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Invited Review

Rheological and geodynamic controls on the mechanisms of subduction and HP/UHP exhumation of crustal rocks during continental collision: Insights from numerical models

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ABSTRACT

While subduction of crustal rocks is increasingly accepted as a common scenario inherent to convergent processes involving continental plates and micro-continents, its occurrence in each particular context, as well as its specific mechanisms and conditions is still debated. The presence of ultra-high pressure(UHP) terranes is often interpreted as a strong evidence for continental subduction (subduction of continental crust) since the latter is seen as the most viable mechanism of their burial to UHP depths, yet if one admits nearly lithostatic pressure conditions in the subduction interface (or "channel"). The presumed links of continental subduction to exhumation of high- and ultra-high-pressure (HP/UHP) units also remain a subject of controversy despite the fact that recent physically consistent thermo-mechanical numerical models of convergent processes suggest that subduction can create specific mechanisms for UHP exhumation. We hence review and explore possible scenarios of subduction of continental crust, and their relation to exhumation of HP and UHP rocks as inferred from last generation of thermo-mechanical numerical models accounting for thermo-rheological complexity and structural diversity of the continental lithosphere. The inferences from these models are matched with the petrology data, in particular, with P–T–t paths, allowing for better understanding of subtleties of both subduction and burial/exhumation mechanisms. Numerical models suggest that exhumation and continental subduction are widespread but usually transient processes that last for less than 5–10 Myr, while long-lasting (>10–15 Myr) subduction can take place only in rare cases of fast convergence of cold strong lithospheres (e.g. India). The models also show that tectonic heritage can play a special role in subduction/exhumation processes. In particular, when thicker continental terrains are embedded in subducting oceanic plate, exhumation of UHP terranes results in the formation of versatile metamorphic belts and domes and in series of slab roll-back and exhumation events with remarkably different P–T–t records.

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1. Introduction

Continental subduction and the mechanisms of formation and exhumation of UHP rocks are two enigmatic processes that are closely linked together (e.g., Ernst, 2001). From geodynamic point of view, the occurrence of HP–UHP rocks raises two types of questions related to the mechanisms of their burial, and to those of their return to the surface. So far the occurrence of HP–UHP rocks in zones of continental convergence is most often interpreted as evidence for subduction (e.g., Hacker and Gerya, 2013; Kylander-Clark et al., 2011; Smith, 1984). In most cases it is supposedly linked to subduction of passive margins and early stages of intercontinental collision associated with subduction of continental lithosphere (Burov et al., 2001; Burtman and Molnar, 1993; Yamato et al., 2007). In other cases UHP exhumation is produced during late stages of oceanic subduction, during the transition from oceanic subduction to continental collision (Hacker and Gerya, 2013; Angiboust et al., 2009) or when small thick continental terrains (i.e., buoyant microcontinents) embedded in "normal" lithosphere are forced down together with the subducting plate and exhumed as a consequence of slab roll-back (Ernst, 2001; Brun and Faccenna, 2008; Husson et al., 2009; Tirel et al., 2013). More specific mechanisms linked to subduction have also been inferred, yet, for the moment, without quantitative match with in-situ P–T-paths. These include slab "eduction" (Andersen and Austrheim, 2008; Duretz et al., 2012), "subduction erosion" leading to diapiric rise of UHP terranes (Gerya and Stöckhert, 2006; von Huene et al., 2004), and foundering of orogenic roots (Hacker and Gerya, 2013).

It is worth mentioning that alternative "non-lithostatic" interpretations for the occurrence of UHP terranes exist (e.g., Mancktelow, 1995, 2008; Petrini and Podladchikov, 2000; Schmalholz and Podladchikov, 2013; Schmalholz et al., 2014–this volume), suggesting that non-lithostatic overpressure of different nature may alter pressure levels recorded by the UHP material by up to a factor of 2, so that the UHP rocks may be formed at about 50 km depth and hence do not need to be transported to such great "subduction" depths (>100–200 km) inferred from the lithostatic hypothesis. It is hence argued that the occurrence of UHP material does not present evidence for continental subduction and, by extrapolation, that the latter might not exist, or at least is not needed for explanation of the occurrence of the UHP terranes. The overpressure models inherently imply that P–T–t data are of limited use as markers of dynamic processes. Indeed, if subduction does not take place, then overpressure can be build up in the compressed media at levels determined exclusively by the local yield strength and loading conditions, which depend on many uncertain factors such as rheological properties, fluid content, porous pressure, etc., resulting in almost +100% error on depth estimations. Alternatively, full-scale subduction models (e.g., Li et al., 2010; Toussaint et al., 2004a) predict no significant non-lithostatic pressures in non-locked subduction channel (<20% below 50 km depth) allowing for reliable interpretation of P–T/P–T–t data. It should also be emphasized, that the "non-lithostatic" models do not explain why the same P/T gradients are found for both oceanic and continental HP/UHP rocks in a given setting (~8-10°C/km; e.g., Agard et al., 2001) and amongst the various continental subduction regimes (Agard and Vitale-Brovarone, 2013), nor why continental HP/UHP material was only found in places where subducted, dense (oceanic) slab material is imaged by tomography at depths.

At the outcome, elucidation of the mechanisms of formation and exhumation of the UHP rocks is of utmost importance both for understanding the mechanisms of continental convergence (e.g. subduction versus pure shear or folding) and for evaluation of the degree of utility of the petrology data for constraining geodynamic processes.

Indeed, "anti-subduction" models of UHP rock formation (e.g., Petrini and Podladchikov, 2000; Schmalholz et al., 2014–this volume) arise from reasonable doubts in physical plausibility of crustal subduction in continental settings where slow convergence rates and high buoyancy of continental crust are largely unfavorable to subduction processes. Subduction is only one of the four possible mechanisms of accommodation of tectonic shortening (Fig. 1): pure-shear thickening; simple shear subduction or underplating; folding (Burg and Podladchikov, 2000; Cloetingh et al., 1999), and gravitational (Raleigh–Taylor (RT)) instabilities in thickened, negatively buoyant lithosphere (e.g., Houseman and Molnar, 1997) dubbed here "unstable subduction." Whereas in oceans subduction is a dominating mode of accommodation of tectonic compression, in continents all of the above scenarios can be superimposed to some degree. For instance, "megabuckles" created by lithospheric folding (Burg and Podladchikov, 2000) can in theory localize and evolve into mega-thrust zones or result in the development of Rayleigh–Taylor (RT)