Earth and Planetary Science Letters 377–378 (2013) 114–131

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

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The Alps 1: A working geodynamic model for burial and exhumation of (ultra)high-pressure rocks in Alpine-type orogens

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ARTICLE INFO

Article history:
Received 30 January 2013
Received in revised form 13 June 2013
Accepted 26 June 2013
Available online 30 July 2013
Editor: L. Stixrude

Keywords:
Alps
ultrahigh-pressure metamorphism
exhumation
tectonics
geodynamic modeling

ABSTRACT

Eocene (ultra)high-pressure ((U)HP) rocks exposed in the Western Alps are generally interpreted to result from subduction of European continental crust beneath Adria and its subsequent exhumation. However, the roles of extension (either from plate divergence or internal to the orogen) and erosion during exhumation remain controversial. Here we use 2D numerical geodynamic models to explain the formation and exhumation of (U)HP rocks in an Alpine-type orogen and interpret the results in the conceptual Prowedge–Uplifted Plug–Retrowedge–Conduit (PURC) framework. (U)HP metamorphism of oceanic and microcontinent crust in the models results from burial and accretion to a subduction channel/conduit formed beneath an advancing retrocontinent. Rapid exhumation from (U)HP conditions is achieved by the buoyancy-driven transport of a composite plume of stacked (U)HP oceanic and microcontinent crust from the subduction conduit to the overlying orogenic prowedge, accommodated by coeval thrusting and normal-sense shearing. Subsequent 'trans-crustal' exhumation is achieved by a combination of doming/internal extension and later retrotransport of the (U)HP plume through the uplifted plug, during underthrusting of the thick continental margin crust, coupled with increased erosion. Our proposed mechanism implies that exhumation-related normal-sense shearing in the Western Alps, *per se*, was driven from below by the buoyancy of the ascending plume, and that extension owing to plate divergence is not required to explain (U)HP rock exhumation. The efficiency of the exhumation mechanism depends strongly on the buoyancy and strength of the (U)HP plume, suggesting that in order to exhume rapidly, it must achieve a critical size. By implication, the multiple small Eocene (U)HP complexes within the Internal Crystalline Massifs may have been exhumed as part of a single composite body comprising diverse units aggregated from different levels of the subduction conduit during burial or ascent, rather than as individual small bodies exhumed in separate pulses.

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1. Introduction

Crustal rocks metamorphosed at (ultra)high-pressures ((U)HP), interpreted to imply burial to and exhumation from depths exceeding 90 km, are important features of several Phanerozoic orogens (Chopin, 2003; Liou et al., 2004). Yet the mechanisms by which these rocks are buried, subjected to high pressure and temperature, and subsequently exhumed remain enigmatic. The current consensus (England and Holland, 1979; Chemenda et al., 1995; Ernst and Liou, 1999; Raimbourg et al., 2007; Gerya et al., 2008; Warren et al., 2008a; Beaumont et al., 2009), with some notable exceptions (e.g., Vrijmoed et al., 2009), is that (U)HP rocks form by burial and metamorphism within a subduction channel. Deeply subducted crust may then flow upwards, driven by buoyancy or tectonically induced stresses, to be exhumed by attendant normal-sense shear, horizontal extension, and syn-convergent surface erosion (Gerya et al., 2008; Warren et al., 2008a; Yamato et al., 2008). Alternative exhumation mechanisms include lithosphere-scale extension (requiring plate divergence), diapirism (Little et al., 2011), and eduction (reverse subduction) of the subducted slab (Duretz et al., 2012).

Despite nearly 30 years of study, problems concerning the mechanics of (U)HP rock exhumation remain. These include the following:

1. The style and extent of deformation, and the causes of weakening in the subduction channel (e.g., by fluid, melt, reaction, or strain-weakening mechanisms; Warren et al., 2008a; Angiboust and Agard, 2010; Labrousse et al., 2011);
2. Whether (U)HP terranes form and exhume as intact pieces of crust (Chemenda et al., 1995; Hacker et al., 2010), and/or as assemblages of crustal units juxtaposed during subduction or exhumation (Warren et al., 2008a; Angiboust and Agard, 2010; Gasco et al., 2013);

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http://dx.doi.org/10.1016/j.epsl.2013.06.039

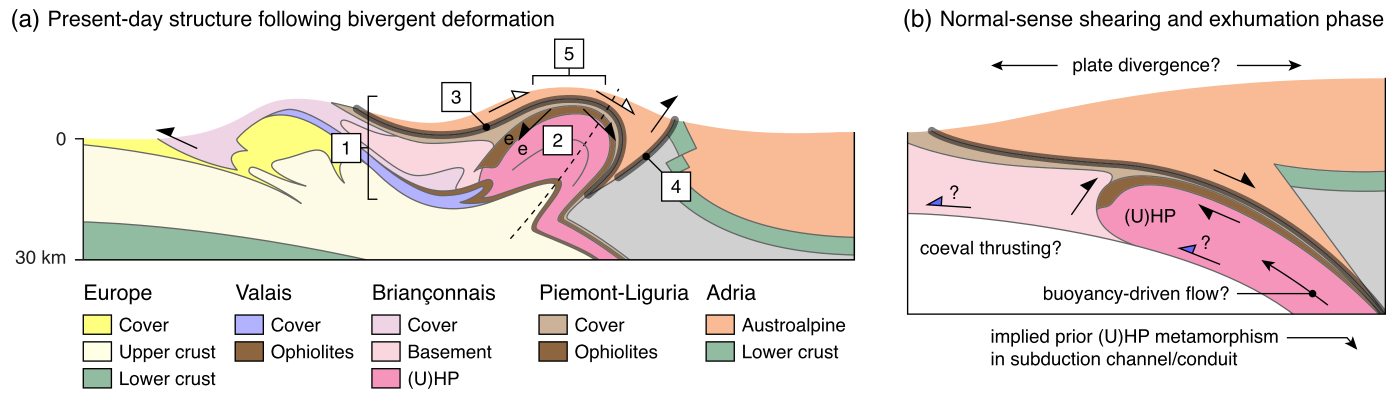

Fig. 1. (a) Generalized cross-section showing key tectonometamorphic features of the Western Alps (modified from Schmid et al., 2004; Gasco et al., 2009; Beltrando et al., 2010). The section is based on the ECORS–CROP transect through the Monte Rosa Massif but is intended to capture the main features of the Western Alps, including: (1) the nappe stack comprising (from top to bottom) more external paleogeographic domains; (2) (U)HP metamorphic rocks exposed in the composite (i.e., comprising stacked units) ICMs (colored '(U)HP') and overlying Piemont–Liguria oceanic units; (3) the approximate position of the top-southeast, normal-sense shear zone separating the exhumed (U)HP units from the overlying greenschist facies units; (4) the backthrust (Insubric Line); and, (5) late normal-sense shear zones, and the domal structure of the ICMs and associated brittle faults. Contacts have implied early top-northwest kinematics related to initial nappe stacking. White-filled arrows show kinematics of top-southeast normal-sense shearing phase. Solid black arrows show later kinematics, with the normal-sense kinematics flanking the ICM schematically representing greenschist-facies normal-sense shear zones and cross-cutting brittle faults (e.g., Avigad et al., 2003; Lardeaux et al., 2006). (b) Schematic representation of normal-sense shearing exhumation phase (modified from Reddy et al., 1999). Grey arrows and text represent contrasting interpretations relating normal-sense shearing alternatively to plate divergence versus internal synorogenic extension (see Section 2 for details).

3. The range of sizes of exhumed (U)HP terranes and the difference in exhumation mechanisms between small and large terranes (Kylander-Clark et al., 2012); and,
4. The relative contribution of erosion versus extension during exhumation, and whether exhumation involves extension at the lithospheric scale (resulting from plate divergence; Fossen, 2010; Malusà et al., 2011), or involves extension from within-orogen normal-sense shearing while plate convergence and shortening continue (Wheeler et al., 2001).

Consequently, there remains a need for quantitative models that fully explore the feedbacks between deep subduction and the overlying lithosphere, including the shallow crustal and surface processes that operate during (U)HP rock exhumation. The model results must also be tested against observations. For clarity, we refer to the two types of horizontal extension as 'lithosphere-scale extension' and 'internal extension', respectively. In the latter case, enhanced shortening elsewhere must compensate for internal extension while convergence continues at the lithospheric scale.

The Western Alpine orogen (Western Alps) (Fig. 1) is a top candidate for constraining such models, owing to the widespread distribution of HP and UHP rocks, and the wealth of data available on its evolution (e.g., Schmid et al., 1996, 2004; Schmid and Kissling, 2000; Steck, 2008). Here, we present results from 2D numerical model experiments designed to explore the geodynamics of (U)HP rock exhumation within an Alpine-type orogen, i.e., one that captures the first-order tectonic characteristics of the Western Alps. Our approach is to develop a general model for Alpine-type orogens, not to simulate any specific Alpine transect, in part because interpretations of Alpine geology are still evolving. In addition, numerical models are inherently simplifications of nature, and so the scale of observations compared with model results must be commensurate with the model resolution. The 1×1 km grid spacing used here can resolve features on the scale of about 3×3 km. Therefore, for comparison with the Western Alps we emphasize the broader tectonics, listed as 'key characteristics' in the next section. Our goal is to understand these basic features.

We interpret the numerical model results, and by implication the Alps, in terms of the 'PURC' geometric/kinematic framework, a generalization of critical wedge mechanics for small orogens (Willett et al., 1993; Beaumont et al., 1999; Butler et al., 2011). The purpose is to represent a complex system in a simple way and to illuminate key features of the model results and, by implication, the Alps. PURC orogens comprise up to four compartments (Fig. 2): two back-to-back orogenic wedges (prowedge, P and retrowedge, R), a central uplifted plug (U), and an underlying subduction conduit (C). The conduit includes the active subduction channel and the region in which material from the subduction channel is accreted to the sides of the channel. The conduit therefore acts as a region below which material is subducted into the mantle, within which material detaches and deforms in the subduction channel, and as a repository where accreted material is stored. This simplifies our original terminology (Beaumont et al., 1999) in that the conduit now includes the active channel. Orogen evolution is described in terms of the formation and transport of crust among these four PURC regions. A PC orogen is one that accretes material to the accretionary/orogenic wedge and subducts material into C (Fig. 2a). Bivergent orogens involve retroward transport of material from P or C, into U, and development of R (Fig. 2b). In PURC terms, (U)HP rocks are subducted into, and stored in C, prior to being exhumed in the PUC′ mode (Fig. 2c), where C′ denotes reverse (upward) flow in the conduit.

2. Key characteristics of the Western Alps

The Western Alps result from a complex paleogeographic and tectonic evolution that culminated in Cretaceous to Tertiary subduction of the Piemont–Liguria Ocean followed by the rifted European margin, including the Briançonnais microcontinent and the Valais 'Ocean' basin, beneath the Adriatic plate, driven by motion of Adria to the north/northwest (Stampfli et al., 1998; Schmid et al., 2004; Rosenbaum and Lister, 2005; Handy et al., 2010). Orogenesis involved an Eocene phase of (north)west-vergent deformation associated with subduction and accretion of oceanic and continental crust beneath the Adriatic plate, and subsequent exhumation of (U)HP rocks to the lower crust. This was followed by an Oligocene phase of bivergent deformation associated with underthrusting of the European margin, local retrotransport and exhumation of (U)HP rocks through the crust, and retrothrusting in the southern foreland (Schmid et al., 1996, 2004).

This evolution involved several key processes (Fig. 1) that successful geodynamic models must explain:

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