ZHENG Yongfei, 2013. Subduction Channel Processes: A Tectonic Mechanism for Orogenic Metamorphism during Continental Collision. *Acta Geologica Sinica* (English Edition), 87(supp.): 530-533.

Subduction Channel Processes: A Tectonic Mechanism for Orogenic Metamorphism during Continental Collision

ZHENG Yongfei*

CAS Kay Laboratory of Crust-Mantle Materials and Environments, School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China

1 Introduction

In continental collision orogens, exposed ultrahigh-pressure (UHP) metamorphic terranes contain the lithotectonic records of Alpine-type subduction. These records highlight metamorphic P-T conditions and mass transfers, indicating subduction of continental crustal rocks to mantle depths of over 100 km. The UHP terranes are characterized by minor occurrences of mafic eclogites and ultramafic peridotites that are hosted by felsic gneisses. Such UHP eclogite-facies parageneses are absent in Pacific-type subduction zones. These UHP rocks are of crustal and mantle protoliths and now occur together with their lower pressure counterparts in continental collision orogens (Zheng et al., 2012). It is intriguing how the UHP slices are exhumed from mantle depths to crustal levels and how the metamorphic rocks of different P-T conditions occur together in the same orogens. The aim of this study is to highlight the subduction channel processes that are suggested as a tectonic mechanism for mixing and transport of these crust- and mantle-derived materials during continental collision.

2 Subduction channel processes

On the basis of tectonic processes in oceanic subduction zones, the concept of subduction channel was proposed by assuming the presence of variable sizes of free space between the upper and lower plates during slab subduction into the mantle (Shreve and Cloos, 1986; Gerya et al., 2002). Thus, the subduction channel denotes a narrow space between the underlying subduction slab and the overlying mantle wedge, in which supracrustal materials of subducting oceanic lithosphere are detached by tectonic offscrapping along channel walls with varying extents of deformation and metamorphism. This concept is extended to continental subduction zones, in which not only variable sizes of crustal fragment are detached from subducted continental lithosphere but also variable sizes of mantle fragments are offscrapped from the bottom of mantle wedge (Zheng, 2012). These scrapped materials form a variety of tectonic melanges in continental subduction channel, experiencing variable extents of metamorphism with heterogeneous deformation and local anatexis. The crust- and mantle-derived fragments are transported either downwards or upwards during subduction, depending on the direction of corner flow inside the subduction channel. While some fragments may be transported downwards for further burial, the other fragments may be transported upwards for exhumation. It is common that the upper low-T/HP layer becomes exhumed when the lower high-T/UHP layer is still subducting. Some fragments may be rotated inside the subduction channel, resulting in different P-T-t paths for different positions of a given UHP slice. These differential processes of subduction and exhumation are recorded by HP and UHP metamorphic rocks in the same collision orogens. Some UHP metamorphosed fragments may be stored in the lower crustal level for long periods, leading to significant retrogression and even thermodynamic reequilibration in the late stage of continental collision.

Convergent continental margins commonly exhibit a wide variation in the tectonic behavior of subducted materials. In the Dabie-Sulu orogenic belt, for example, negative $\delta^{18}O$ rocks of supracrustal origin were subducted to mantle depths whereas a deformed accretionary wedge was accumulated at the continental margins without subduction to mantle depths. These differences can be explained by three levels of crustal detachment at different depths during continental subduction: (1) the shallow detachment between sedimentary cover and crystalline basement, (2) the intermediate detachment between the upper crust and the lower crust, and (3) the deep

* Corresponding author. E-mail: yfzheng@ustc.edu.cn

detachment between the continental crust and the subcontinental lithospheric mantle (SCLM). The continental crust is detached at different depths, yielding different sizes of fragments and slices in the subduction channel. Metamorphic dehydration and partial melting are facilitated by structural shearing of these crustal fragments and slices. Aqueous fluid and hydrous melt may be generated in these rocks, which may rise to metasomatize the overlying mantle wedge and to form mafic to ultramafic metasomes in orogenic lithospheric mantle (Zheng, 2012).

Because continental subduction zones exhibit lower geothermal gradients than oceanic subduction zones, UHP metamorphism in continental subduction channels is usually characterized by lower temperatures than that in oceanic subduction channels. As a consequence, dehydration of deeply subducting crustal rocks at subarc depths is much less significant in continental subduction zones than in oceanic subduction zones. This explains why no synsubduction arc magmatism occurs above the overridding continental lithosphere. Nevertheless, the SCLM wedge peridotite would undergo alteration and metasomatism, respectively, by the aqueous fluid and hydrous melt derived from the subducting continental crust and its derived fragments. On the other hand, dehydration of UHP metamorphic rocks is significant during their exhumation from mantle depths to the lower crustal level (Zheng, 2009), leading to amphibolite-facies retrogression and local sinking of aqueous fluids for quartz veining. Anatexis of UHP rocks may also take place at elevated temperatures (Zheng et al., 2011), giving rise to felsic melts that metasomatize the overlying SCLM wedge to form mantle sources for synexhumation alkali magmatism (Zhao et al., 2012) and postcollisional mafic magmatism (Dai et al., 2012).

Although there are hot debates on the mechanism of exhuming UHP terrane from mantle depths to crustal levels, various sizes and shapes of UHP slices can be exhumed inside cold subduction channels. Both internal and external forces in the subduction channels have played the roles of exhumation. The internal force is indicated by the buoyancy-driven upward motion, including channel flow during ongoing continental subduction, wedge extrusion induced by the detachment of deeply subducted crustal materials from the downgoing lithosphere, and the diapiric ascent of subducted crustal materials under the action of fluid/melt. The external force is indicated by the upward flow of delaminated materials, involving large-scale intracrustal thrusting with coeval erosion, pure-shear thickening and coeval erosion during continental collision, decoupling and eduction of the continental crust and changes in lithospheric kinematics at convergent margins. A combination of the internal and external forces in the cold subduction channels can result in the varying extents of metamorphism with heterogeneous deformation and local and anatexis of the subducted crustal materials at different depths, extents and fashions.

The applications of subduction channel model to continental collision orogens enable us to focus on the lithotectonic property of subducted crust and its overlying mantle wedge. The subducted continental crust is primarily composed of basement granite, granulite and gabbro with sedimentary cover, containing very minor peridotite. It contains less water than the subducted oceanic crust that is primarily of altered oceanic basalt and gabbro with thin cover sediment. The mantle wedge above the subducting continental slab is of high viscosity, low temperature and low water fugacity, in contrast to the mantle wedge above the subducting oceanic slab that is of low viscosity, high temperature and high water fugacity.

A combination of results from the study of petrology, numerical modelling, geophysics and geochemistry suggests at least three-stage processes during continental collision. First, crustal materials are detached from subducting continental lithosphere at different depths, suffering different extents of deformation and metamorphism along the interface between the subducted continental crust and the overlying SCLM wedge. Second, crustally derived materials are mixed not only with each other but also with peridotite fragments scrapped from bottom of the SCLM wedge, yielding UHP mixtures at mantle depths. Third, the UHP mixtures are returned to crustal levels by the corner flow in the continental subduction channel, forming the exposed mélanges that exhibit variable P-T conditions and lithologies. Thus, variable extents of physical mixing and chemical reaction along the continental subduction channel are a key to the formation and exhumation of orogenic mélanges. Consequently, all UHP metamorphic rocks in continental collision orogens can be viewed as three-component mixing systems that are primarily composed of continental basement and sedimentary cover with minor peridotite from the SCLM wedge. They are the tectonic melanges due to mechanical mixing of these three components in the continental subduction channel. Therefore, the subduction channel processes are the tectonic mechanism that can account for various occurrences of microscale to macroscale lithotectonic units in continental collision orogens.

3 Control of protolith nature

Continental subduction zones exhibit a large diversity in the protolith nature of UHP metamorphic rocks. For example, in some subduction zones such as Alps-Himalaya and Tianshan-Ural, the Tethys basalt of juvenile origin was involved in UHP metamorphism at mantle depths. But in other subduction zones such as Dabie-Sulu and Western Gneiss Region, the continental basement of ancient origin was metamorphosed under UHP conditions. In either case, the configuration of subduction zones is uniform in that the mantle wedge is always present between the subducting continental lithosphere and the overriding continental lithosphere. In the Andean-type subduction zones where the oceanic lithosphere is subducted beneath the continental lithosphere, the overlying mantle wedge may be of juvenile origin due to the accretion of oceanic arc terranes. In the Alpine-type subduction zones, on the other hand, the continental lithosphere is subducted beneath the continental lithosphere and the overlying mantle wedge may be of either ancient origin (craton mantle) or juvenile origin (subarc mantle).

Different origins of crustal rocks were subducted to mantle depths for UHP metamorphism during continental collision. The difference in protolith origin is correlated with the type of collisional orogens and the size of UHP metamorphic terranes (Zheng, 2012). Although there are various types of collisional orogens, they are generally categorized into accretionary-type and collision-type. Substantially, many accretionary-type orogens are also arc-continent collision orogens in the advanced stage, so that they had better to be referred as accretionary-type arc-continent collision orogens. In such orogens, mafic UHP eclogites primarily have the protolith of juvenile Tethys basalts whereas felsic UHP gneisses mostly have the protolith of accretionary wedge sediments. In continent-continent collision orogens, on the other hand, protolith of the eclogites is primarily ancient mafic rocks whereas protolith of the gneisses is mostly ancient granites with minor amounts of continental sediment. In either case, very small volumes of the UHP eclogites are enclosed by very large volumes of the UHP gneisses in various UHP terranes. Despite their variation in metamorphic ages from the Early Paleozoic to the Late Cenozoic, durations of UHP metamorphism fall into two groups in light of the available geochronological data (Zheng et al., 2009). One group exhibits short durations in a few millions of years (e.g., the Dora Maira of Western Alps, the Kaghan Valley of Himalaya, and the Woodlark of Papua New Guinea), whereas the other group exhibits long durations in tens of millions of years (e.g., Dabie-Sulu, Western Gneiss Region). The two groups of metamorphic durations are generally correlated with the geometric size and protolith nature of UHP terranes. Small UHP terranes of juvenile crustal protoliths tend to metamorphose over the short timescales and thus exhume at rapid rates, whereas large UHP terranes of ancient crustal protoliths tend to metamorphose over the long timescales and hence exhume at slow rates. These two types of relationships can be well explained by the subduction channel processes during continental collision.

During the continental collision, the continental crust was subducted either beneath the juvenile subarc lithosphere (e.g., Alps-Himalaya, Tianshan-Ural) or beneath the ancient craton lithosphere (e.g., Dabie-Sulu, Western Gneiss Region). The former corresponds to the accretionary-type arc-continent collision that results in wide orogens with intervened arc terranes, whereas the latter corresponds to the continent-continent collision that leads to narrow orogens without intervened arc terranes. Within the framework of plate tectonics, there are a series of processes from oceanic subduction to continental collision: (1) subduction of the Tethys lithosphere beneath the Tethys lithosphere to cause oceanic arc magmatism, (2) rollback of subducting slab to cause backarc basin extension and magmatism, (3) the closure of backarc basins in association with the Andes-type arc-continent collision, (4) subduction of the Tethys lithosphere beneath the newly accreted arc terranes to cause continental arc magmatism, (5) subduction of the ancient continental lithosphere beneath the newly accreted arc terrane to cause the Himalaya-type arc-continent collision (e.g., Dora Maira, Kaghan Valley and Woodlark). While UHP metamorphism of the subducted crustal rocks is common in the Himalaya-type arc-continent collision orogens, it is absent in the Andes-type arc-collision orogens; (6) subduction of the ancient continental lithosphere beneath the ancient continental lithosphere to cause the continent-continent collision (e.g., Dabie-Sulu, Western Gneiss Region).

4 Conclusions

The subduction channel processes are an important development of plate tectonic theory toward continental dynamics. These processes have left notable and directly accessible records at the surface in the form of exhumed UHP metamorphic terranes. While the deep burial of UHP metamorphic rocks is due to further subduction of those HP rocks with the downgoing slab, the exhumation of UHP metamorphic crustal slices is primarily driven by the corner flow in the continental subduction channel. Small UHP terranes of juvenile crustal protolith resided at mantle depths in short durations with rapid exhumation, whereas large UHP terranes of ancient crustal protolith resided at mantle depths in long durations with slow exhumation. However, the concrete mechanism of exhumation for different lithotectonic units may vary from case to case, depending on the temporal and spatial positioning in the subduction channel with the competition between internal and external forces. Therefore, there are various types of physical mixing and chemical reaction between crust- and mantle-derived rocks in the continental subduction channel.

Acknowledgments

This study was supported by funds from the Natural Science Foundation of China (41221062) and the Chinese Ministry of Science and Technology (2009CB825004).

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