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Hydration of the lithospheric mantle by the descending plate in a continent–continent collisional setting and its geodynamic consequences

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ABSTRACT

At the beginning of continent–continent collision the descending plate dehydrates. The influence of this dehydration on the adjacent lithospheric mantle was studied. For this reason, pressure (*P*), temperature (*T*) and *T*-H_2O pseudosections were calculated for an average mantle composition using the computer software PERPLE_X. These pseudosections were contoured by isopleths, for instance, for volumes of amphibole, chlorite, and serpentine. In addition, *P–T* pseudosections were considered for four psammopelitic rocks, common in the upper portion of the continental crust, in order to quantify the release of H_2O in these rocks during prograde metamorphism. At pressures around 1 GPa, a maximum of slightly more than 10 vol.% chlorite, almost 20 vol.% amphibole, and some talc but no serpentine forms when only 1.8 wt.% H_2O is added to the dry ultrabasite at temperatures of 600 °C. For example, hydrous phases amount to about 35 vol.% serpentine and 10 vol.% each of chlorite and amphibole at 1 GPa, 550 °C, and 5 wt.% H_2O. The modelled psammopelitic rocks can release 0.8–2.5 wt.% H_2O between 450 and 650 °C at 0.8–1.4 GPa. On the basis of the above calculations, different collisional scenarios are discussed highlighting the role of hydrated lithospheric mantle. In this context a minimum hydration potential of the front region of the descending continental plate is considered, which amounts to 4.6×10^{16} kg releasable H_2O for a 1000 km wide collisional zone, due to a thick sedimentary pile at the continental margin. Further suggestions are that (1) the lower crustal plate in a continent–continent collisional setting penetrates the lithospheric mantle, which is hydrated during the advancement of this plate, (2) the maximum depths of the subduction of upper continental crust is below 70 km and (3) hydrated mantle above the descending crustal plate is thrust onto this continental crust.

1. Introduction

Different scenarios of continent–continent collision have been proposed over the last decades for various orogens. Usually, a subduction of oceanic crust precedes this collision (scenario I of Fig. 1) and an extended mountain range forms after the beginning of continent–continent collision by thickening of continental crust. An exception could be caused by compressional strike-slip tectonics, that can also lead to a mountain belt albeit narrow as in the New Zealand Alps (e.g., Walcott, 1998), but must not necessarily be the result of former subduction of an oceanic plate. Problematic is, however, the orogenic process directly after the complete subduction of the oceanic plate, i.e. the processes during the contact of the colliding plates and shortly after. In principle, two end-member scenarios are conceivable (scenario II a and b of Fig. 1) both involving the separation of the downgoing oceanic plate from the adherent continental plate. This is the case in the slab break-off model by Davies and von Blanckenburg (1995), which was frequently cited to explain, among others, ultrahigh-pressure (UHP) rocks in denuded orogens. In a corresponding model (scenario IIa of Fig. 1) the separation of the oceanic and continental plates occurs after the continental plate was also subducted for a while to reach depths of at least 90 km to form coesite from quartz, the main criterion for UHP metamorphism. This separation is explained by buoyancy forces of the continental plate which is relatively light compared to eclogitized oceanic crust and (dry) ultrabasic mantle. For this reason, it is also conceivable that the separation process starts already earlier (scenario IIb of Fig. 1) after the tip of the descending continental plate was just in place below the upper continental plate. In this case, rocks of the lower continental plate experienced only high-pressure (HP) but no UHP metamorphism. In addition, the problem, what happens with the overlying

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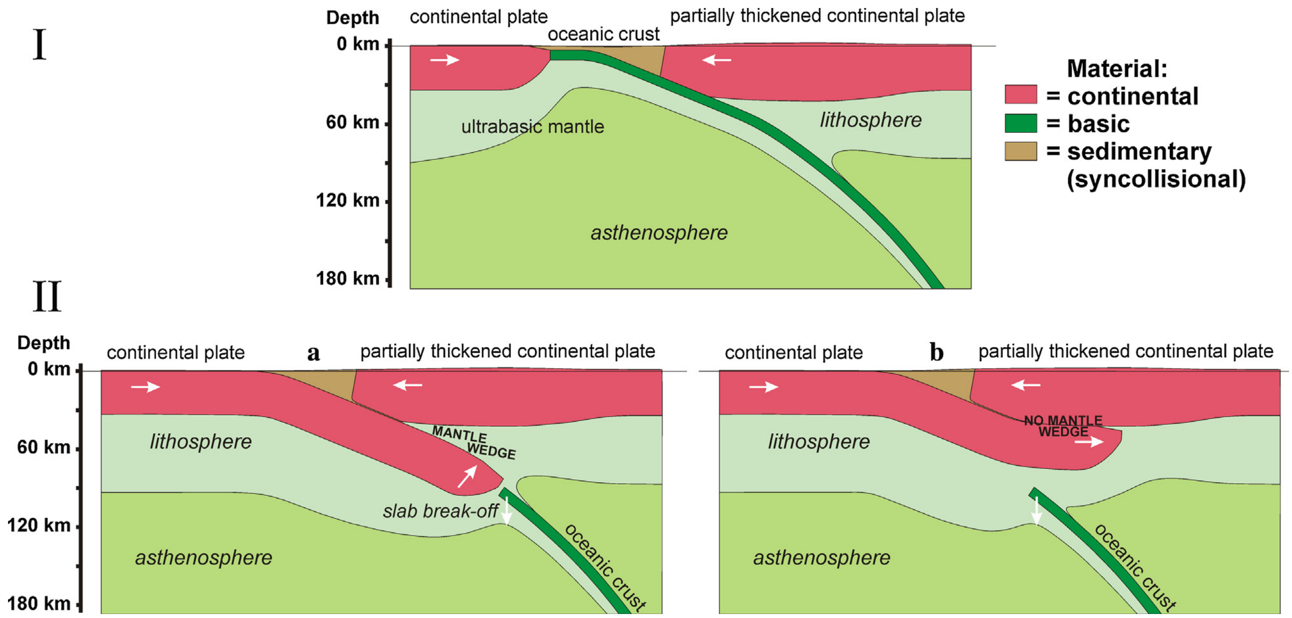

Fig. 1. Geodynamic collisional scenarios shown by two-dimensional profiles (white arrows are related to the relative movement of a crustal segment). Situation before (I) the collision of two continental plates and after (II) this collision. The slab break-off event occurred relatively late (a) or early (b) after the initial continent–continent collision. Situation (a) results in a major lithospheric mantle wedge between the colliding plates whereas this wedge is lacking in (b). The partial thickening of the upper continental plate before continent–continent collision is due to the collision with the subducted oceanic plate during which a continental magmatic arc was formed. Note that no major backthrusting of the material of the lower continental crust is considered here as, for instance, the results of diverse numerical modelling experiments suggest (see text).

mantle wedge during the ascent of the subducted continental crust, is insignificant. But is, for instance, a major displacement of the lithospheric mantle above the relatively deeply subducted continental crust of scenario IIa (Fig. 1) necessary? Attempts to model a collisional scenario similar to that of IIa, for instance, by Stöckhert and Gerya (2005) and Warren et al. (2008), demonstrate that the mass flow of the continental crust after its deep burial is more or less backwards directed as it was earlier suggested by Ernst (2001). Alternatively, crustal material does not (completely) float back but is recycled into the mantle (e.g., Hildebrand and Bowring, 1999; Regard et al., 2003) especially if the density contrast of various common rock types of the continental crust at UHP conditions (e.g. 100 km Earth depth) is taken into account (see Massonne et al., 2007).

In order to distinguish between both scenarios IIa and b and their advancement and to avoid confusion, which scenario is meant later in the text, each of it is related here to a specific term which is "continental subduction" for IIa and "continental underthrusting" for IIb. In spite of the difference between these scenarios, it is obvious that at least the tip of the downgoing continental plate comes in direct contact to the lithospheric mantle of the upper plate so that chemical interactions, in which dehydration/hydration processes are involved, must be considered. The hydration and, thus, the rheology of the ultrabasic mantle in contact with the descending continental plate is an important factor for the above designed collisional developments especially those which follow the scenarios II a and b of Fig. 1. Therefore, weak zones or mantle material with relatively low viscosity, being representative of the hydrated mantle, are usually considered in numerical modelling experiments of collisional scenarios (e.g., Pysklywec et al., 2000; Toussaint et al., 2004; Gerya and Stöckhert, 2006; Beaumont et al., 2009; Burov et al., 2014).

For the understanding of the dehydration/hydration processes isochemical phase diagrams (=pseudosections) were constructed for the here relevant rock types and pressure–temperature (*P*–*T*) regimes up to 2.7 GPa (~90 km depth) and 1000 °C. These rock types are psammopelites on top of the downgoing slab near the interface of continental and oceanic crusts and a common ultrabasite which is hydrated by prograde metamorphism of these psammopelites. In previous works, thermodynamic relations were considered to model the dehydration behaviour of mid-ocean ridge basalt and various metasediments on top of the oceanic crust during subduction either along specific geotherms (Baxter and Caddick, 2013) or over a wide *P*–*T* range (Kerrick and Connolly, 2001a,b; Rüpke et al., 2004; Hacker, 2008; Li et al., 2008; van Keken et al., 2011). In addition, Massonne and Willner (2008) and Massonne (2010) studied the dehydration of such rocks also for low temperatures (150–450 °C) over an extensive pressure range (0.1–2.5 GPa) to better understand the events in the subduction zone near the trench and the build up of an accretionary wedge above this zone. The hydration and dehydration of mantle rocks were thermodynamically calculated by Rüpke et al. (2004), Hacker (2008), and van Keken et al. (2011). Moreover, Magni et al. (2014) modelled the dehydration of an oceanic slab as a function of different subduction velocities.

The here presented new results obtained by pseudosection modelling add to the previous ones, but it was the intention to relate them to a different geotectonic environment compared to that of a subducting oceanic slab. Thus, hypotheses are offered to the reader how a continent–continent collision could further develop after continental subduction or underthrusting.

2. Method and addressed rock compositions

In order to model the interaction of a common lithospheric ultrabasite with water, *P*–*T* pseudosections were calculated with the PERPLE_X computer programme package (see Connolly, 2005; version from August 2011 downloaded from the internet site http://www.perplex.ethz.ch/). For this purpose, the thermodynamic data set of Holland and Powell (1998, updated 2002) for minerals and H_2O (model CORK: Holland and Powell, 1991) was applied. For the calculations, undertaken in the system K_2O–Na_2O–CaO–MgO–FeO–Al_2O_3–TiO_2–SiO_2–H_2O, the following solid-solution models, which are compatible with this data set,