Exhumation rates of high pressure metamorphic rocks in subduction channels: The effect of Rheology

T. V. Gerya
Institute of Experimental Mineralogy Russian Academy of Sciences, Moscow, Russia

B. Stöckhert
Institut für Geologie, Mineralogie und Geophysik, Ruhr-Universität Bochum, Bochum, Germany

Received 31 October 2001; revised 31 January 2002; accepted 19 February 2002; published XX Month 2002.

[1] Exhumation of high-pressure metamorphic rocks can take place with typical plate velocities of cm/year. This is consistent with a model of forced flow in a subduction channel. The (micro)structural record of exhumed metamorphic rocks indicates that stresses are generally too low to drive deformation of the bulk material by dislocation creep, according to a power-law rheology. Instead deformation appears to be localized in low-strength shear zones, and is dominated by dissolution precipitation creep or fluid assisted granular flow, implying a Newtonian rheology. 1D modeling shows that the effective rheology of the material in the subduction channel has a significant influence on the rate of exhumation. When the subduction flux either equals or exceeds the return flux, the maximum exhumation rate for Newtonian behavior of the material is at least twice as high ($\sim$1/3 of the subduction burial rate) compared to that for power-law creep ($\sim$1/6 of the subduction burial rate). *INDEX TERMS:* 5120 Physical Properties of Rocks: Plasticity, diffusion, and creep; 8020 Structural Geology: Mechanics; 3210 Mathematical Geophysics: Modeling

1. Introduction

[2] Recent studies on ultrahigh pressure (UHP) metamorphic rocks exhumed from depths of >100 km at subduction zones have shown that (1) exhumation can take place with typical plate velocities on the order of cm/year prior to collision (e.g., [*Gebauer et al.*, 1997; *Amato et al.*, 1999; *Rubatto and Hermann*, 2001]), that (2) in many cases significant cooling takes place during decompression, thus limiting the size of the exhumed UHP metamorphic crustal slices, and (3) that considerable portions of the rocks remained undeformed, indicating that deformation must have been localized in low strength shear zones (e.g., [*Stöckhert and Renner*, 1998; *Renner et al.*, 2001]). In combination, this is consistent with a model of forced flow in a subduction channel (e.g., [*Cloos*, 1982; *Shreve and Cloos*, 1986]), extending to depths of more than 100 km.

[3] As most (U)HP metamorphic rocks show no evidence of deformation by dislocation creep at (U)HP metamorphic conditions, the magnitude of stress must have been generally too low to activate this deformation mechanism. Instead, suspected deformation mechanisms allowing the required high strain rates at low stresses in the subduction channel are dissolution precipitation creep (e.g., (*Rutter*, 1983]) and fluid assisted granular flow [*Paterson*, 1995, 2001], both operative in the presence of aqueous fluids or hydrous melts. Direct microstructural evidence for the predominance of these low stress deformation mechanisms along interplate shear zones in subduction zones is primarily provided by the record of low to intermediate grade high pressure metamorphic rocks (e.g., [*Schwarz and Stöckhert*, 1996; *Stöckhert et al.*, 1997, 1999]). However, it has so far been inferred for ultrahigh pressure (UHP) metamorphic conditions [*Stöckhert and Renner*, 1998; *Renner et al.*, 2001], as there is a lack of direct microstructural evidence probably due to the limited potential for the preservation of an unequivocal record.

[4] Notably, at UHP metamorphic conditions (i.e., at pressures exceeding about 3 GPa and temperatures of over ca. 700°C) complete miscibility exists between silicate melts and hydrose fluids [*Bureau and Keppler*, 1999]. Such supercritical high density fluids have been identified in diamond-bearing inclusions in garnet from ultrahigh pressure metamorphic rocks [*Stöckhert et al.*, 2001], and may be expected to constitute a small but significant component in many rock types at UHP metamorphic conditions (e.g., [*Phillipot and Rumble*, 2001]), resulting in a very low flow strength.

[5] For all kinds of diffusion creep, including dissolution precipitation creep and fluid assisted granular flow, a linear viscous (Newtonian) behavior is predicted, in contrast to the power-law rheology of materials undergoing deformation by dislocation creep (e.g., [*Ranalli*, 1995]). Here we present the results of simple 1D modelling on the influence of rheology on the exhumation rate of high pressure metamorphic rocks in subduction channels.

2. 1D Modeling of Subduction Channel Flow

[6] Figure 1 shows the 1D model of a laminar flow in a planar subduction channel used in our study. Forced circulation of crustal material occurs in a channel of width L, driven by narrowing of the channel at greater depth (e.g., [*Shreve and Cloos*, 1986]). Consequently, circulation is driven by the pressure gradient along the channel. The pressure gradient controls the circulation pattern and the proportion of subduction and return fluxes. The flow pattern across the channel can be described by Stokes equation as follows

$$\partial\sigma_{XZ}/\partial X = E, \qquad (1)$$

where X and Z are coordinates (Figure 1), given in meters; σ_{XZ} is a viscous stress tensor, given in Pa; $E = \partial P/\partial Z - \rho g_Z$ is the effective pressure gradient along the channel, given as $\mathrm{Pa{\cdot}m^{-1}}$; P denotes pressure in Pa; ρ is the density of the material in the subduction channel, given as $\mathrm{kg{\cdot}m^{-3}}$; g_Z is the Z-component of acceleration within the gravity field, given in $\mathrm{m\ s^{-2}}$.

[7] We assume that density variations are small and that the effective pressure gradient, E, does not change across the channel. Also, we assume that temperature and grain size variations across the channel are insignificant, or cancel each other, with a small grain size and/or high temperatures both favoring deformation by grain size sensitive diffusional creep. For the two principal flow regimes relevant in rock rheology at high temperatures, the distribution of σ_{XZ} is given by the

0094-8276/02/2001GL014307$05.00

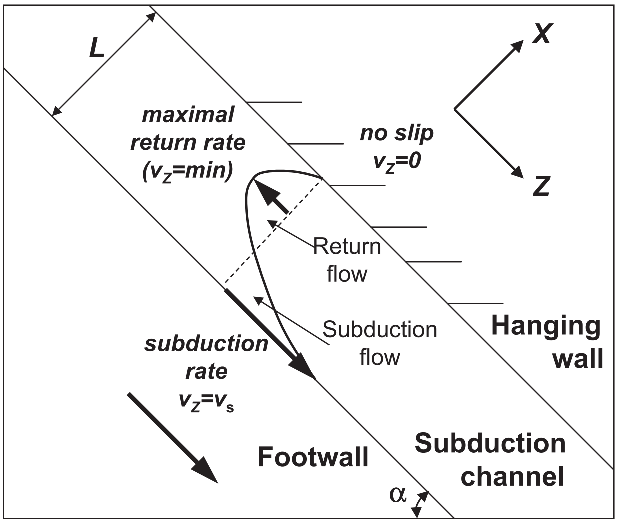

Figure 1. Schematic geometry and boundary conditions of the 1D model for forced flow in a subduction channel.

following relations. For Newtonian flow (diffusional creep, respectively dissolution precipitation creep and fluid assisted granular flow) the relation is

$$\sigma_{XZ} = \eta \partial v_Z / \partial X, \tag{2}$$

where η is the viscosity in Pa·s, v_Z is the Z-component of velocity in m·s^{-1}, and for power-law flow (dislocation creep), with a power-law exponent of 3, the relation becomes

$$\sigma_{XZ} = D(\partial v_Z / \partial X)^{1/3}, \tag{3}$$

where D is a material constant with the dimension Pa·s$^{1/3}$, (e.g., [*Turcotte and Schubert*, 1982; *Ranalli*, 1995]).

[8] Taking equations (2) and (3), and the boundary conditions $v_Z = v_s$ at $X = 0$, and $v_Z = 0$ at $X = L$, where v_s is the subduction rate and L is the channel width (Figure 1), integration of equation (1) gives the following dimensionless velocity, $v_n = v_Z/v_s$, profiles

$$v_n = C_3 X_n^2 + C_4 X_n + C_5 = (1 - X_n)(1 - X_n C_3) \tag{4}$$

for Newtonian flow, and

$$v_n = (1 + X_n C_0)^4 C_1 + C_2 = 1 - \left[1 - (1 + X_n C_0)^4\right] \Big/ \left[1 - (1 + C_0)^4\right] \tag{5}$$

for power-law flow, where $X_n = X/L$ is a dimensionless distance across the channel. $C_0 - C_5$ are dimensionless constants defined by equations

$$\begin{aligned} C_5 &= 1, \\ C_4 &= -(C_3 + 1), \\ C_3 &= L^2 E / (v_s 2\eta), \end{aligned} \tag{6}$$

and

$$\begin{aligned} C_2 &= 1 - C_1, \\ C_1 &= 1 \Big/ \left[1 - (1 + C_0)^4\right], \end{aligned}$$

$$G = C_0^4 \Big/ \left[1 - (1 + C_0)^4\right] = L^4 E^3 / \left(v_s 4 D^3\right), \tag{7}$$

where G is dimensionless constant dependent on C_0.

[9] The maximum dimensionless return velocity v_m (see Figure 1) is defined by the relation

$$v_n = min = v_m \text{ when } \partial v_n / \partial X_n = 0 \tag{8}$$

[10] The proportion of subduction and return fluxes are given by an average dimensionless velocity, v_a, across the channel

$$v_a = \int_{X_n=0}^{1} v_n \mathrm{d} X_n. \tag{9}$$

[11] As follows from equation (9), subduction flux dominates for $v_a > 0$ and return flux dominates for $v_a < 0$. These two different regimes are likely to be applicable for contrasting tectonic situations. For example, $v_a > 0$ should be typical for the case of steady state subduction with partial closure of subduction channel at a greater depth, and $v_a < 0$ should hold for the episodic processes of escape of material from the deeper part of the channel. The transition between these regimes depends both on the physical characteristics of the subduction channel and on the actual state of the subduction system as a whole. Therefore, to isolate effects of the rheology of the subduction channel media on the exhumation of high-pressure metamorphic rocks we compare the same flow regime for the cases of Newtonian and power-law rheology. In the

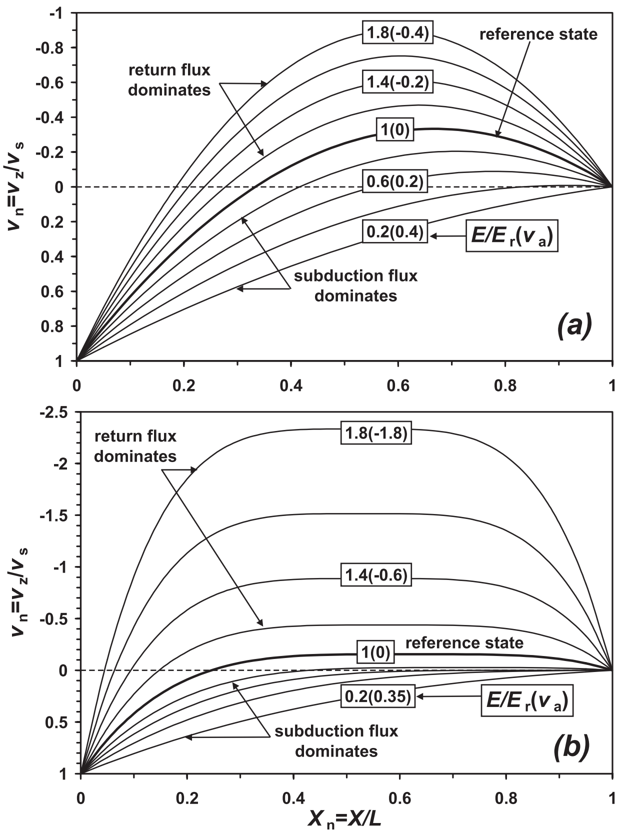

Figure 2. Dimensionless velocity profiles across the subduction channel for (a) Newtonian and (b) power-law flow, calculated using equations (4), (12) for (a) and (5), (13) for (b).

following we consider an intermediate regime of "simple circulation" where subduction flux equals return flux (i.e., $v_a = 0$). For this reference state, solving of equations (4)–(9) yields the following results

$$E_r = C_{3r}(v_s 2\eta)/L^2 = 3(v_s 2\eta)/L^2 \quad C_{3r} = 3, \quad v_{mr} = -0.333 \tag{10}$$

for Newtonian flow, and

$$E_r = G_r\left(v_s 4D^3\right)/L^4 = 7.685\left(v_s 4D^3\right)/L^4 \quad G_r = C_{0r}^4 \Big/ \left[1-(1+C_{0r})^4\right] = 7.685, \quad C_{0r} = -1.606, \quad v_{mr} = -0.156, \tag{11}$$

for power-law flow, where C_{3r}, C_{0r}, E_r, G_r and v_{mr} are the values of correspondent parameters, calculated for the reference state of $v_a = 0$. These results show that the maximum return velocity for Newtonian flow amounts to 1/3 of the subduction velocity. This is approximately twice as high as that for a power-law rheology, where the maximum rate of return flow amounts to only ~1/6 of the subduction velocity.

[12] Figure 2 reveals the dependence of the velocity field on the effective pressure gradient, E, for various proportions of subduction and return flux. The velocity profiles across the subduction channel were calculated using equations (4) to (7), (10), and (11), and defining coefficients C_3 and C_0 as follows

$$C_3 = C_{3r}(E/E_r) = 3(E/E_r), \tag{12}$$

$$G = C_0^4 \Big/ \left[1-(1+C_0)^4\right] = G_r(E/E_r)^3 = 7.685(E/E_r)^3. \tag{13}$$

Figure 2 shows that the velocity profiles obtained for Newtonian flow are characterized by a narrow peak for the return flux. In contrast a broad plateau is obtained for the power-law rheology. This is further visualized in Figure 3, where the maximum return velocity attained for the two types of rheological behavior is shown as a function of E/E_r (Figure 3a) and v_a (Figure 3b). Where subduction flux either equals or exceeds return flux, obviously a common situation in steady state subduction, the return velocity for a Newtonian rheology of the material in the subduction channel is systematically higher by a factor >2 compared to a power-law rheology.

[13] Thus, the rapid exhumation of high pressure metamorphic rocks by forced flow in subduction channels is favored by a Newtonian bulk rheology, consistent with the (micro)structural record of exhumed material. This holds for the case where the subduction flux either equals or exceeds the return flux, which can be assumed to hold for steady state subduction in general (e.g., [*Cloos*, 1982; *Shreve and Cloos*, 1986]), where only a small portion of the subducted material is returned by forced flow within the subduction channel. In this case the magnitude of the exhumation rate, $v_m \sin\alpha$, can be on the order of plate velocity. For the reference situation, where subduction flux equals return flux (i.e., $v_a = 0$), the exhumation rate is between 0.17 to 0.29 of the plate convergence rate, for an inclination of the subduction zone α between 30° and 60°. On the other hand, in the case of episodic exhumation of high pressure metamorphic crustal slices, as considered by *Chemenda et al.* [1995], return flux may significantly exceed subduction flux ($v_a < 0$), although in their model exhumation is driven by buoyancy forces and not by forced flow. If a similar episodic large scale exhumation process occurred in a subduction channel, then — according to our model — a power-law rheology would provide the highest return flow rates. In this case the return rate could even exceed the rate of convergence (Figures 2 and 3). The transition from steady state subduction ($v_a \geq 0$) to episodic exhumation ($v_a < 0$) is likely to be associated with an episodic increase in the effective pressure gradient, e.g., by squeezing of the subduction channel at a greater depth.

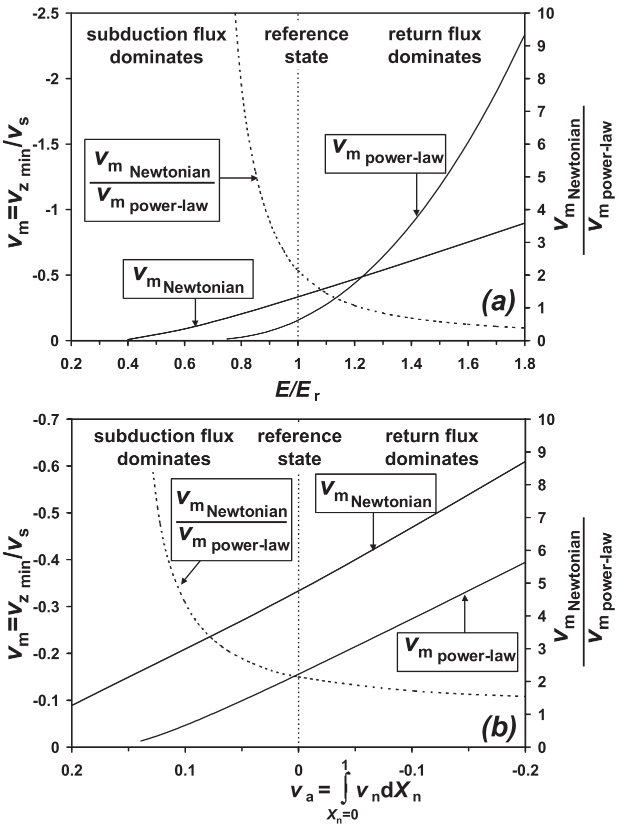

Figure 3. Dependence of the maximum return velocity v_m on the relative changes in effective pressure gradient E (a) and the average dimensionless velocity v_a (b) calculated for Newtonian and power-law behavior of the material undergoing forced flow in the subduction channel.

[14] Finally, the variation of return velocity and shear strain rate across the subduction channel are displayed in Figure 4. The figure shows that the highest rate of return flow occurs where the shear strain rate is minimum. As such, rocks returning with the highest velocity towards the surface are expected to undergo little deformation. This prediction is in accordance with the fact that many high- and ultrahigh-pressure metamorphic rocks exhumed from subduction zones appear to be at best weakly deformed [*Stöckhert and Renner*, 1998; *Renner et al.*, 2001]. Deformation at higher strain rate is concomittant with relatively slower exhumation, and thus the preservation potential of the metamorphic record related to the deepest stage of burial is greatly reduced.

3. Summary and Conclusions

[15] Our simple 1D model indicates that for a subduction channel with forced flow, and when subduction flux either equals or exceeds return flux, the highest rates of return flow are attained for a Newtonian rheology of the bulk material in the subduction channel. Furthermore, the highest rate of return flow is correlated with the lowest shear strain rates, which is consistent with the widespread occurrence of rapidly exhumed but at best weakly deformed (ultra)-high-pressure metamorphic rocks. The high exhumation rates of (U)HP metamorphic rocks on the order of plate velocity thus

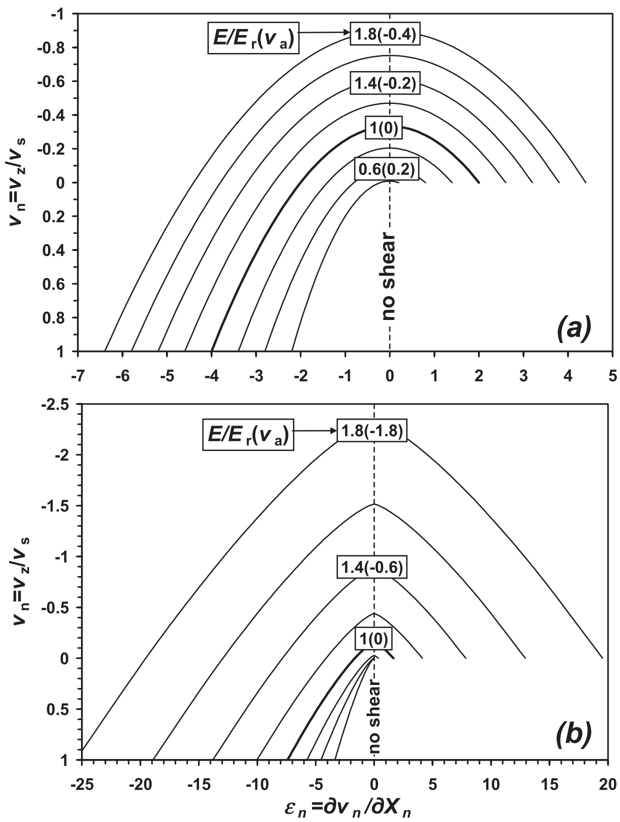

Figure 4. Relation between velocity v_n and shear strain rate $\varepsilon_n = \partial v_n/\partial X_n$ in the subduction channel, calculated for (a) Newtonian behavior using equations (4) and (12), and for (b) power-law flow using equations (5) and (13).

reconcile with the microstructural record of exhumed high- and ultrahigh pressure metamorphic rocks that suggests deformation by diffusion creep, respectively dissolution precipitation creep or fluid-assisted granular flow localized in weak shear zones.

[16] **Acknowledgments.** This work was supported by RFBR grant # 00-05-64939, by an Alexander von Humboldt Foundation Research Fellowship to TVG, and by the Deutsche Forschungsgemeinschaft within the scope of Sonderforschungsbereich 526 "Rheology of the Earth — from the upper crust into the subduction zone" at Ruhr-University. Stuart Thomson is thanked for checking the English. Constructive reviews by Susan Ellis and Shaocheng Ji are gratefully acknowledged.

References

Amato, J. M., C. M. Johnson, L. P. Baumgartner, and B. L. Beard, Rapid exhumation of the Zermatt-Saas ophiolite deduced from high-precision Sm-Nd and Rb-Sr geochronology, *EPSL*, *171*, 425–438, 1999.

Bureau, H., and H. Keppler, Complete miscibility between silicate melts and hydrose fluids in the upper mantle: Experimental evidence and geochemical implications, *EPSL*, *165*, 187–196, 1999.

Chemenda, A. I., M. Mattauer, J. Malavieille, and A. N. Bokun, A Mechanism for syn-Collisional Deep Rock Exhumation and Associated Normal Faulting: Results from Physical Modeling, *EPSL*, *132*, 225–232, 1995.

Cloos, M., Flow melanges: Numerical modelling and geologic constraints on their origin in the Fransiscan subduction complex, California, *Geol. Soc. Am. Bul.*, *93*, 330–345, 1982.

Gebauer, D., H. P. Schertl, M. Brix, and W. Schreyer, 35 Ma old ultrahigh-pressure metamorphism and evidence for very rapid ehxumation in the Dora Maira Massif, Western Alps, *Lithos*, *41*, 5–24, 1997.

Paterson, M. S., A theory for granular flow accomodated by material transfer via an intergranular fluid, *Tectonophys.*, *245*, 135–151, 1995.

Paterson, M. S., A granular flow theory for the deformation of partially molten rock, *Tectonophys.*, *335*, 51–61, 2001.

Phillipot, P., and D. Rumble, Fluid-rock interractions during high-pressure and ultrahigh-pressure metamorphism, *Intern. Geol. Rew.*, *42*, 312–327, 2001.

Ranalli, G., *Rheology of the Earth*, 2nd ed., Chapman and Hall, London, 1995.

Renner, J., B. Stöckhert, A. Zerbian, K. Röller, and F. Rummel, An experimental study into the rheology of synthetik polycrystalline coesite aggregates, *J. Geophys. Res.*, *106*, 19,411–19,429, 2001.

Rubatto, D., and J. Hermann, Exhumation as fast as subduction?, *Geology*, *29*, 3–6, 2001.

Rutter, E. H., Pressure solution in nature, theory and experiment, *J. Geol. Soc. London*, *140*, 725–740, 1983.

Shreve, R. L., and M. Cloos, Dynamics of sediment subduction, melange formation, and prism accretion, *J. Geophys. Res.*, *91*, 10,229–10,245, 1986.

Schwarz, S., and B. Stöckhert, Pressure solution in siliciclastic HP-LT metamorphic rocks — constraints on the state of stress in deep levels of accretionary complexes, *Tectonophysics*, *255*, 203–209, 1996.

Stöckhert, B., H.-J. Massonne, and E. U. Nowlan, Low differential stress during high-pressure metamorphism — the microstructural record of metapelite from the Eclogite Zone, Tauern Window, Eastern Alps, *Lithos*, *41*, 103–118, 1997.

Stöckhert, B., M. Wachmann, M. Küster, and S. Bimmermann, Low effective viscosity during high pressure metamorphism due to dissolution precipitation creep: The record of HP-LT metamorphic carbonates and siliciclastic rocks from Crete, *Tectonophysics*, *303*, 299–319, 1999.

Stöckhert, B., and J. Renner, Rheology of crustal rocks at ultrahigh-pressure, in *When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks*, edited by B. R. Hacker and J. G. Liou, Kluwer Acad. Publ., Dordrecht, 57– 95, 1998.

Stöckhert, B., J. Duyster, C. Trepmann, and H.-J. Massonne, Microdiamond daughter crystals precipitated from supercritical COH silicate fluids included in garnet, Erzgebirge, Germany, *Geology*, *29*, 391–394, 2001.

Turcotte, D. L., and G. Schubert, Geodynamics: Applications of Continuum Physics to Geological problems, John Wiley, New York, 1982.

T. V. Gerya, Institut für Geologie, Mineralogie und Geophysik, Ruhr-Universität Bochum, 44780 Bochum, Germany. (Taras.Gerya@ruhr-uni-bochum.de)

B. Stöckhert, Institut für Geologie, Mineralogie und Geophysik, Ruhr-Universität Bochum, 44780 Bochum, Germany. (Bernhard.Stoeckhert@ruhr-uni-bochum.de)