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Divergent plate motion drives rapid exhumation of (ultra)high pressure rocks

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ABSTRACT

Exhumation of (ultra)high pressure [(U)HP] rocks by upper-plate divergent motion above an unbroken slab, first proposed in the Western Alps, has never been tested by numerical methods. We present 2D thermo-mechanical models incorporating subduction of a thinned continental margin beneath either a continental or oceanic upper plate, followed by upper-plate divergent motion away from the lower plate. Results demonstrate how divergent plate motion may trigger rapid exhumation of large volumes of (U)HP rocks directly to the Earth's surface, without the need for significant overburden removal by erosion. Model exhumation paths are fully consistent with natural examples for a wide range of upper-plate divergence rates. Exhumation rates are systematically higher than the divergent rate imposed to the upper plate, and the modeled size of exhumed (U)HP domes is invariant for different rates of upper-plate divergence. Major variations are instead predicted at depth for differing model scenarios, as larger amounts of divergent motion may allow mantle-wedge exhumation to shallow depth under the exhuming domes. The transient temperature increase, due to ascent of mantle-wedge material in the subduction channel, has a limited effect on exhumed continental (U)HP rocks already at the surface. We test two examples, the Cenozoic (U)HP terranes of the Western Alps (continental upper plate) and eastern Papua New Guinea (oceanic upper plate). The good fit between model predictions and the geologic record in these terranes encourages the application of these models globally to pre-Cenozoic (U)HP terranes where the geologic record of exhumation is only partly preserved.

1. Introduction

Exhumed slivers of ultra-high pressure (UHP) rocks of continental origin have been found in many localities since their discovery in the 1980s (Fig. 1) (e.g., Chopin, 2003; Guillot et al., 2009). They provide compelling evidence of continental subduction, which is also revealed in seismic sections (Roecker, 1982; Zhao et al., 2015). Exhumation of these rocks to the surface and the processes responsible still remain a matter of debate (e.g., Hacker and Gerya, 2013; Ducea, 2016, and references therein). Quantitative insights are provided by thermo-mechanical numerical models (Beaumont et al., 2001; Li et al., 2011), most of which rely on synconvergent exhumation. These models typically predict the buoyant rapid rise of relatively small (U)HP rock volumes to the base of the crust, followed by slower transcrustal exhumation (e.g., Yamato et al., 2008; Butler et al., 2013), but significant erosion is also required to exhume these rocks to the surface. Models of synconvergent exhumation are therefore inadequate to explain (U)HP terranes that have reached the Earth's surface rapidly, and within a tectonic scenario characterized by negligible erosion during exhumation, such as the Western Alps and eastern Papua New Guinea (PNG) (e.g., Baldwin et al., 2012; Malusà et al., 2015) (Fig. 1). Recent models of trans-mantle diapiric exhumation (Yin et al., 2007) applied to eastern PNG (Ellis et al., 2011) are in conflict with part of the geologic and geophysical record (e.g., Petersen and Buck, 2015; Abers et al., 2016). Alternative hypotheses for (U)HP exhumation that consider divergence within the subduction zone have been proposed since the early 1990s (e.g., Andersen et al., 1991). These include subduction in-

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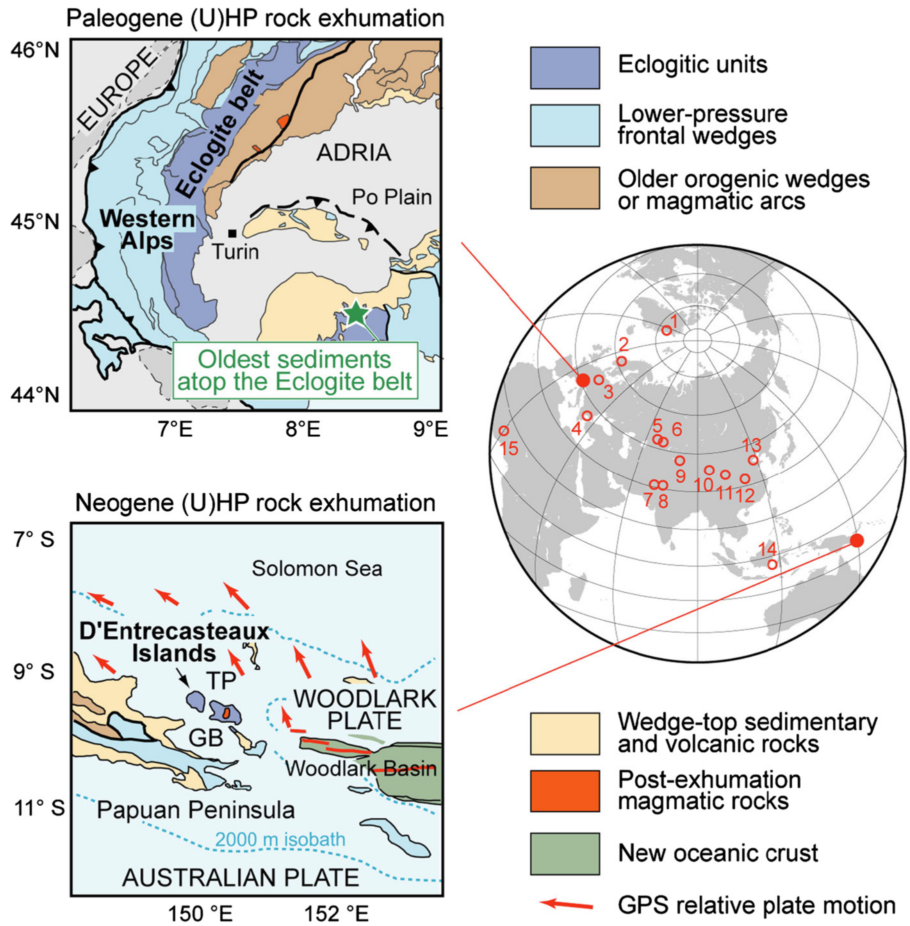

Fig. 1. On the left, tectonic sketch maps of the (U)HP terranes of the Western Alps (after Malusà et al., 2011) and eastern PNG (after Baldwin et al., 2008); GB, Goodenough Basin; TP, Trobriand platform. On the right, location of other UHP occurrences in continental units: 1, East Greenland; 2, Western Gneiss Region; 3, Bohemia; 4, Rhodope; 5, Chara; 6, Kokchetav; 7, Kaghan; 8, Tso Morari; 9, West Tianshan; 10, North Qaidam; 11, Quinling; 12, Dabie Shan; 13, Sulu; 14, Central Sulawesi; 15, Gourma (after Guillot et al., 2009). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

version (Webb et al., 2008), slab eduction after breakoff (Petersen and Buck, 2015), slab rollback (Brun and Faccenna, 2008), and subduction-wedge exhumation triggered by upper-plate divergent motion above an unbroken slab (Malusà et al., 2011). In the eduction model of Andersen et al. (1991), significant erosion of ∼30 km, in combination with tectonic extension, is required to exhume the deepest rocks exposed in the Western Gneiss Region. Slab rollback may explain the multiple exhumation pulses of blueschists in the Mediterranean (Brun and Faccenna, 2008), but this mechanism is not documented for higher pressure belts such as the Western Alps (Malusà et al., 2015). (U)HP rock exhumation triggered by upper-plate divergent motion above an unbroken slab, first proposed in the Western Alps (Malusà et al., 2011), is potentially consistent with the geologic record of several (U)HP belts worldwide, including eastern PNG where (U)HP exhumation is active. However, the ability of this mechanism to exhume large volumes of (U)HP rocks without the requirement of significant erosion, and in the absence of slab breakoff, has never been investigated using numerical methods.

The objective of this paper is to evaluate (U)HP rock exhumation due to upper-plate divergent motion above an unbroken slab using a 2D thermo-mechanical numerical model. Results indicate that upper-plate divergent motion can trigger rapid exhumation of large volumes of (U)HP rocks directly to the Earth's surface, without the requirement of significant overburden removal by erosion. This mechanism produces the main tectonic structures observed in most continental (U)HP belts, and may provide insight for the exhumation of many (U)HP terranes worldwide.

2. Rationale and geodynamic framework

Orogenic belts associated with former subduction of continental rocks may preserve an accurate geologic record of (U)HP rock exhumation. The Paleogene Western Alps in southern Europe and the Neogene D'Entrecasteaux Islands of eastern PNG (Fig. 1) provide two examples of terranes that include (U)HP rocks of continental origin (Compagnoni, 2003; Baldwin et al., 2012). The Western Alps, also include (U)HP metaophiolites (e.g., Groppo et al., 2009). We focus our attention on the exhumation of continental (U)HP rocks, which is invariably very rapid in these two examples (Rubatto and Hermann, 2001; Baldwin et al., 2004). In our numerical models, we consider subduction beneath a continental upper plate, as observed in the Western Alps, and beneath an oceanic upper plate, as observed in eastern PNG (Fig. 1). While a perfect fit of the 2-D models with natural examples should not be expected due to the influence of trench-parallel plate motion (e.g., Baldwin et al., 2012; Malusà et al., 2015), the 2-D models reproduce the main geologic features observed in both (U)HP belts. These include:

a) Continental (U)HP rocks are exhumed within tectonic domes bounded by extensional shear zones (e.g., Hill, 1994). These domes are located at the rear of an accretionary wedge that includes lower-pressure metamorphic rocks (Malusà et al., 2011; Webb et al., 2014) (Fig. 1).
b) Both in the Western Alps and eastern PNG, (U)HP rock exhumation takes place when formation of the lower-pressure frontal wedge is complete. Available geologic constraints sug-