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Kinematics and dynamics of tectonic nappes: 2-D numerical modelling and implications for high and ultra-high pressure tectonism in the Western Alps

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A B S T R A C T

We present two-dimensional numerical simulations of lithospheric shortening with a crust containing weak and strong inclusions. Thermo-mechanical coupling is included, and a crustal-scale shear zone develops self-consistently due to viscous heating and thermal softening of temperature dependent viscosities. Several tests for crustal conditions are performed showing that 1) the thickness of and strain rates within the shear zone are independent on the numerical resolution and applied numerical method (finite element and finite difference method), 2) the shear zone is stable and rotates during large strain deformation, 3) the numerical algorithm conserves total thermal and mechanical energies, and 4) the bulk horizontal force balance is fulfilled during large strain deformation. A fold nappe develops around the shear zone in the lithospheric shortening simulation. In this simulation the stresses in the crust are limited by a friction angle of 30°. Significant tectonic overpressure (P_O) occurs in strong lower crustal rocks and in strong inclusions. Significant P_O also occurs in a weak inclusion that is only partly surrounded by strong crustal rock suggesting that a continuous strong "vessel" is not required to generate significant P_O in weak rocks. Maximal values of P_O are ~2.2 GPa with corresponding deviatoric stresses ~1.5 GPa and occur in a depth of ~42 km. Maximal pressure of ~ 3.4 GPa and maximal temperatures > 700 °C occur during the formation of the fold nappe in crustal depth. Synthetic pressure–temperature paths exhibit entire cycles of pressure and temperature increase and decrease, and suggest that crustal rocks in depths < 50 km can reach the ultrahigh pressure metamorphic facies fields. Applications to tectonic nappes with high and ultra-high pressure rocks in the Western Alps are discussed, and a dynamic model for the evolution of fold nappes in the Western Alps is proposed.

1. Introduction

1.1. Conceptual models for tectonic nappes

The Western Alps are a mountain range made of tectonic nappes, and have long been a testing ground for revolutionary ideas in tectonics, such as the nappe theory (e.g. Argand, 1916; Escher et al., 1993; Handy et al., 2010; Trümpy, 1991). There is a general agreement that the overall tectonic structure of the Western Alps represents an imbricate nappe stack, and that the emplacement of the nappes happened in an ordered succession such that the stacked order from top to bottom reflects the palaeogeographic position from internal to external, respectively (e.g. Argand, 1916; Escher and Beaumont, 1997; Handy et al., 2010; Schmid et al., 1996). However, the discovery of high pressure and ultra-high pressure ((U)HP) metamorphism in the Western Alps (e.g. Chopin, 1984) invoked mantle depth tectonism that opened an extensive debate on the dynamics of tectonic nappes. Based on the nappe forming mechanism, the existing tectonic models of convergent orogens can be summarised by a combination of two end-members: 1) thrust and 2) intrusion models (Fig. 1). 1) Thrust models usually approximate the orogen as wedge-shaped continua with a rigid buttress behind and a subducting lithospheric slab beneath (e.g. Brandon, 2004; Konstantinovskaia and Malavieille, 2005; Platt, 1986). In the thrust model the dominant process of nappe formation is accretion of tectonic units from the subducting plate into the above orogenic wedge by thrusting (brittle and/or ductile). This thrusting generates a dominant top-to-the-foreland shear sense in the nappes. In the thrust model the rocks building the orogen remain within crustal depth (say < ~60 km; e.g. Platt, 1986). Exhumed rocks did not subduct significantly into the mantle, and uplift and exhumation of HP rocks occurs by underplating accompanied by isostatic uplift, extension in higher levels of the wedge and erosion (e.g. Platt, 1986). Thrust models can successfully explain the coherent and imbricate nappe stacking and the first-order structural observations in the Western Alps (e.g. Platt, 1986). However, in the last decades the magnitudes of pressure estimated from observed minerals in exhumed rock in the Western Alps has increased steadily (e.g. Agard et al., 2009). It is usually assumed that the pressure estimates

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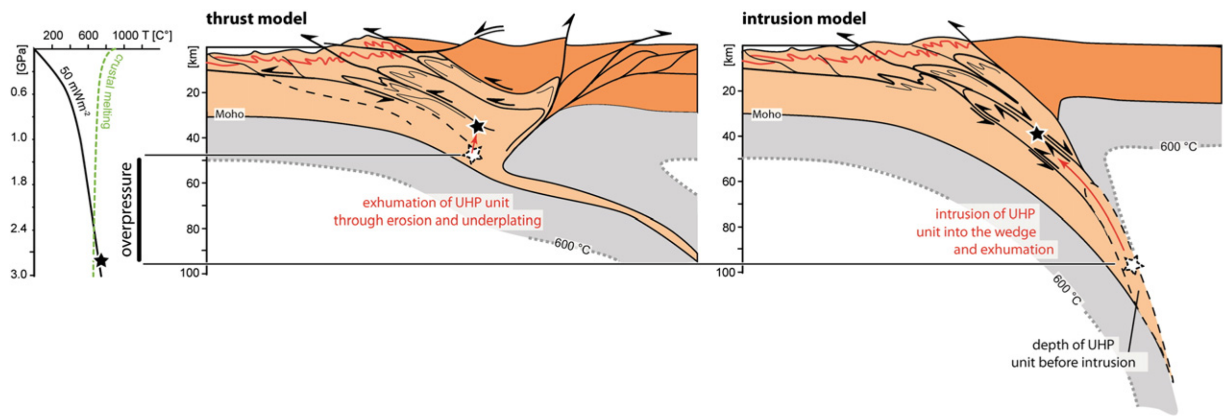

Fig. 1. Sketch of the thrust model and the intrusion model for the formation of a tectonic nappe that exhibits UHP rocks and is situated in an imbricate nappe stack. In the thrust model the nappe exhibits a penetrative top-to-the-foreland shear sense, whereas in the intrusion model the nappe exhibits a major extensional shear zone at the top with a top-to-the-hinterland shear sense. In both models the shearing must be active during the pressure peaks.

from observed (U)HP rocks is close to the lithostatic pressure, and hence that metamorphic pressure is a good indication of maximum burial (Jolivet et al., 2003). The assumption that metamorphic pressure is a good indicator for maximum burial poses a fundamental problem to the thrust model, namely to account for the large burial depth of (U) HP rocks. Maximal pressure estimates in the Western Alps for the Zermatt-Saas "ophiolites" (2.8–3.2 GPa; e.g. Frezzotti et al., 2011; Reinecke, 1991), for the Dora Maira unit (2.8–3.5 GPa; e.g. Chopin, 1984; Rubatto and Hermann, 2001), or for the Adula nappe (~3 GPa; e.g. Nimis and Trommsdorff, 2001, and references therein) indicate depths in excess of 100 km. Nappe formation at these mantle depths cannot be explained anymore by the thrust model because the UHP units intrude into the orogenic wedge from mantle depth. 2) In intrusion models (U)HP rocks are subducted to mantle depths and return to crustal depths usually by buoyancy driven or tectonically forced flow (see Hacker and Gerya, 2013; Warren, 2013, for recent reviews on the formation and exhumation of (U)HP rocks). In intrusion models the nappes are formed during the return flow of the UHP rocks, depicting thrust shear sense at the bottom and normal-fault shear sense at the top of the nappe. In the field, the latter normal-fault shear sense is diagnostic for the intrusion model since it does not form in the thrust model (e.g. Butler et al., 2013; Fig. 1). In the intrusion model the rocks are extruded from mantle depths by channel flow (e.g. England and Holland, 1979) and then intrude as nappes into the structurally higher imbricate crustal nappe stack (e.g. Butler et al., 2013; Escher and Beaumont, 1997). Numerical intrusion models could reproduce the first-order patterns of data-calibrated pressure–temperature (P–T) time paths of the Western Alps (e.g. Butler et al., 2013; Gerya and Stöckhert, 2006; Yamato et al., 2008). However, there are several problems with intrusion models, such as: First, a fundamental kinematic (rheology and driving force independent) feature of the intrusion scenario is the upward movement of tectonic units from depths >100 km that requires the presence of a major extensional shear zone in the hanging wall of each exhuming (U)HP unit (e.g. Butler et al., 2013). However, in several well-studied nappes of the Western Alps exhibiting (U)HP rocks such a major extensional syn-(U)HP shear zone has yet to be identified. By contrast, the earliest and dominant coherent structures recorded along the upper boundary of these (U)HP units are top-to-the-foreland shear zones that are consistent with the thrust model, and were active under amphibolite- or greenschist facies conditions (e.g. Michard et al., 1993, for Dora Maira unit, and Pleuger et al., 2005, for Zermatt-Saas; see also Pleuger and Podladchikov, 2014). Particularly, for the Dora–Maira (U)HP unit Avigad et al. (2003) conclude that 1) all rock units of the Dora–Maira massif were sheared and juxtaposed together within a top-to-the-foreland ductile contractional shear zone, 2) the (U)HP unit was incorporated into the orogenic pile before extension, and 3) the extensional structures in the Western Alps do not define the upper boundaries of tectonic wedges formed during extrusion. Second, numerical intrusion models are often unable to generate a coherent and imbricate nappe stack. For example, the studies of Stöckhert and Gerya (2005) and Gerya and Stöckhert (2006) could reproduce the first-order features of P–T paths of the Western Alps, but the authors also state that the corresponding structural evolution of the orogenic belt in their models is dominated by large-scale curl. Such large-scale curl generates a repetition of tectonic units (nappes) with rocks from the same paleogeographic domain along a section across the orogeny. However, the kinematics of a large-scale curl and the related repetition of tectonic units are in contrast to the observed imbricate nappe stack of the Western Alps. Third, intrusion models often require extremely fast exhumation rates of several centimetres per year as suggested by the estimation from P–T–time data of (U)HP rocks assuming lithostatic pressure; for example ~3.4 cm/yr for the Dora Maira (Rubatto and Hermann, 2001). Ford et al. (2006) show that the exhumation rate required for the Dora Maira unit considerably exceeds the estimated rates of plate convergence of ~5 mm/yr during the time of exhumation. Such high exhumation rates should lead to high erosion rates and elevated upper crustal shortening. In contrast, the reconstruction of Ford et al. (2006) shows that upper crustal horizontal shortening in the North Alpine Foreland Basin is only ~25 km between 35 and 30 Ma what contrasts the ~124 km of horizontal movement estimated from the P–T–time path of the Dora Maira during the same period (assuming a pressure-to-depth relation and a subduction channel dip of ~40°). Ford et al. (2006) suggested tectonic overpressure as one possible solution to this "Dora Maira problem".

1.2. Tectonic overpressure

The major argument against the application of a thrust model to the Western Alps is the assumption that pressure recorded by (U)HP rocks indicates maximum burial depth, and the same assumption is a major argument for an intrusion model. If significant tectonic overpressure (i.e. the pressure deviation from the lithostatic pressure, e.g. Mancktelow, 2008) existed during the evolution of the Western Alps, and if the correspondingly higher-than-lithostatic pressures would have been recorded by exhumed (U)HP rocks, then (U)HP rocks would have formed in significantly less depth, and thrust models including tectonic overpressure could be applicable to the Western Alps (Fig. 1). Therefore, the quantification of tectonic overpressure during tectonic nappe formation is essential to eventually determine whether a thrust model or an intrusion model can better explain the tectonic evolution of the Western Alps.

There is a longstanding debate on tectonic overpressure as a cause of (U)HP metamorphism in crustal rocks. This debate on overpressure is closely related to the strength of rocks or to the magnitudes of differential stress in the Earth's lithosphere (e.g. Kanamori, 1980). From a