Understanding continental subduction: A work in progress

Mihai N Ducea*
University of Arizona, Department of Geosciences, Tucson, Arizona 85721, USA, and Universitatea Bucuresti, Facultatea de Geologie Geofizica, Bucharest, Romania

A study by Froitzheim et al. (2016, p. 223 in this issue of Geology) adds new constraints to our rapidly evolving ideas and models regarding the process of continental subduction. Classic plate tectonics concepts suggested that continents do not subduct. Instead, when two continents collide at a convergent boundary following the consumption of an ocean by subduction, they accommodate the shortening within the lithosphere, which is thickened up to twice the normal values. The subducted oceanic slab that brought the continents together stalls and eventually breaks off and sinks into the mantle due to its negative buoyancy. In contrast to that view, modern petrologic, tectonic, and geophysical observations have completely changed this picture still prevalent in many textbooks: continental lithosphere does, in fact, subduct to great depths at major long-lived collisional boundaries, and the two colliding plates can be separated by a section of convective upper mantle (mantle wedge) similar to the case of oceanic subduction.

There are three important types of observations supporting these assertions. First, the discovery over three decades ago (Chopin, 1984) of ultrahigh-pressure (UHP) metamorphic rocks—crustal rocks in which the stable silica polymorph at peak pressure temperature conditions was coesite—documented that continental crustal rocks have been buried to >90–100 km in some orogens. After their initial discovery in the Alps, tens of localities of UHP or near-UHP metamorphic rocks have been described globally in a variety of Phanerozoic and older orogenic belts (Gilotti, 2013). Most of these are unambiguous continental crustal rocks. Some even contain microdiamonds, indicating that they were buried to as much as 150 km (McClelland and Lappen, 2013, and references therein). Fundamentally, all UHP rocks are eclogite facies rocks and the better-preserved ones have only limited products of retrogression overwritten along their exhumation path. UHP or near-UHP crustal xenoliths found in volcanic rocks from the Pamir Mountains (Central Asia; Hacker et al., 2005; Ducea et al., 2003) also document the process of continental subduction—in contrast to exhumed UHP rocks, they are crustal fragments caught in the process of subduction with no evidence for tectonic decompression/cooling in their thermobarometric record. Because it is unlikely that continental crust is ever 100–150 km thick anywhere on the planet, the implication is that such rocks were subducted to mantle depths before being returned to the surface (Hacker et al., 2013).

Second, refined plate-tectonic reconstructions and plate kinematics models for the Indo-Asian collision (van Hinsbergen et al., 2012) since its beginning, as early as the Paleocene, make very specific predictions regarding the total amount of shortening along this margin, which is significantly more than what can be accounted for by crustal shortening in the Himalayas (DeCelles et al., 2011). More than 1000 km of Indian lithosphere are missing and must have been subducted under the Asian continent.

Third, seismic images of the ongoing Pamir–Hindu Kush collision system show that Indian lithosphere is being subducted to as much as 500 km beneath the surface (Sippl et al., 2013).

Between these lines of evidence, a compelling case can be built for the fact that continental lithosphere (crust and mantle) is subductable to great depths and significant distances away from the collision’s principal suture. One can further assume that only a small fraction of subducted continental crust makes it back to the surface of Earth, making UHP rocks extraordinarily important.

Six distinctive geodynamic mechanisms have been proposed in the literature for continental subduction and development of UHP metamorphic rocks, and also six mechanism exist that explain the subsequent unroofing of these rocks (Hacker and Gerya, 2013; Gerya, 2011). The unroofing of such rocks is as fascinating a subject as their burial: UHP terrains underwent the most amount of exhumation of any rocks from Earth’s surface. The proposed mechanisms for exhumation are mechanically and geologically plausible but, at this point, also very speculative, since they are so difficult to test. In a very general sense, UHP rocks can move upward within the crust toward their final resting place at Earth’s surface either as a part of a large rigid crustal block or, alternatively, via some kind of opportunistic route that does not require large scale en-masse exhumation (Hacker et al., 2013). One of the proposed mechanisms for the first type of unroofing is the eduction mechanism (Andersen et al., 1991) in which continuing convergence at a collisional margin takes place synchronous with ejection of the intervening oceanic crust downward into the mantle. Among the mechanisms for selective exhumation, two particularly intriguing ones are (1) exhumation along a narrow “subduction channel” along which materials can travel both ways (up or down) depending on boundary conditions, and (2) reflation of subducted sediments by solid-state and/or partially molten-state diapirism through the uppermost mantle (Hacker et al., 2011). Understanding exhumation of UHP rocks remains very much a work in progress and an area in which much is left to be discovered.

Froitzheim et al. (2016) report the discovery of a new near-UHP locality on Lofoten Island, which is part of the Norwegian Caledonides (Kylander-Clark et al., 2009). Variably retrogressed kyanite eclogites that have a mafic bulk composition containing omphacite, garnet, and minor kyanite, phengite, and quartz make up an assemblage that is mafic in bulk chemistry, but also appears continental and crustal. The assemblage was at a peak metamorphic pressure of as much as 2.8 GPa (equivalent to >90 km depth) and temperatures of 650 °C degrees at ca. 400 Ma, as determined from garnet whole-rock Lu-Hf geochronology. The peak temperature-pressure is indicative of a low thermal gradient that this rock was subjected to during burial (~7 °C/km), which is typical for materials buried very fast along a plate boundary (subduction complexes around the world give similarly low thermal gradients). Whole-rock Hf isotope systematics (extremely low initial 187Hf/177Hf) suggests that the analyzed rock may have an Archean protolith. Together, these results indicate that the analyzed rock was a lower crustal piece of Baltica, an old lithospheric fragment that was subducted beneath Laurentia during the broadly defined Caledonian orogeny as a consequence of the collision and continental subduction that followed after the consumption of the Iapetus Ocean.

This is not the first evidence for UHP metamorphism in the Scandinavian Caledonides (Hacker et al., 2010). In fact, the Lofoten rocks (exposed on an island off the northern coast of Norway) are spatially and tectonically correlated to the Western Gneiss Complex (Root et al., 2005), one of the largest UHP metamorphic terrain known worldwide (Gilotti, 2013). The Caledonian Western Gneiss Complex has similar ages of peak metamorphism (although, on average, they are older than the age determined in this new study of Froitzheim et al.). However, Lofoten rocks are much

*E-mail: ducea@email.arizona.edu

© 2016 Geological Society of America. For permission to copy, contact editing@geosociety.org.
less deformed than most of the Western Gneiss, suggesting that they may represent legitimate autochthonous Baltica from the hinterland of the collision, and not some potentially allochthonous terranes positioned in between Baltica and Laurentia.

Froitzheim et al. also deduce a rapid exhumation path following peak metamorphism. At >6 mmyr (and possibly approaching 1 cm/yr), such exhumation rates are really fast compared to most rates of orogenic unroofing, not quite as high but similar to the rates determined for the Namche Barwa metamorphic rocks from the eastern Himalayan syntaxis (Ding et al., 2001). In fact, such exhumation rates are so large that they require some special causative process, whether that is driven by climate conditions prone to high erosion rates, unusual local geomorphology at the time of exhumation, extensional tectonics, or a combination of these. The data in hand for the Lofoten eclogite are not capable of specifically addressing the cause of exhumation.

So, what do these results mean in terms of our current understanding of collisional tectonics and continental subduction? This and other examples suggest that old and presumably cold continental plates are likely to get subducted under the hotter and more ductile upper plates that hosted the magmatic arcs during subduction periods which must have preceded all collisional events. The Lofoten example, and the inferred subducted Baltica, is possibly similar to what the cold Indian craton represented in more recent times for the Himalayan collision, or the East European craton for the Carpathian orogen. The lower plate represented by the Lofoten basement in the Froitzheim et al. study underwent very little internal deformation despite being transported to almost 100 km below the surface at plate boundary rates. Whatever the mechanism for the subsequent exhumation, it brought the subducted material back to or near Earth’s surface rather fast, but also as a more or less intact block, according to Froitzheim et al. This was clearly not a case of selective and opportunistic transport of the exhumed material along a “fastlane” (e.g., channelized flow or relaxation) but rather the product of some large-scale structural unroofing. This example argues that exhumation rates are so large that they require a likely mechanism to exhume the deeper crust of the autochthon (lower plate) while convergence was still ongoing.

Some of these interpretations remain speculative. Decades after the initial discovery of UHP metamorphism, the topic of continental subduction is as mysterious and exciting as ever, and each new discovery adds important constraints to the possible mechanisms involved. Geodynamic modeling, igneous/metamorphic petrology and seismology are observational and theoretical disciplines expected to produce major insights into our understanding of the process in years to come. Among the major issues that are in need of quantification in the near future are the rates of recycling in the mantle versus the rates of return to the upper plate, and the magmatic compositions and fluxes of melt at various evolutionary stages of a collisional margin. And finally, we need to distinguish between crustal subduction and crustal delamination in thick orogenic areas as the causative processes leading to the development of UHP rocks.

ACKNOWLEDGMENTS
I acknowledge support from the Romanian Executive Agency for Higher Education, Research, Development and Innovation Funding (project PN-II-ID-PCE-2011–3-0217) for research in orogenic areas.

REFERENCES CITED

Printed in USA