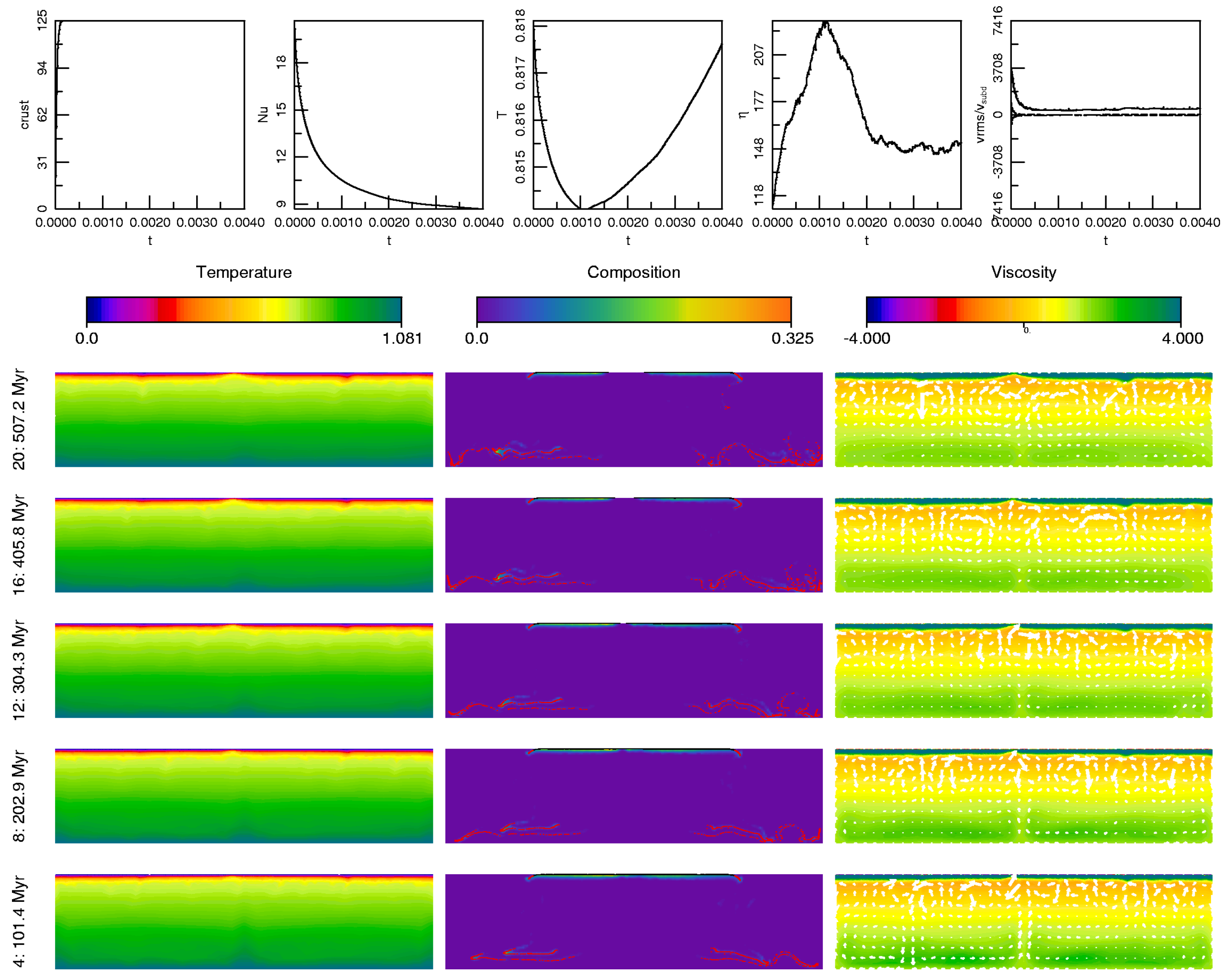


Figure 3: T_{pot} = 1450°C

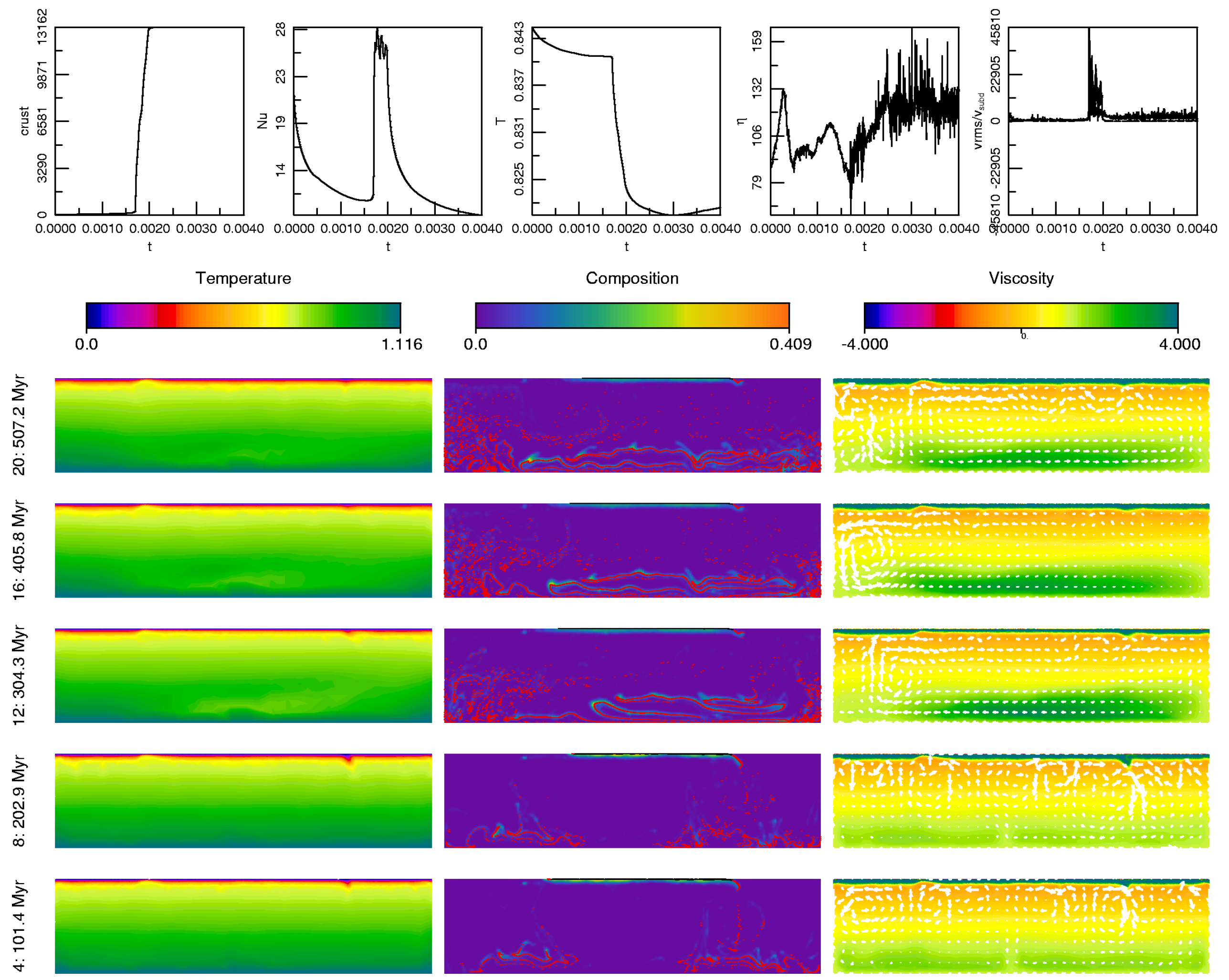


Figure 4: T_{pot} = 1500°C

Rheology

We apply a Newtonian temperature and pressure dependent rheology, using parameter values from Karato and Wu (1993), combined with a stress limiter mechanism which applies Byerlee's law.

Results

Figures 1-4 show the evolution of the temperature, composition, viscosity and flow field for four different potential mantle temperatures of 1350, 1400, 1450 and 1500 ºC,a s well as time series of the cumulative crustal production, Nusselt number, volume averaged temperature and viscosity, root mean square velocity of the entire domain and subduction velocities. In the composition frames, basaltic crust is indicated in black, and eclogite in red. The colour scale indicates the degree of depletion, of mass fraction of melt extracted.

For T_{pot}=1350 and 1400ºC, we see a continuously operating system, in which the rate of convection, subduction and crustal production are steadily declining as a function of the secular decrease of mantle temperature. The latter case clearly has much higher crustal production and subduction rates, which results in the formation of a marble cake type mantle in the lower half of the domain in a 500 Myr period.

When a somewhat higher mantle temperature of 1450ºC is prescribed, the slab becomes too weak to sustain the stress of a full slab, and breakoff occurs a couple of times before the subduction system shuts down. This frequent slab break-off for higher mantle temperatures was also observed in more detailed subduction zone models by Van Hunen and Van den Berg (2006).

The same effect is also observed at even higher mantle temperatures, where the chemical buoyancy of the basalt-harzburgite stratification imposes an additional problem for subduction of the lithosphere. In this case, sections of eclogitized crust may trigger episodic large-scale subduction events which last some tens of Myr, similar to the effect observed in early earth models by Van Thienen et al. (2004).

Preliminary Conclusions

- Continuous subduction and crustal production are characteristic of relatively low mantle potential temperatures (below 1400-1450ºC).
- Rapid subduction at the high temperature range of this interval may cause rapid mantle differentiation.
- For intermediate mantle potential temperatures (around 1450ºC), small sections of slab may subduct, but these rapidly break off.
- High mantle temperatures (above 1450-1500ºC) show episodic subduction of long sections of crust (on the order of thousands of km) on very short timescales (some tens of Myr).

References: S. Karato and P. Wu (1993), Science, 260:771-778. A. Segal and N. Praagman (2002), technical report. J. van Hunen and A.P. Van den Berg (2006), submitted to Lithos. P. van Thienen, A.P. Van den Berg and N.J. Vlaar (2004), Tectonophysics, 386:42-65.

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