PROSPECTS OF THE NEW CENTURY

Some new ideas about the deep subduction of continental crust*

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Received December 15, 1999; revised January 19, 2000

Abstract The discovery of coesite in metasedimentary rocks not only implies that the materials of continental crust with low density could subduct down to mantle depth, but also initiates a series of studies on continent-deep-subduction. Could continental crust be subducted down to the depth of more than 300 km? Water played a role in ultra-high-pressure (UHP) metamorphism although limited. Was the fluid really limited within meter-scale, as the authors suggested, at mantle depth? Erosion and extension could remove the overburden of the UHP rocks, while squeezing and buoyancy could lift up the UHP rocks through the overburden. What, however, is the main process and mechanism with which the UHP rocks have exhumed from mantle depth? All progress of these studies will eventually form and complete a new paradigm of geodynamics.

Keywords: UHP metamorphism, continental lithosphere, deep subduction.

In 1984, a small mineral inclusion of coesite was discovered in meta-sedimentary rocks from the Western Alps. This discovery has initiated a heat wave in studying ultra-high-pressure metamorphism, which, in turn, led to the study of deep subduction of the continental crust and opened a new field in geodynamics.

The composition of coesite is SiO_2, exactly the same as quartz. However, its density (2.92 g/cm^3) is larger than that of quartz (2.65 g/cm^3), because it is in an UHP phase of quartz. The metamorphic pressure to form coesite is 2.4—2.8 GPa, equal to lithostatic pressure at the depth of 80—100 km and the temperature of 600—800℃. In 1953, a British scientist, L. Coes, made the first synthetic crystal of SiO_2 in laboratory under high-temperature and high-pressure condition[1]. Lately, a natural product of the high-pressure SiO_2 phase was found from a meteoric crater in Arizona in 1960[2], and named coesite, after the name of L. Coes.

The discovery of coesite in meta-sedimentary rocks from the Western Alps indicates that the sedimentary rocks with low density (2.6—2.7 g/cm^3) could subduct to a depth of 90 km[3] in upper mantle featuring with high density (3.2—3.4 g/cm^3). Such a process of deep subduction of continental crust has never been included in the plate tectonic theory that is looked upon as a revolution in the earth science (fig. 1). According to the plate tectonics, only cold and heavy oceanic lithosphere could subduct to a depth beneath continental lithosphere and further to the depth of 670 km. The continental lithosphere will grow with the subduction of the oceanic lithosphere. When the continental

* Project supported by the National Natural Science Foundation of China (Grant No. 49794042) and the Chinese Academy of Sciences (No. KZ951-A1-401-05).

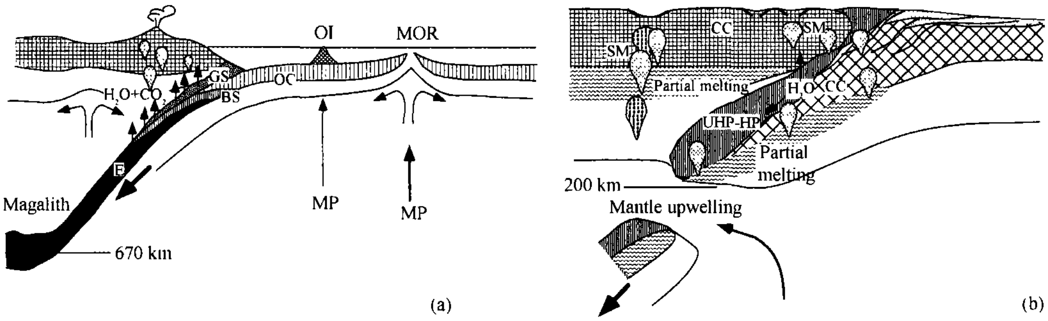

Fig. 1. Diagram showing deep subduction of oceanic and continental lithosphere. (a) Cold and heavy oceanic lithosphere could subduct down to a depth of 670 km and form megalith. During subduction, oceanic crust (OC) and sediments would experience greenschist (GS), blueschist (BS) to eclogite (E) facies metamorphisms. Some fluids (H_2O, CO_2) would be released and others brought to mantle. Volcanic arc and backarc basin might form above the mantle wedge. Mantle plume under the oceanic lithosphere might result in middle ocean ridge and oceanic island. (b) Continental lithosphere might also subduct deeply beneath another continental lithosphere. During subduction, the materials of continental crust (CC) would experience a process from high-pressure (HP) to ultrahigh-pressure (UHP) metamorphism. Some fluids will be released and others brought to mantle. The continental lithosphere with low density might be broken off when it subducted to a certain depth. The lower section would sink into mantle, while the upper section would exhume. The mantle upwelling through the breakpoint would melt partially the subducted crustal materials and result in syn-collision magmatism (SM).

lithosphere rifts, a new oceanic basin will develop. The circulation of materials between crust and mantle, lithosphere and asthenosphere could be realized during the above processes. In other words, continental lithosphere plays a more passive role than oceanic lithosphere in the theory of plate tectonics.

After the discovery of coesite from the Western Alps, many coesite-bearing UHP rocks were found in the Dabie-Sulu collisional orogenic belt of China in the late 1980s and early 1990s[4—7]. At the same time, new outcrops of high-pressure (HP) and UHP rocks were also found in the Altun Shan of China, the Western Gneiss Region of Norway, the Imjingang and Okcheon Belts of Korea, the Serbo-Macedonlan Massif of Bulgaria, the Northern Tien-Shan of Kyrghystan, the Mozambique Orogen of Tanzania, a widespread eclogite province in East Greenland, coesite-bearing terrane in Indonesia, and diamond-bearing gneiss terrane of Saxonian Erzgebirge in Germany[8]. These discoveries indicate that the distribution of UHP metamorphic rocks is spatially and temporally more extensive than what people thought before. The geodynamic processes underlying the formation and exhumation of UHP rocks are showing their importance in the evolution of continental lithosphere. UHP rocks have become a new natural window to observe the interior of the earth, with the emphasis of the studies laid on the "deep".

1 Continent deep-subduction

How deep can continental lithosphere subduct during continent-continent collision? This is one of the interesting questions studied in the field of UHP metamorphism. More and more UHP minerals or mineral phases have been found in the continental collision zones. For examples, diamond with metamorphic pressures ranging from 4—5 GPa was found in Kokchetav and Dabie Mountains[7,9], and $FeTiO_3$ rods of micrometer-scale were found in olivine of the UHP lherzolite in Alpe Arami[10]. The titanite rods have four types of structures: ilmenite and three previously unrecognized crystal structures between ilmenite and denser perovskite. The $FeTiO_3$ rods were interpreted as exsolution of perovskite at pressure of 10—15 GPa (correspondsing to the depth of 300—400 km) from olivine rich in TiO_2 (about 0.7 wt%). Theoretically, the olivine should be transformed into denser wadsleyite or ringwoodite structure at the pressure of 10—15 GPa. Therefore, the Alpe Arami lherzolite was considered as a kind of the mantle transition zone. Two special exsolution phenomena have been discovered in the peridotite from the Dabie-Sulu area[11,12]. One is Cr-rich ilmenite exsolutions in olivine. The preferred orientation of the exsolutions is parallel to [010] of the host olivine. The other is Ti and Cr bearing magnetite exsolutions in olivine. Although the crystal structure of the Cr-rich ilmenite has not been measured precisely, the exsolution of magnetite from olivine implies that at least parts of the olivine might be transformed into spinel structure. It was reported also that clinopyroxene bundle was often developed surrounding the garnet grain. Such a structure has been observed so far only in mantle rock inclusions coming from very deep resource (> 300 km). It implies that the clinopyroxene was transformed into garnet structure and lately went back deep in the mantle transition zone (380 km) or even deeper.

In the AGU meeting of 1998[13], clinoenstatite exsolutions in diopsite were further reported from UHP lherzolite of Alpe Arami, and from garnet-pyroxenite of Donghai, north Jiangsu, China. The minimum depth to develop such a kind of exsolution is 250 km. The real depth in the Alpe Arami and Donghai cases should be greater than 250 km because of a few percentage of $CaSiO_3$ present in the clinoenstatite. Now geoscientists are trying to find whether or not continental lithosphere, like oceanic lithosphere, could be dragged down to a depth of 670—720 km. There is a long way to go to answer this question.

2 Deep circulation of water

Another interesting question is how a continental lithosphere changed itself physically and chemically during subduction down to the depth of hundred kilometers. What kind of interaction could happen between the subducting continental lithosphere and the upper mantle? Could atmospheric fluids (H_2O and CO_2) contained in sedimentary rocks deposited on surface be brought into the upper mantle? So far, all theories about the earth's evolution have considered the atmosphere and hydrosphere as the products of mantle degassing. When more and more H_2O- and CO_2- bearing minerals, such as epidote, zoisite, phengite, and dolomite, have been found from the UHP rocks, scientists have to think whether or not there exists a reverse process. Experimental work[14] showed that various H_2O-bearing minerals could be synthesized under UHP condition. For examples, the stability range of Mg-chloritoid, $MgAl_2SiO_5(OH)_2$, is 1.8—5.8 GPa at 400—800℃, that of Mg-staurolite, $Mg_4Al_{18}Si_8O_{46}(OH)_2$, greater than 1.3 GPa at 700—950℃, and that of Mg-carpholite, $MgAl_2[Si_2O_6](OH)_4$, 0.7—5.0 GPa at a temperature higher than 650℃. Clinohumite-OH ($Mg_9Si_4O_{18}H_2$) and chondrodite-OH ($Mg_5Si_2O_{10}H_2$) are stable at a pressure greater than 2.9 GPa and a temperature below 730℃. Glaucophane will be stable in the pressure range of 1—3 GPa when temperature runs higher than 700℃. Ti-ellebergerite, which is stable at 2.7—4.2 GPa and 650—725℃, has been found in white schists from Western Alps. MgMgAl-pumpellyite and topaz-OH, $Al_2SiO_4(OH)_2$, have been synthesized at a pressure greater than 3.7 GPa and a temperature below 700℃ and a pressure greater than 5.5 GPa and 400—900℃, respectively[14]. All these experimental studies indicate that water did join in the UHP metamorphism.

However, the studies of stable isotopes like O, C, H, seem to indicate that no fluid reacted with supracrustal rocks when they subducted down to mantle depth[15—18]. Therefore, their isotopes still preserved the character of meteoric water, and showed an heterogeneity of O-isotope at meter scale. On the other hand, that study of reaction dynamics showed that the mass exchange by solid-solid diffusion was limited within meter scale in the period of million years. This indicates that no water has joined in the UHP metamorphism. One implication from the controversy is that water has joined in the UHP environment in a limited field or through some special channel. No doubt, a large scale of mass exchange between lithosphere and asthenosphere could be realized only through fluid medium. Therefore, water-rock (fluid-rock) reaction and circulation of water have drawn more and more attention in the studies on continental evolution.

3 Exhumation of deep materials

It is also an attracting question how the UHP rocks could exhume from depth of more than 100 km to surface. So far the published data have indicated that almost all UHP rocks were developed in collision orogenic belts. For examples, Dora Maira where coesite was first discovered is located in the west section of Alpine orogeny that was built up by the collision between European and African plates. The western gneiss region containing UHP rocks in Norway belong to a collisional orogenic belt between the Baltica and Laurentia continents. The UHP rocks were found in the Dabie-Sulu orogenic belt, which was built up by the collision of the Sino-Korean and Yangtze plates. Temporally, the peak and retrograde metamorphic ages fall into the span when the due collision orogenic belt was built up. The spatial and temporal coincidence implies that the formation and exhumation of UHP rocks could be caused by the same process that resulted in the collision orogenic belt. The study on exhumation of UHP rocks is another version of deciphering continental collision geodynamics.

Various hypotheses have been advanced to explain the exhumation of UHP rocks. For example, the erosion hypothesis[19,20] held that overburden of 100 km thick was eroded away and deposited in peri-orogenic basin, while the extension hypothesis[21] held that the thick overburden was extended to become thinner at an extent that UHP rocks could easily emerge to the earth surface. The wedge-extrusion hypothesis[22] emphasized that UHP rocks, as a thin wedge, could be squeezed up from mantle depth to shallow crust, while the buoyancy hypothesis[23] insisted that buoyancy itself could exhume UHP rocks with low density from the mantle rocks with high density. These hypotheses can be divided into two groups. One is to remove the overburden either by erosion or by extension, while the other is to lift up the UHP rocks through the overburden by squeezing or by buoyancy. However, none of the above-mentioned hypotheses can completely match the architecture of UHP belt and the P-T paths of UHP rocks. The erosion hypothesis is challenged by the lack of large basin that should receive thick sediments, and the extension hypothesis by the scale of Dabie orogenic belt. If no material is lost, when an overburden as thick as 100 km is thinned to 1 km, its original width should be enlarged by 100 times. This does not match the Dabie-Sulu orogenic belt whose width is about 200 km at most. The wedge-extrusion hypothesis enjoyed no support because no paired faults have ever been found.

The buoyancy hypothesis also met a series of problems. If the continental materials had low density, how could they be dragged down to a great depth? When and how did the buoyancy play its role? All these questions must be related to the deep geodynamic process. To solve these puzzles will no doubt result in a break-through in geodynamic paradigm.

4 Remarks

The international enthusiasm in studying ultra-high-pressure metamorphism and deep subduction has lasted a decade. A project "Processes and Geodynamics in Formation and Exhumation of the Ultrahigh-pressure Metamorphic Terrains" led by Chinese scientists has been listed as International Lithosphere Project III-8. The National Natural Science Foundation of China established a grant to support the study of UHP metamorphism and orogenic belt in the years 1997—2001. Every important progress in the study of continental deep subduction will influence and even change the prevalent geodynamics, as well as many branches of geoscience. For examples, in the field of geochemistry, the highest $\varepsilon_{Nd}(+260)$[24] in the world was found from the Weihai UHP eclogite. Many other important questions have been put forward during the studies of UHP rocks, such as what is the influence of UHP metamorphism on fractionation of isotopes, and how can we trace precisely the peak metamorphic age and quick exhumation time. In the geophysics field, how could we find the detailed structures of continent-continent collision zone?

The study of continent deep subduction will have important influences not only on geoscience, but also on some other fields. One of the examples is to determine the composition and structure of those tiny UHP minerals at μm scale, which requires to develop precise *in-situ* analysis methods. To simulate the role of fluids in phase change and reactions under UHP condition needs to develop high-temperature-high-pressure techniques in laboratory. These high technical developments no doubt will impact the material science.

Five years ago, Maruyama described 3 important progresses in geoscience[25]: (i) introducing new analyzing instruments and technology, such as ion probe and synchro-radiation; (ii) developing and applying seismic tomography technology in investigating deep structure of the earth; iii) applying space survey technology in geoscience. He forecasted that a new revolution in geoscience is coming. If it could be accepted that the above mentioned three progresses have laid a material foundation for the new revolution, the study of continental deep subduction is settling a theoretical foundation for the coming revolution. We should make good use of the historical chance, join the coming revolution that results from the study of continental deep subduction and make our active contribution to the progress in geoscience of the 21st Century.

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