The consequences of crustal melting in continental subduction

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ABSTRACT

Orogens grow in part by thrusting and burial of continental crust, in some cases, into the mantle by continental subduction. Deeply buried continental crust may partially melt during ascent, adding magma to the overlying continental crust, creating a continental plateau, and accounting for the large melt volumes observed in modern and ancient orogens. Thermal-mechanical models support a link among continental subduction, melting, and crustal flow in the overriding plate and show that partial melting may be a significant process in exhumation of ultrahigh-pressure (UHP) rocks and orogenic evolution in general. In Cordilleran orogens, the overriding plate is hot and thin and includes a back-arc region favorable for crustal-scale thrusting and high-temperature metamorphism. Collisional orogens have thicker lithosphere and experience lithosphere-scale thrusting and deeper burial of continental crust. In either case, the ultimate fate of continental crust is partial melting, the depth of which controls the processes and rates of crustal differentiation and exhumation. This paradigm relates continental subduction and crustal melting to lower-crustal flow and plateau development in the overriding plate and explains the presence of UHP rocks in migmatite and granite and their occurrence in the overriding plate of some orogens.

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INTRODUCTION

Despite its low density relative to mantle rocks, continental crust subducts into the mantle and returns to Earth's surface (Chopin, 1984). This process has operated in most Phanerozoic collisional orogens and continues into the present (Searle et al., 2001). In the past 25 yr, much attention has been given to documenting ultrahigh-pressure (UHP) mineral assemblages, including those containing coesite and diamond, and to determining possible mechanisms and rates of exhumation (Chemenda et al., 1995; Gerya et al., 2002; Gerya and Stöckhert, 2006). A missing factor in these discussions has been an evaluation of melting during continental subduction and the consequences of deep crustal melting for exhumation of subducted continental crust and for the orogenic evolution of the nonsubducting plate. Using a thermal-mechanical model and natural examples, we discuss the consequences of continental subduction-related crustal melting for the evolution of orogens.

In many exhumed orogens, migmatite terrains contain 20–40 vol% of crystallized melt, much of which is crustally derived (Teyssier and Whitney, 2002). These observations are consistent with geophysical studies that indicate the possibility of large amounts of partial melt in active orogens (Nelson et al., 1996). The mechanisms by which such large amounts of melt are generated must involve dehydration melting reactions that are likely driven by heating and/or decompression, but it is unlikely that such large amounts of melt can be generated via classic models of crustal thickening and thermal relaxation (e.g., England and Thompson, 1984). Models for deep crustal heating therefore commonly invoke replacement of colder upper mantle by hotter convecting mantle (e.g., by delamination or slab break-off), driving melting in the lower continental crust.

We explore an alternative model that involves partial melting of subducted continental crust, a scenario for which there is increasing evidence (Zhong et al., 2001; Labrousse et al., 2002; Whitney et al., 2004a; Lang and Gilotti, 2007), although, at present, there are only a few studies in which geochronologic data show that magmatism and UHP metamorphism occurred contemporaneously (e.g., Wallis et al., 2005). In continental subduction, melt may be generated in the deep section of the continental slab and enhanced by decompression melting when the buoyant crust ascends. The partially molten material may continue to rise buoyantly within the crust, creating migmatite diapirs (gneiss domes) and granitic intrusions within an overall context of lateral (channel) flow and orogenic plateau development.

NUMERICAL EXPERIMENTS

Previous numerical modeling studies have investigated the rates and mechanisms of continental subduction and have revealed the importance of ductile return flow of subducted material (Burov et al., 2001; Gerya et al., 2002) and the competition between subduction (downward) and buoyancy (upward) forces (Warren et al., 2008). Numerical models help predict the likely modes by which continental slabs respond to thermal relaxation, partial melting, and viscous and gravitational forces. The purpose of our two-dimensional (2-D) numerical experiments is to investigate how a single continental slab evolves under the action of buoyancy forces, viscous forces, and partial melting. No kinematic or dynamic conditions are applied to the sides of the model, and we disregard erosion.

We use Ellipsis, a Lagrangian integration point finite-element code, to solve the governing equations of momentum, mass, and energy in incompressible flow (Moresi et al., 2003; O'Neill et al., 2006). We summarize here the main model characteristics; details about density, rheology, and thermal structures, including parameter values, are in a supplementary

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document.[1] Our model is made of visco-plastic material, and we use a temperature- and stress-dependent viscosity for stresses below the yield stress and a depth-dependent plastic branch above the yield stress. For the continental crust and the mantle, we use dislocation creep parameters of quartz-rich rocks and olivine, respectively (see supplementary material [[see footnote one]). In our models, the rheology of crust also involves diffusion creep, since this mechanism of deformation becomes important under low differential stress, high-temperature conditions, and when partial melt is present. The geotherm results from radiogenic heat production in the continental crust, a constant mantle heat flux, and a constant temperature at the surface. Each material has a solidus and liquidus over which its viscosity linearly decreases over two orders of magnitude for the mantle (Hirth and Kohlstedt, 2003) and three orders of magnitude for the crust (e.g., Richet and Bottinga, 1995). The bulk of the decrease occurs between 3% and 8% melt for the mantle and between 20% and 30% melt for the crust. Significant weakening likely occurs at ~7% melt (Rosenberg and Handy, 2005). From the solidus to the liquidus, the density decreases by 13% for both the crust and the mantle; given the melt fractions reached in our models, density commonly drops by less than 5%.

Our model starts with a continental slab having a tip that reaches 110 km depth (Fig. 1). The thermal state of the slab results from a far velocity field that pushes the continental lithosphere at a velocity of 7 cm/yr, a reasonable rate based on modern plate-velocity measurements. Models run at slower rates (e.g., 2 cm/yr) do not differ significantly from the results for the 7 cm/yr rate. No force other than gravity is applied to the model. This is a simplified case in which the continental slab stops at 110 km, such as might occur when shortening steps over to another zone; model results are also applicable to the case where the subcrustal mantle continues subducting, as Moho temperatures would remain essentially the same. Our interest is in the dynamic behavior of the continental part of the slab when it stops subducting and is subjected to thermal relaxation and partial melting associated mainly with internal heat generation and conductive heating from the overlying mantle wedge.

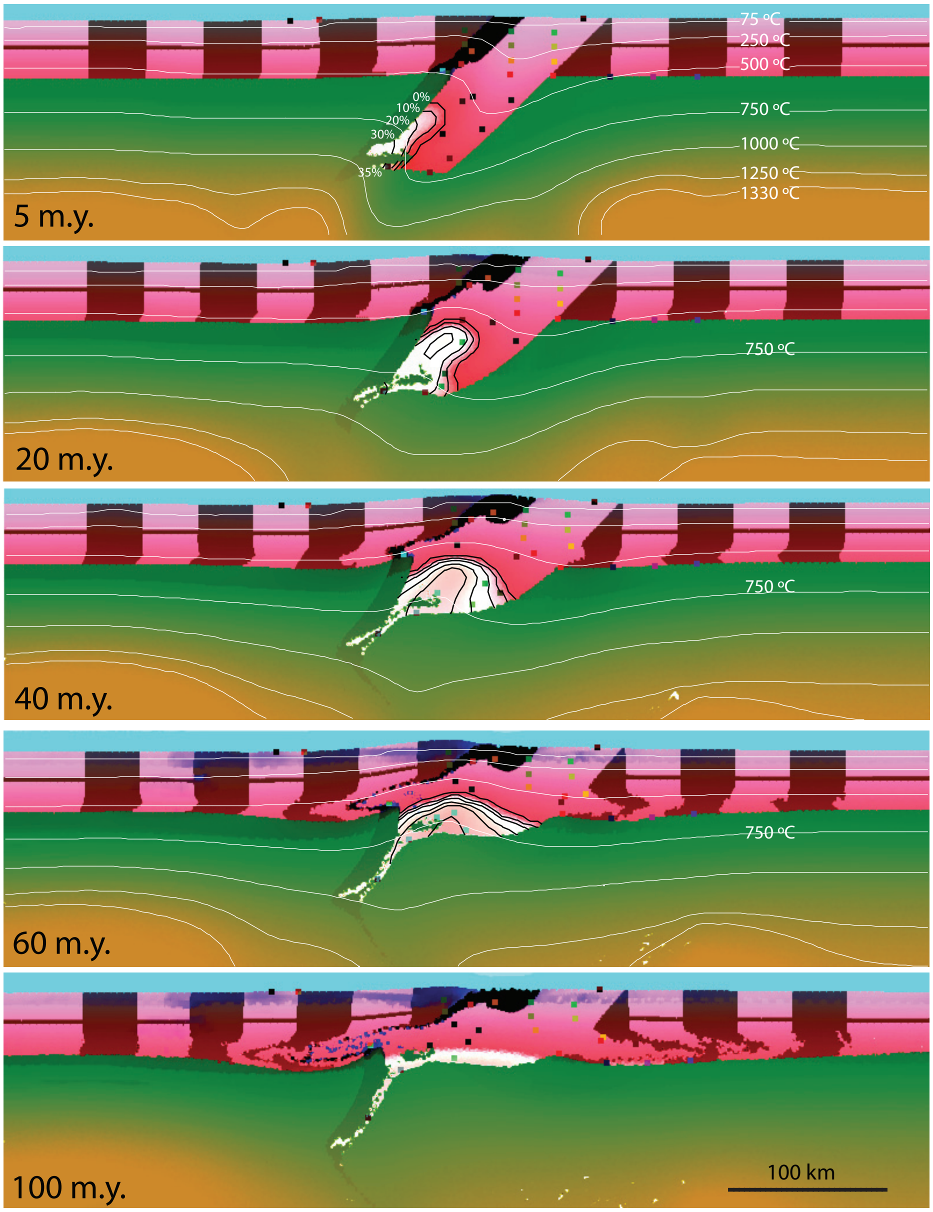

Figure 1. Ellipsis models showing evolution of continental lithosphere subducted to a depth of 110 km. Time in millions of years is indicated in the lower left of each panel; each panel is contoured for temperature (white) and melt fraction (black). Decompression melting occurs in the slab; partially molten crust is indicated by the light color at the base of the subducted slab. Buoyancy induces an upward viscous force that is confined to the slab by the stronger lithospheric mantle above and below.

In the model, the buoyancy of the partially melted continental slab induces an upward viscous flow that is confined to the slab by the lithospheric mantle on either side (Fig. 1). The rheology of the subducted crust significantly influences the particle paths of the partially molten crust and, therefore, the interaction of melt with the continent of the overlying plate (Figs. 1–2).

Upward Flow of Partially Molten Crust

In the model, no extension is applied at the boundaries, and therefore the upward flow of crust is controlled by buoyancy and rheology. The crustal melt from the slab is confined to the slab and ponds at the Moho. The overlying crust is extruded horizontally into the weak lower crust of the overlying continent and displaces Earth's surface upward to form an orogenic plateau and the Moho downward to accommodate the influx of material into the lower crust (Fig. 1). The volume of melt in the slab controls the rate of these processes, which can be accomplished in less than 10 m.y. when

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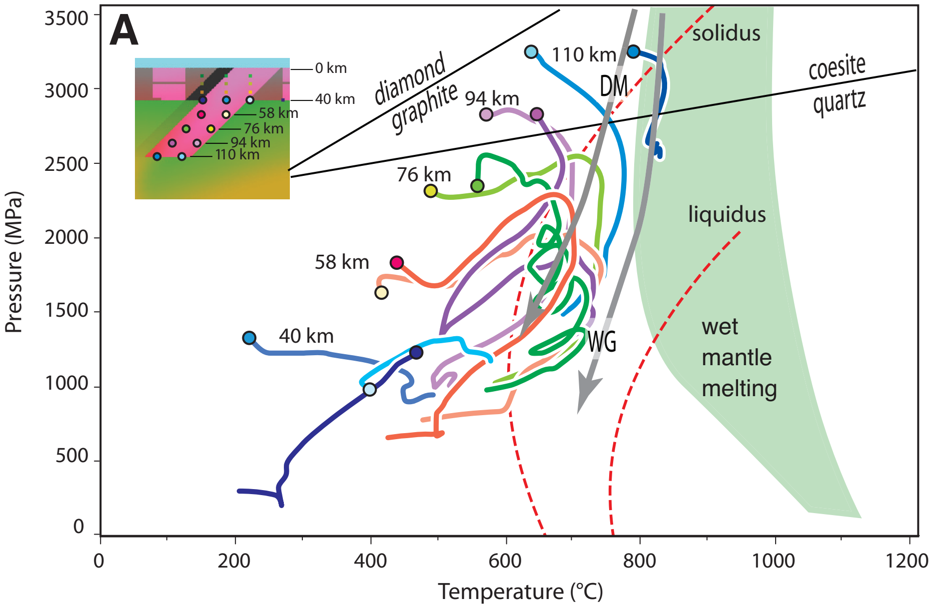
[1] GSA Data Repository item 2009283, parameters and other information about the model setup and implementation, is available at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.



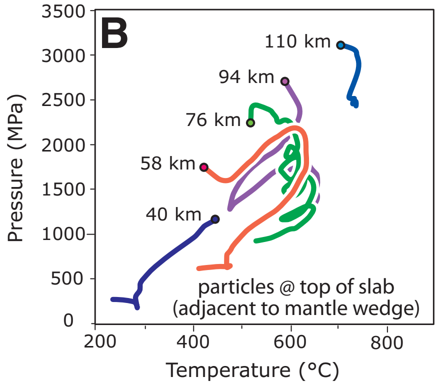


Figure 2. Pressure-temperature (*P-T*) paths for model rocks at different subduction depths and positions relative to the top and bottom of the subducted slab. (A) *P-T* paths for particle locations shown in the inset; *P-T* paths for particles at the top of the slab, near the mantle wedge, are shown separately in B. *P-T* paths for the Dora Maira (DM; Schertl et al., 1991) and Western Gneiss (WG; Carswell et al., 2003) ultrahigh-pressure (UHP) terranes are shown for reference, the latter of which contains abundant migmatite surrounding UHP rocks.

large volumes of melt (>75%) are present. For lower melt fractions (<38%), the time scale for buoyancy-driven flow is a few tens of millions of years. The combination of melt-driven bulging and lower-crustal extrusion contributes to the construction of the orogen.

Pressure-Temperature (*P-T*) Paths

In the model, rocks experience varying amounts of heating relative to decompression, depending on the maximum depth of subduction of the rock and its position in the slab (Fig. 2). Particles at the bottom of the slab experience heating: either heating during decompression, followed by a near-isothermal phase of decompression for particles subducted to depths >90 km, or near-isobaric heating followed by decompression and cooling (Fig. 2). Particles adjacent to the mantle wedge have complex paths, including convection within the partially molten region (e.g., the path starting at 76 km). The 110 km rock at the top of the slab remains entrained in the mantle and stays at high temperature without significant decompression. Such a process would contribute to mixing of continental and mantle material and would influence the geochemical character of the mantle. The shallowest rocks that were tracked in the model (40 km) are not incorporated into the partially molten region and experience only heating as they are extruded into the lower crust of the overriding continent. These results are consistent with those of previous modeling studies that show that exhumation of subducted crust is assisted by a reduction in effective viscosity (e.g., Burov et al., 2001; Gerya et al., 2002), as would occur during crustal melting.

Continental rocks exhumed from the coesite stability field exceed typical solidus temperatures (~700 °C) during decompression if bulk composition and exhumation rate are suitable for partial melting. Rocks subducted to <80 km may partially melt depending on maximum subduction depth and position in the subducted slab. The fact that some high- and ultrahigh-pressure terrains contain large volumes of migmatite (Carswell et al., 2003) and others do not is likely related in part to these differences.

A PARADIGM FOR OROGENY

Our numerical model consists of a single continental subduction zone and examines the paths and consequences of partial melting in this zone for evolution of the orogen as a whole. To understand the evolution of wide orogens that contain evidence for large volumes of partially molten crust, we can also consider the effects of deep burial of continental crust at various scales, including continental subduction.

At convergent plate boundaries characterized by relative forward motion of the trench/collision zone (Royden, 1993), orogens widen by propagation of crust- or lithosphere-scale thrusting away from the subduction zone into the overriding plate. This orogenic double wedge (cf. Willett et al., 1993) consists of the subduction/collision zone, in which deformation concentrates over time, and an inboard region (back-arc or inboard continental region), in which deformation propagates away from the plate-boundary zone (Fig. 3). Large-scale thrusting at the long-lived suture (subduction) and thrusting inboard from the suture both have consequences for high-grade metamorphism, partial melting, and the thermal-mechanical evolution of orogens.

A requirement for development of a wide orogen by inboard thrusting is the presence of weak regions, such as a continental margin that evolved via terrane accretion (North American Cordillera) or a collision zone that involved a previously rifted margin (Alps). This scenario applies to the growth of collisional and Cordilleran-style orogens, e.g., modern Himalaya-Tibet and the ancient North American Cordillera and European Variscides. In the case of Himalaya-Tibet, subduction of Indian lithosphere beneath Eurasia created a south-verging thrust zone (orogenic wedge). Northward growth of the Tibetan Plateau may have occurred in part by progressive thrusting (Willet et al., 1993; Tapponnier et al., 2001), although other plateau growth models have been presented (e.g., England and Houseman, 1989; Molnar et al., 1993). In the North American Cordillera, subduction occurred along an east-dipping subduction zone, but deformation propagated eastward into the continent, and a large orogenic plateau likely developed (e.g., Whitney et al., 2004b). The principle of large-scale inboard thrusting, albeit more modest in magnitude than in collisional systems and unlikely to involve mantle, may be applicable to western North America and may have con-

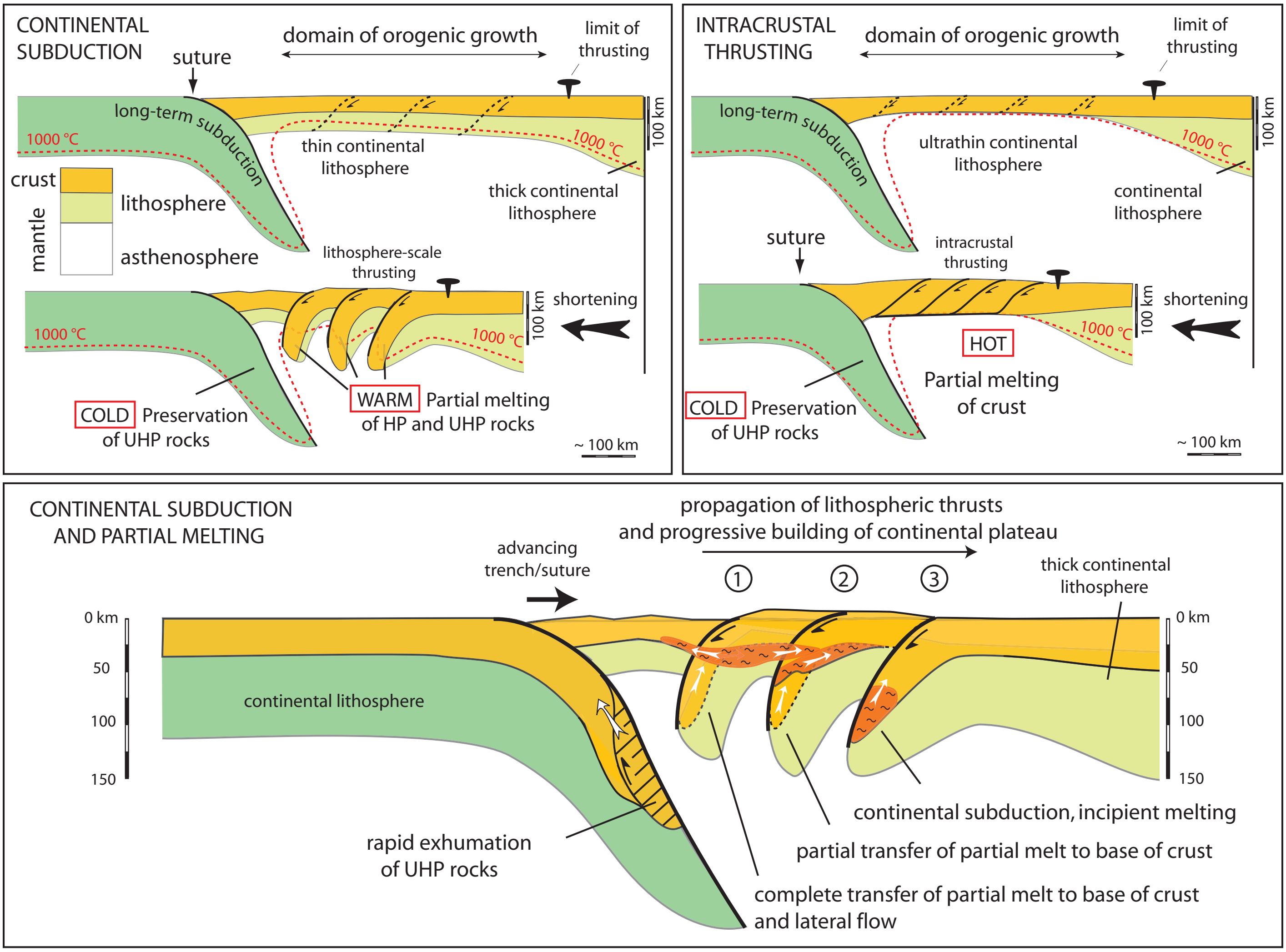


Figure 3. A schematic model for the way in which orogeny might proceed by sequential development of large-scale thrusts. The orogen grows along a series of thrusts that propagate away from the long-lived suture. The figure contrasts lithosphere-scale thrusting (subduction) in a collisional orogen with crustal-scale thrusting in a Cordilleran orogen, and contrasts "cold" continental subduction with "hot" continental subduction in terms of scale of thrusting and likely preservation of ultrahigh-pressure (UHP) assemblages. Continental crust is buried along each thrust, ascends owing in part to buoyancy, and partially melts. A thick layer of partially molten crust develops in and above the thrust faults. This crust may flow laterally (forming an orogenic plateau) and vertically (creating migmatite domes).

tributed to the building of the plateau via partial melting of the deeply buried continental crust. Whether entrained by lithosphere-scale thrusting (rocks are colder but reach greater depths before melting) or crustal-scale thrusting (rocks are hotter and melt at shallower depths), the fate of continental crust is to melt.

In orogens with wide intracrustal or lithospheric imbrication, thrust propagation ends when cold, thick lithosphere is encountered. Lateral and vertical growth of the orogen may cease soon after, and collapse may unfold via gravity or a change in boundary conditions (slowing of convergence, slab rollback). The Cordilleran orogen, for example, switched from contraction- to extension-dominated processes in the Early Tertiary. The orogenic plateau collapsed diachronously in the Tertiary, and the belt of metamorphic core complexes is the expression of crustal flow and final exhumation of the partially molten crust at the end of orogeny.

Continental subduction at a long-lived suture will not result in melting of continental crust if (1) geothermal gradients are low (5–15 °C/km); and (2) the subducted crust is largely composed of dry (granulite) rocks. In these cases, the buoyancy of the continental crust also drives intraslab channel flow, albeit at a slow rate. Moderate thermal relaxation of the slab unfolds over a few tens of millions of years, preserving a narrow mountain belt. Therefore, orogens with little or no inboard thrusting remain narrow (e.g., Appalachians) and do not develop a plateau underlain by partially molten crust.

This paradigm for orogeny accounts for the growth of orogens that widen in a direction away from the main plate boundary (subduction zone or collision suture) and relates the processes of continental subduction and crustal melting to lower-crustal flow and plateau development in the overriding plate (i.e., orogenic width). In addition, this paradigm may also account for observations in exhumed orogens that contain UHP relics in migmatite and granite (e.g., parts of the Variscan belt and the Western Gneiss region, Norway), the occurrence of UHP rocks in the overriding plate of some orogens (Greenland Caledonides; Gilotti and McClelland, 2007), and differential preservation of UHP assemblages in different orogens.

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