A plate tectonics oddity: Caterpillar-walk exhumation of subducted continental crust

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ABSTRACT

Since plate tectonics began on Earth, grandiose "subduction factories" have continually shaped the continents, accreting continental blocks and new crust at the convergent plate boundaries. An enigmatic product of subduction factories is the high-pressure to ultrahigh-pressure (HP-UHP) metamorphic crustal rocks, regurgitated to Earth's surface, sometimes from depths as great as 200 km. The Aegean backarc domain comprises two continental blocks that underwent HP metamorphism during the subduction of the African plate. Here, we use thermomechanical numerical simulations to show that subduction of small continental-lithosphere blocks separated by oceanic domains induces variations in the slab buoyancy, giving rise to episodic rollback-exhumation cycles. The single, self-consistent numerical model successfully reproduces the major structural patterns and pressure-temperature-time paths of HP rocks across the Aegean. We suggest that the "caterpillar walk" of exhuming HP rock units, revealed by our simulations, is a fundamental mechanism behind HP exhumation globally.

INTRODUCTION

Subduction of continental crust (Molnar and Gray, 1979) is increasingly accepted to be a common process inherent to tectonic plate convergence. However, large tracts of subducted continental crust have been exhumed, sometimes rapidly, back to the surface as high-pressure to ultrahigh-pressure (HP-UHP) metamorphic belts (Ernst et al., 1997; Chopin, 2003). The mechanism of the exhumation remains a subject of controversy (see recent reviews by Hacker, 2007; Burov and Yamato, 2008; Agard et al., 2009; Guillot et al., 2009; Vanderhaeghe, 2012, and references therein). Recent modeling studies of subduction processes associated with slab rollback (Faccenna et al., 2001; Royden and Husson, 2009) and their potential impact on HP rock exhumation (Brun and Faccenna, 2008; Husson et al., 2009; Bialas et al., 2010) suggest that they may hold the key to the puzzle. Here, we present the first numerical model that captures, in its entirety, the complex dynamic process comprising the subduction of a lithospheric plate with microcontinents, slab rollback, HP exhumation, and metamorphic-core-complex development.

Aegean Tectonics

The structural complexity of subducting plates, in particular the presence of small continental blocks within them, influenced the Tertiary evolution and rate of retreat of the subduction zones in the Mediterranean Sea; it must also have had an effect on HP rock burial and exhumation cycles (Brun and Faccenna, 2008) (Fig. 1). The Aegean Sea's three main continental blocks—Adria, Pelagonia, and Rhodopia—were once separated by the Pindus and Vardar Oceans, their closure being recorded in the Pindus and Vardar suture zones (Figs. 1A and 1B). Following the Vardar Ocean closure, Pelagonia subducted below Rhodopia, with thrusting ending at 60–55 Ma (Burchfiel et al., 2008). In the middle Eocene, after the Vardar suturing was complete, Pelagonia

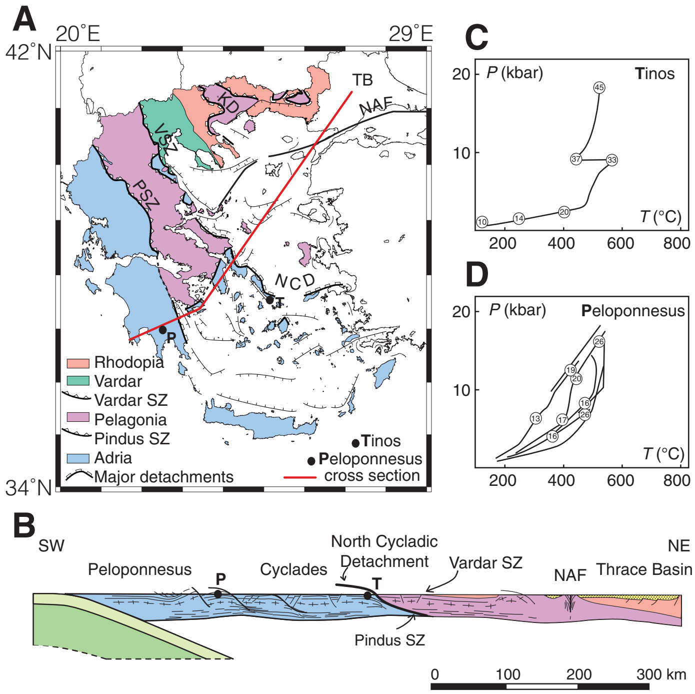

Figure 1. Tectonic setup of the Aegean and pressure-temperature-time (*P-T-t*) paths of high-pressure rocks. The three main continental blocks and other major features of the Aegean are shown in map view (A) and in cross section (B). SZ—suture zone; KD—Kerdylion Detachment; VSZ—Vardar suture zone; PSZ—Pindus suture zone; NCD—North Cycladic Detachment; NAF—North Anatolian fault; TB—Thrace Basin. *P-T-t* paths are from northwest Cyclades, Tinos (Parra et al., 2002) (point T) (C), and from Peloponnese (Jolivet et al., 2003) (point P) (D). Times (in Ma) are circled.

and the oceanic blueschists of the Cyclades began to exhume. With the Pindus Ocean now subducting, Pelagonia and Rhodopia have undergone extension since 45 Ma, and high-temperature (HT) core complexes have developed in northern Greece and southern Bulgaria (Brun and Sokoutis, 2010; Jolivet and Brun, 2010).

The eclogites and blueschists in the northernmost Cyclades Islands derive from Pindus oceanic material and were exhumed in two stages, first from the mantle to lower crustal depths (45–37 Ma) and then up to upper crustal levels (Jolivet et al., 2003) (30–14 Ma) (Fig. 1C). The blueschists atop Adria's granitic basement were subducted below Pelagonia until the middle Eocene in the Cyclades and until the Oligocene in Peloponnese and Crete, where they recorded pressures of up to 17 kbar at ca. 26 Ma and reached upper crustal depths at ca. 12–10 Ma (Jolivet et al., 2010) (Fig. 1D).

In the second, late Oligocene stage of their exhumation—during the subduction of the Mediterranean oceanic lithosphere—the HP rocks of the Cyclades, Peloponnese, and Crete formed a flat-lying domain of HP

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metamorphic rocks, over 250 km in width (Fig. 1B). Since 15 Ma, the entire Aegean domain has been affected by distributed extension, with deposition of sedimentary basins (Mascle and Martin, 1990).

We perform numerical simulations with FLAMAR (Burov and Yamato, 2008), state-of-the-art thermomechanical code that handles large strains and realistic elasto-visco-plastic rheologies (see the GSA Data Repository[1]). P-wave tomography (Wortel and Spakman, 2000) shows that the docking and subduction of continental blocks in the Aegean are related to the subduction of a single lithospheric slab (van Hinsbergen et al., 2005). We thus assume an initial geometry with an already initiated oceanic subduction and with two blocks of continental crust, with dimensions constrained by the volume of exhumed terrains, located on the subducting plate, each destined to be accreted to the overriding plate in the course of the experiment (Fig. 2A at 0 m.y.; Fig. DR1 in the Data Repository). Subduction is unforced, i.e., driven solely by the gravitational slab pull force.

RESULTS

Figure 2A shows the step-by-step evolution of the model at the upper-mantle scale. Two continental blocks are subducted and then exhumed one after the other during the continuous retreat of the subduction zone (see also Movie DR1 in the Data Repository). It is noteworthy that the subduction of a continental block induces an increase in the slab dip angle and a decrease in the subduction velocity, due to the change in slab buoyancy (Martinod et al., 2005; Royden and Husson, 2009). The slab breaks at the former location of the continental block.

The structural development associated with the two subduction-exhumation cycles is summarized in the key snapshots in Figure 2B. Pressure-temperature (*P-T*) paths through time (*t*) of material points within block 2 are illustrated using colored markers (Figs. 2B and 2C). At 6.1 m.y. after the start of the experiment, the subducting slab drags down the tip of the overriding plate, inducing asthenospheric ascent

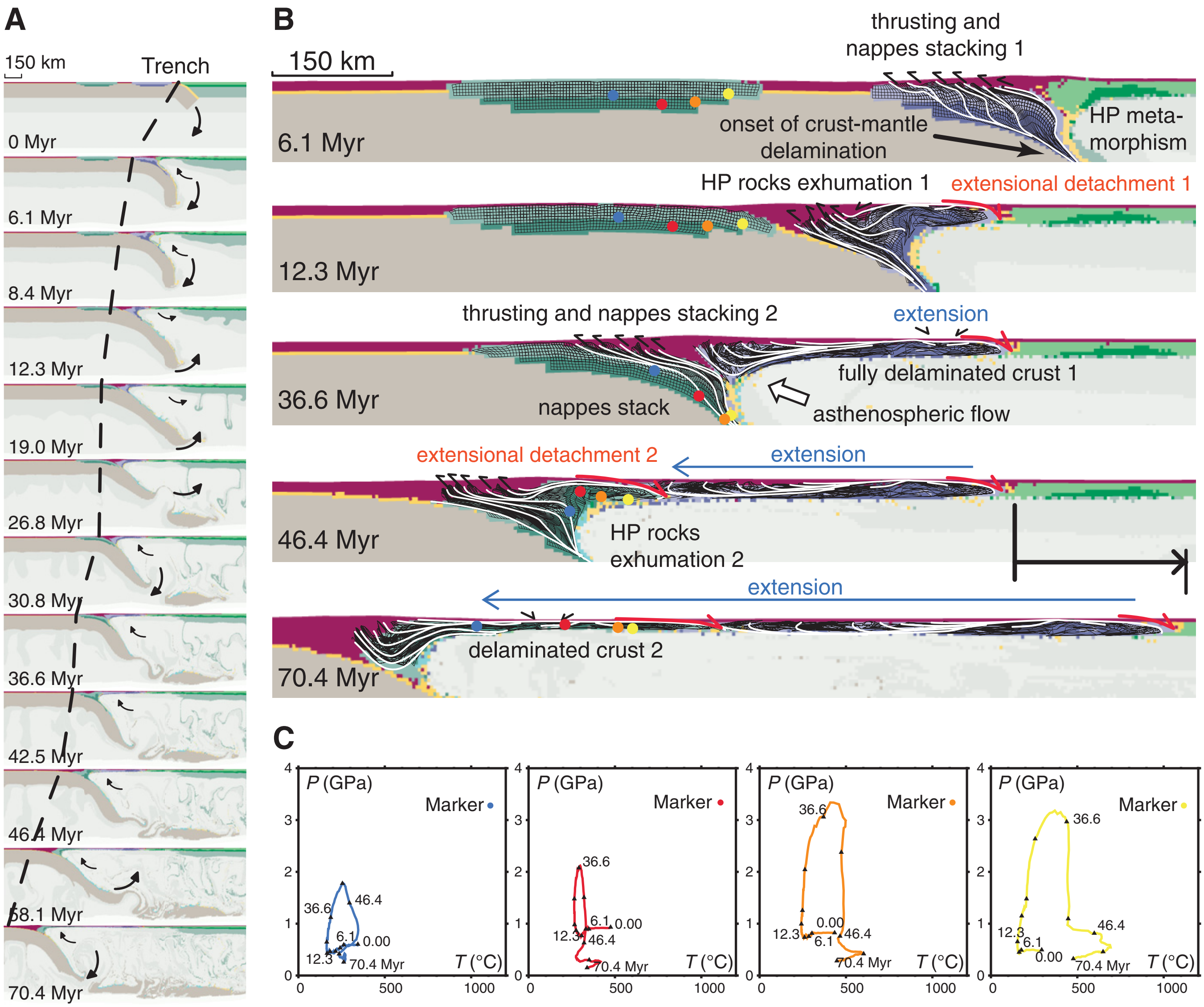

Figure 2. Step-by-step development of the subduction-exhumation cycles. A: The evolution at the lithosphere and upper-mantle scale (gray is subducting lithosphere mantle). Dashed line shows retreat of the trench. B: Zooms to block deformation during the subduction-exhumation cycle (lithosphere mantle is marked in gray). Interpreted shear zones are plotted with white lines. HP—high-pressure. C: Pressure-temperature-time (*P-T-t*) paths of the color-coded markers shown in B.

[1]GSA Data Repository item 2013155, numerical method, supplemental figures, and Movie DR1 (movie of the experiment), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

below the extending overriding continental lithosphere. Slab rollback, driven by the negative slab buoyancy, is responsible for the upper-plate extension. The subducting continental block reaches HP-UHP metamorphic conditions and is progressively delaminated from the mantle lithosphere, as it is accreted beneath the accretionary wedge. Despite the deep burial, continental-crust rocks remain cold, partially insulated from the warm asthenosphere by the lithospheric-mantle material of the upper plate that is dragged down (Movie DR1), as already suggested by Hacker (2007) (Fig. 2). The delaminated rear part of the subducting block then moves back to the surface along an extensional detachment that reactivates the suture zone, while the front part continues to move downward (12.3 m.y.), to be exhumed later. On the way back to the surface, the crustal blocks undergo reverse rotation, and the lower crust is exhumed to the surface. When at the surface, the blocks are delaminated completely from the underlying lithospheric mantle, and the asthenosphere flows into the wedge that opens (36.6 m.y.). During the exhumation process (6.1–36.6 m.y.), the block-scale deformation mimics one step of a caterpillar walk, with the block's tail slipping along a basal décollement, approaching the head, and making a large buckle, which then unrolls as soon as the entire block is delaminated. This caterpillar-walk process is accommodated structurally by stacking of thrust slices at the rear of the block and followed by extensional detachment at the rear when the thrusting reaches the front of the block. When exhumed completely, the block that has been accreted to the overriding plate undergoes extension almost along its entire length. It is noteworthy that small slices of oceanic lithosphere that are thrust on top of the continental-block rear are then exhumed together with the continental block. These oceanic slices correspond to ophiolites and undergo HP-UHP metamorphism prior to their thrust emplacement atop continental crust at the surface.

When block 2 enters the subduction zone, it undergoes subduction and exhumation like block 1 before it (Fig. 2A; 36.6–70.4 m.y.). The ascent of asthenosphere due to slab dip increase causes strong heating and thermal weakening of the first exhumed continental block. Consequently, the exhumed block 1 undergoes extension during the exhumation of block 2, with extensional reactivation of thrust faults and development of HT metamorphic core complexes (MCCs). The yellow marker (Fig. 2) shows an isobaric heating reaching 700 °C at ~1 GPa. Pervasive flow in the middle and lower crust accommodates considerable stretching, allowing the Moho to remain flat, as observed in MCCs (Tirel et al., 2008).

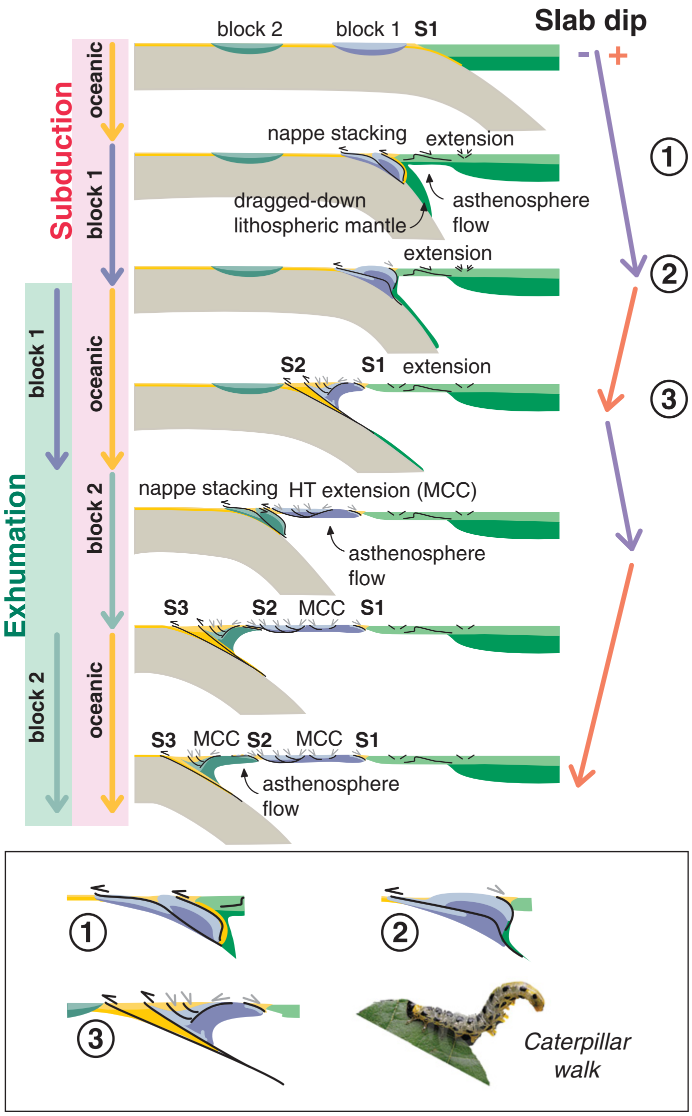

Figure 3. Summary of the revealed relationship between the continental-block subduction and caterpillar-walk exhumation, slab dip changes, and crustal deformation. Numbers "1", "2", and "3" indicate turning buckles in the caterpillar walk of the exhuming crustal block. S—suture; HT—high-temperature; MCC—metamorphic core complex.

DISCUSSION

The modeled deformation sequence during subduction-exhumation cycles of continental blocks (Figs. 2 and 3) shows remarkable similarity to the evolution of the blueschist and eclogite units of the Adria block (Fig. 1):

1. Thrust emplacement of HP ophiolites over continental crust at the block rear is observed in the northwest Cyclades (Avigad et al., 1997; Jolivet et al., 2003; Jolivet and Brun, 2010; Philippon et al., 2011).

2. The stacking of thrust slices starting at the block rear and propagating forward directly corresponds to middle Eocene thrusting in the Cyclades (Avigad et al., 1997), ending in the Oligocene in the external Hellenides (Jolivet et al., 2003; Jolivet and Brun, 2010).

3. Block exhumation accommodated by extensional reactivation of the suture zone—coeval with the last stages of thrusting at the block front (Brun and Faccenna, 2008; Jolivet and Brun, 2010)—is illustrated by the reactivation of the Vardar suture zone at the front of the Adria block (relative to its entrance in subduction) (Fig. 1).

4. Partial melting and HT core-complex development in the exhumed block is observed, for example, in Naxos, central Cyclades (Gautier et al., 1993; Vanderhaeghe, 2004; Duchêne et al., 2006).

5. Pervasive flow in the lower crust associated with MCC development in the Cyclades is evidenced by seismic anisotropy (Endrun et al., 2011).

6. Distributed extension of the exhumed block is seen in the widespread development of sedimentary basins across the Aegean since the late Miocene (Mascle and Martin, 1990).

7. The modeled *P-T-t* paths closely match those observed in the northern Cyclades (including the isobaric increase of temperature at the Adria block front [Parra et al., 2002]; Fig. 1C) and in Peloponnese (Jolivet et al., 2003; Jolivet and Brun, 2010) (Adria block rear; Fig. 1D).

Our numerical experiments show that the subduction of small continental blocks, as documented in the Mediterranean, is followed by a rapid exhumation of HP metamorphic belts, enabled by slab rollback (Brun and Faccenna, 2008; Husson et al., 2009; Bialas et al., 2010; Vanderhaeghe, 2012). As noted above, the continental rocks stay cold during burial due to their insulation from the warm asthenosphere by lithospheric-mantle material dragged down from the upper plate (Hacker, 2007) (Fig. 3; Movie DR1). Because it is the space created by the trench retreat that allows the block to reach the surface, the exhumation of the block, driven by its positive buoyancy, is controlled by the velocity of the trench retreat. Tectonically, exhumation promoted by slab rollback invokes extensional reactivation of a suture zone and accounts for the emplacement at the surface of HP rock units, with a horizontal envelope at regional scale, that keep their lithological and stratigraphical continuity over long distances (several hundred kilometers) along the direction of trench retreat. Our results also cast doubt on the common view that HP rock exhumation must necessarily occur during continental collision (see Hacker, 2007) (Fig. 1). Subduction of a small continental block that rapidly returns to the surface as subduction continues does not indicate, strictly speaking, a collisional setting. Until now, this has been difficult to establish because HP units exhumed in this way are often overprinted by later continental collision. The tectonic setting of the early Mesozoic blueschist-bearing Qiangtang metamorphic belt, in central Tibet, appears comparable to the situation observed in the Mediterranean (Kapp et al., 2003). We also suggest that the Oligocene exhumation of HP-UHP metamorphic rocks in the Alps (Rubatto and Hermann, 2001; Chopin, 2003) occurred prior to collisional shortening and was driven, presumably, by slab rollback. We are convinced that the same could likely hold in several other mountain belts, including the Himalayas or Hercynides.

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