Gondwana Research 25 (2014) 464–493

Contents lists available at ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

Mechanisms of continental subduction and exhumation of HP and UHP rocks

Evgene Burov [a,b,*], Thomas Francois [a,b], Philippe Yamato [c], Sylvie Wolf [a,b]

[a] UPMC SORBONNE UNIVERSITES, ISTEP UMR 7193, Université Pierre et Marie Curie, F-75005, Paris, France
[b] CNRS, ISTEP, UMR 7193, F-75005, Paris, France
[c] Géosciences Rennes, CNRS UMR 6118, Université de Rennes 1, 35042 Rennes Cedex, France

ARTICLE INFO

Article history:
Received 9 May 2012
Received in revised form 5 September 2012
Accepted 20 September 2012
Available online 6 November 2012

Keywords:
Continental collision
Subduction
Orogeny
Metamorphism
HP/UHP exhumation
Eclogites
Modeling
Rheology

ABSTRACT

We discuss possible scenarios of continental collision, and their relation to mechanisms of exhumation of HP and UHP rocks, inferred from thermo-mechanical numerical models accounting for thermo-rheological complexity of the continental lithosphere. Due to this complexity, mechanisms of continental convergence are versatile and different, in many aspects from those that control oceanic subduction. Elucidating these mechanisms from conventional observations is difficult, and requires additional constraints such as those derived from petrological data. Indeed, exhumation of HP/UHP rocks is an integral part of convergent processes, and burial/exhumation dynamics inferred from metamorphic *P–T–t* paths provides strong constraints on the collision scenarios. Metamorphic rocks also play an active role due to their contrasting physical properties (rheology, density, fluid transport capacity). Numerical thermo-mechanical experiments suggest that HP/UHP exhumation can only be produced in subduction contexts, as well as that long-lasting (>10 Myr) continental subduction can only occur in case of cold strong lithospheres (T_{Moho}<550 °C, the equivalent elastic thickness T_e>50 km) and of relatively high convergence rates (>3–5 cm yr^{-1}). In this case, high density UHP material in the crustal part of subduction interface provides additional pull on the slab and is not always exhumed to the surface. In case of slower convergence and/or weaker lithosphere (T_e<40 km), continental subduction is a transient process that takes a limited time span in the evolution of collision zone. Under these conditions, hot mechanically weak UHP rocks enhance decoupling between the upper and lower plate while their exhumation may be rapid (faster than convergence rate) and abundant. Therefore, the UHP exhumation paths can be regarded as sensitive indicators of subduction. Rheological changes and fluid exchanges associated with low-to-middle pressure phase transitions along the subduction interface, such as serpentinization during the oceanic phase and schisting, play a major role producing necessarily mechanical softening of the subduction interface and of the hydrated mantle wedge. The oceanic UHP rocks are exhumed thanks to mixing with low-density continental crustal units during transition from oceanic to continental subduction. At the continental phase, the UHP exhumation occurs as a result of a multi-stage process: at the deep stage (<40 km depth) the exhumation is rapid and is driven by buoyancy of partly metamorphosed (or partly molten) UHP material often mixed with non-metamorphosed crustal volumes. At final stages, exhumation takes common slow path through the accretion prism mechanism and the erosional denudation. The experiments suggest that formation of UHP rocks requires that continental subduction starts at higher oceanic subduction rate. It then may progressively slow down until the lockup of the subduction interface and/or slab-break-off. A rate of ~1–2 cm yr^{-1} is generally sufficient to drive continental subduction during the first several Myr of convergence, but pertinent subduction requires faster convergence rates (>3–5 cm yr^{-1}). We suggest that most continental orogenic belts could have started their formation from continental subduction but this process has been generally limited in time.

1. Introduction

In continents, 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 (Cloetingh et al., 1999; Burg and Podladchikov, 2000), and gravitational (Raleigh–Taylor (RT)) instabilities in thickened, negatively buoyant lithosphere (e.g., Houseman and Molnar, 1997) dubbed here "unstable subduction." All these scenarios can be superimposed in nature. For instance, "megabuckles" created by lithospheric folding (Burg and Podladchikov, 2000) can localize and evolve into subduction-like thrust zones or result in the development of Rayleigh–Taylor instabilities. On the other hand, RT and boudinage instabilities leading to slab-break-off may occur in subducting lithosphere when it loses its mechanical strength due to conductive heating from the surrounding mantle (Pysklywec et al., 2000).

General physical conditions for subduction include (1) presence of sufficient slab-pull/push forces, (2) strong mechanical decoupling between the upper and lower plate (i.e., weak subduction interface)

* Corresponding author.
E-mail address: evgenii.burov@upmc.fr (E. Burov).

1342-937X/$ – see front matter © 2012 International Association for Gondwana Research. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.gr.2012.09.010

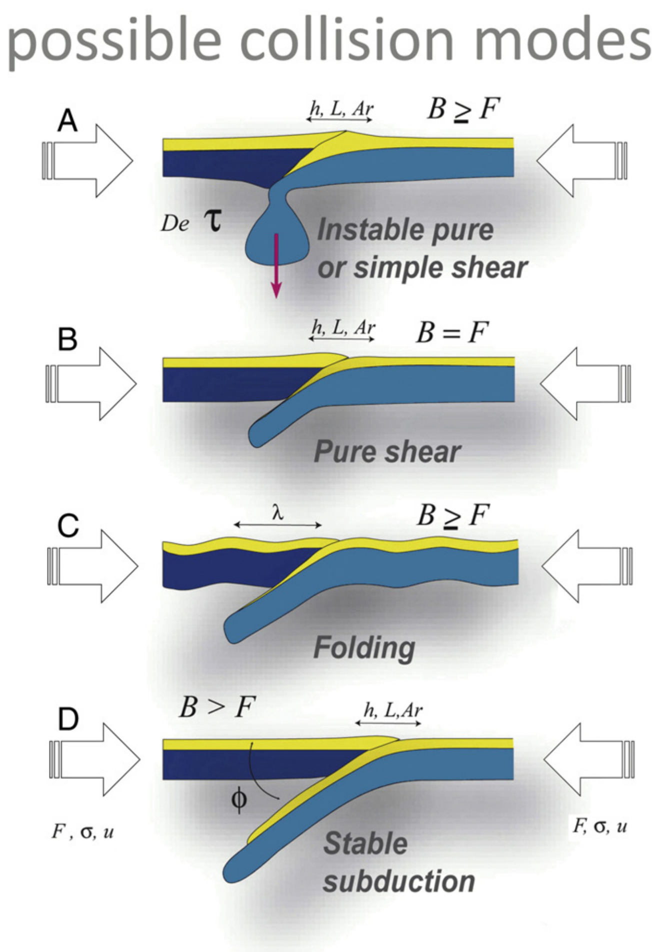

Fig. 1. Possible collision scenarios: (A) unstable (Rayleigh–Taylor) pure or simple shear instability; (B) pure shear in stable mode and (C) unstable mode (folding); (D) simple shear in stable mode (subduction). Related large-scale parameters characterising collision style, lithospheric strength and rheology: T_e, F, σ, u, De, τ_m, h, L, λ, ϕ. T_e is equivalent elastic thickness. F, σ , u are respectively the horizontal force, stress and convergence/extension velocity, that are linked to the lithospheric strength and possible deformation styles. *De* and τ_m are respectively Deborah number and relaxation time related to viscosity contrasts in the lithosphere. λ is the characteristic wavelength of unstable deformation related to the thickness of the competent layers in the lithosphere. h, L are respectively the vertical and horizontal scale for process-induced topography supported by lithospheric strength, Argand number $\mathrm{Ar} = \rho ghL/F$. φ is subduction or major thrust fault angle that is indicative of the brittle properties and of the overall plate strength.

and (3) sufficient mechanical strength of the lower plate assuring preservation of its geometric and mechanical integrity during subduction. Additional mechanisms are also needed for subduction initialization and for downward bending of strong lithosphere when it slides below the upper plate (Cloetingh et al., 1982). In oceans, lithospheric buoyancy and flexural strength (measured in terms of the equivalent elastic thickness, T_e) are functions of plate age and thus of the distance from the ridge (Watts, 2001). Hence, when the lithosphere attains negative buoyancy needed for subduction, it also reaches maximal flexural strength that prevents slab from downward bending (Cloetingh et al., 1982). This controversy has been resolved by showing that pre-subduction bending of the oceanic lithosphere is possible due to localized inelastic flexural weakening, that is, ductile yielding and "plastic hinging" produced by high flexural stresses near the peripheral bulge (Burov and Diament, 1995a, 1995b, 1992; Burov, 2011). Flexural weakening is then enhanced by rheological softening due to metamorphic reactions produced by fluids penetrating in small normal faults created by tensional flexural strains in the upper parts of the peripheral bulge (Faccenda et al., 2009a, 2009b). In continental settings subduction initialization is "natural" since the continental lithosphere follows the path open by the preceding oceanic subduction.

Since the slab pull/push forces can be roughly estimated from gravitational force balance, the most uncertain conditions refer to the mechanisms of weakening of the subduction interface and to the preservation of slab strength during subduction. The former seem to be ultimately related to the metamorphic processes. In oceans, it is already generally agreed that the subduction interface is lubricated due to the presence of serpentinize mantle layer below the oceanic crust and the reactions with free and hydrous fluids released or absorbed during metamorphic reactions (e.g., Guillot et al., 2000, 2001, 2009). In continents, the governing weakening mechanisms are not clear but the presence of thick, relatively weak and rheologically stratified crust as well as strength drops and density changes due to metamorphic transformations also appear to be of primary importance (e.g., Burov et al., 2001a, 2001b; Yamato et al., 2008). Preservation of slab integrity is a major problem for continental subduction, since continental convergence occurs at much slower rates than in oceans. In case of oceanic subduction (at rates of 5–15 cm yr^{-1}), slab has no time to heat up due to the thermal diffusion from the surrounding asthenosphere. As a consequence, it loses its strength only by the moment when it is already sunk to a great depth. In continents, convergence rates are much slower, sometimes not exceeding several mm yr^{-1}. Under these conditions, the lithosphere may heat up, thermally weaken and break-off before it reaches the HP depth.

Despite all complications, continental subduction appears to be a pervasive process, as indicated by geological and geophysical observations (e.g., Ford et al., 2006; Zhang et al., 2009; Handy et al., 2010; Tetsuzo and Rehman, 2011). However, in difference from oceans, here we do not dispose such clear evidences for subduction as Benioff zones, tomographic images of subducting slabs or straight kinematic inferences from paleomagnetic data. In continents, all data are highly "blurred", so that probably the most straightforward evidence for continental subduction refers to the presence of HP and UHP metamorphic material in convergence zones (e.g., Guillot et al., 2000, 2001, 2009; Li et al., 2009; Ernst, 2010; Maruyama et al., 2010; Shigenori et al., 2010; Lanari et al., 2012). The high- to ultrahigh-pressure (HP/UHP) metamorphic belts are believed to be witnessing subduction processes as the exhumed continental blocks appear to bear a strong overprint of the subduction record as they return to surface (e.g. Ring et al., 2007; Zhang et al., 2009; Hacker et al., 2010; Diez Fernández et al., 2012). This evidence is generally preserved in small and disconnected lenses (Teyssier et al., 2010), as mineral relicts within a dominant low- to medium-pressure metamorphic matrix, and more rarely as relatively large HP/UHP units (e.g., Yamato et al., 2008). If one assumes *P–T* conditions inferred for subduction zones, then UHP material should have been buried to depths of 100–150 km and brought back to the surface. Consequently, if the UHP depth estimates are correct (e.g., Spear, 1993), the HP/UHP rocks can be regarded as direct markers of continental subduction and their *P–T–t* paths can be used for reconstruction of subduction dynamics and of the conditions at the subduction interface. Under these assumptions, detailed studies of HP/UHP rocks provide direct constraints on thermo-mechanical processes in subduction zones (Coleman, 1971; Ernst, 1973, 2010). These data would provide insights on mechanisms of exhumation as well, since different processes and contexts would potentially result in different styles of deformation and hence exhumation *P–T–t* paths. In particular, based on the analysis of metamorphic data (Ernst, 2010) it has been suggested that two main types of continental convergence can be distinguished: fast "Pacific underflow" , where continental subduction is preceded by that of thousands of km of oceanic lithosphere, and slow "Alpine closure" of an intervening oceanic basin leading to short-lived continental subduction soon followed by pure shear collision. It has been also pointed out that the exhumed HP–UHP complexes display low-aggregate bulk densities (e.g., Ernst, 2010), while the exhumation rates in some cases largely exceed the convergence rates (e.g., Yamato et al., 2008), jointly suggesting a buoyancy-driven ascent mechanism.