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

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[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 (~1/3 of the subduction burial rate) compared to that for power-law creep (~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 (UHP) metamorphic rocks show no evidence of deformation by dislocation creep at (UHP) 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 hydrous 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

\[
\frac{\partial \sigma_{XZ}}{\partial X} = E.
\]

where X and Z are coordinates (Figure 1), given in meters; \(\sigma_{XZ}\) is a viscous stress tensor, given in Pa; \(E = \partial P/\partial Z - g_{Z}\) is the effective pressure gradient along the channel, given as Pa·m⁻¹; \(P\) denotes pressure in Pa; \(\rho\) is the density of the material in the subduction channel, given as kg·m⁻³; \(g_{Z}\) is the Z-component of acceleration within the gravity field, given in 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 \(\sigma_{XZ}\) is given by the
following relations. For Newtonian flow (diffusional creep, respectively dissolution precipitation creep and fluid assisted granular flow) the relation is

$$\sigma_{XZ} = \eta \frac{\partial v_Z}{\partial X},$$  \hspace{1cm} (2)

where $\eta$ 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

$$\sigma_{XZ} = D \left( \frac{\partial v_Z}{\partial X} \right)^{1/3},$$  \hspace{1cm} (3)

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

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, $v_n = v/s$, profiles

$$v_n = C_0 X_0^2 + C_4 X_0 + C_3 = (1 - X_0)(1 - X_0 C_3)$$  \hspace{1cm} (4)

for Newtonian flow, and

$$v_n = (1 + X_0 C_0)^4 C_1 + C_2 = 1 - \left[ 1 - (1 + X_0 C_0)^4 \right] / \left[ 1 - (1 + C_0)^4 \right]$$  \hspace{1cm} (5)

for power-law flow, where $X_0 = X/L$ is a dimensionless distance across the channel. $C_0$–$C_5$ are dimensionless constants defined by equations

$$C_0 = 1,$$
$$C_4 = -(C_3 + 1),$$
$$C_3 = L^3 E^3 / \left( \nu_s 2 \eta \right),$$

and

$$C_2 = 1 - C_1,$$
$$C_1 = 1 / \left[ 1 - (1 + C_0)^4 \right].$$

where $G$ is dimensionless constant dependent on $C_0$.

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

$$v_m = \min \text{ when } \frac{\partial v_n}{\partial X_n} = 0$$  \hspace{1cm} (8)

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

$$v_a = \int_{X_n=0}^{1} v_n dX_n.$$  \hspace{1cm} (9)

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

$$G = C_0^4 \left[ 1 - (1 + C_0)^4 \right] = L^3 E^3 / \left( \nu_s A D^3 \right),$$

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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

\[
E_r = C_3\left(\frac{v_e}{2\eta}\right)/L^2 = 3\left(\frac{v_e}{2\eta}\right)/L^2
\]

\[
C_3 = 3,
\]

\[
v_{\text{ref}} = -0.333
\]

for Newtonian flow, and

\[
E_r = G_1\left(\frac{v_e}{2\eta}\right)/L^4 = 7.685\left(\frac{v_e}{2\eta}\right)/L^4
\]

\[
G_1 = C_4\left[1 - (1 + C_4)^4\right] = 7.685,
\]

\[
C_4 = -1.606,
\]

\[
v_{\text{ref}} = -0.156,
\]

for power-law flow, where \( C_3, C_4, E_r, G_1 \) and \( v_{\text{ref}} \) 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 \( \sim 1/6 \) 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 \( C_4 \) as follows

\[
C_3 = C_4\left(\frac{E}{E_r}\right) = 3\left(\frac{E}{E_r}\right),
\]

\[
G = C_4\left[1 - (1 + C_4)^4\right] = G_1\left(\frac{E}{E_r}\right)^3 = 7.685\left(\frac{E}{E_r}\right)^3.
\]

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 \( \geq 2 \) 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, \( v_{\text{ref}}\sin\alpha \), 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 \( \alpha \) 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.

[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 [Stockhert 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
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.

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