HYDROUS PHASES IN UHP METAMORPHIC ROCKS FROM THE DABIE-SULU UHP TERRANE, EAST-CENTRAL CHINA

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Summary

Abundant hydrous minerals occur as stable ultrahigh-pressure (UHP) phases in a variety of UHP metamorphic rocks from the Dabie-Sulu terrane, China. These include Ti-clinohumite, chlorite, phlogopite and pargasite in garnet peridotite, talc, phengite, and zoisite/epidote in both coesite eclogite and metasediments, topaz-OH in kyanite-quartzite and nyböite in coesite eclogite. OH-Ti-clinohumite with high TiO_2 of 4 - 5 wt% and low F (0.05 - 0.20 wt%) coexists with garnet, pyroxene and olivine (Ol_1) in garnet peridotite and was partially replaced by ilmenite + olivine (Ol_2) during decompression. Talc is characterized by low Al (0.03 - 0.04 pfu) and rimmed by tremolite. Topaz-bearing quartzites consist of quartz + kyanite + topaz (5-20 vol%) ± phengite + minor pyrite and rutile; some topaz grains display compositional zoning with decreasing F content from core (12 - 16 wt%) to rim (<10 wt%). The maximum replacement of F by (OH) is up to 55%, much higher than previously reported 30% for natural topaz. OH-Ti clinohumite, low-Al talc and topaz-OH from Dabie-Sulu UHP rocks were formed at P-T conditions within the stability fields of diamond and/or coesite based on P-T estimates (700-900 ^oC, >3-6.7 GPa) of their host and associated rocks and experimental results. Parageneses and stabilities of these hydrous UHP minerals suggest that H_2O is an important component in subducted slab and may be carried to deep mantle by these UHP hydrous phases; some H_2O may be released to the overlying mantle wedge through their dehydration.

Introduction

The transportation and recycling of H_2O in subduction slab and its overlying mantle wedge play a significant role in generation of arc magma and deep-focus earthquakes, and in metasomatism of upper mantle rocks (e.g., Ulmer and Trommsdorff 1999; Kogiso et al. 1997). Synthesis and stability studies of hydrous phases indicate that some hydrous phases are stable at very high pressures at mantle depths and relatively low temperatures (Fig.1); these include lawsonite (Poli and Schmidt 1995), MgMgAl-pumpellyite (Fockenberg 1998), Phase A (Luth 1995; Pawley and Wood 1996), phengite (Domanik and Holloway 1996), and topaz-OH (Wunder et al. 1993). These, together with antigorite and chlorite for ultramafic system could store significant amount of H_2O at depths ≤ 200 km, whereas the dense hydrous magnesium silicate (DHMS) is the prominent H_2O-reservoir along a cold subduction path to a depth of ~ 300 km or more (Thompson 1992; Ulmer and Trommsdorff 1999).

Formation of most UHP metamorphic belts located at convergent plate boundary is caused by continent subduction and collision. Identification of hydrous phases in UHP metamorphic rocks is critical in understanding recycling process of H_2O in continental subduction zone. Among synthetic hydrous phases, only some have been recently found in natural rocks as the laboratory syntheses were conducted in the presence of excess H_2O at P-T conditions with extremely low geotherms not compatible with natural environment. This study describes parageneses and stabilities of recognized hydrous phases in diamond-, coesite - grade UHP rocks from the Dabie-Sulu terrane, and discusses the role of H_2O in continental subduction zone.

Hydrous phases in the Dabie-Sulu UHP rocks

The Triassic Qinling-Dabie-Sulu collision zone marks a junction between the Sino-Korean and Yangtze crotons. Representative UHP rocks including coesite eclogite, garnet peridotite, metasediments such as kyanite quartzite and marble are widespread in the Dabie-Sulu UHP terrane. In addition to the presence of coesite in eclogite and metasediments, these rocks are characterized by occurrence of UHP hydrous phases. Phengite, zoisite, epidote, nyböite and talc as eclogite facies mineral occur in many coesite-bearing eclogites; phengite, zoisite, epidote, topaz-OH occur in kyanite quartzites, and Ti-clinohumite, chlorite, phlogopite and pargasite are present in garnet peridotites (Zhang et al. 1994, 1995a, b; Liou et al. 1998). Some of these hydrous minerals, together with their experimentally determined stabilities are described below.

Hydrous phases in coesite-bearing eclogite and metasediments

Many petrological studies constrain P-T conditions for coesite-bearing eclogites and metasediments from the Dabie-Sulu UHP terrane at 600-850 ^oC and > 2.7 GPa; the maximum pressure is less constrain. Phengite is the most common phase in coesite eclogite and has Si values in pfu ranging from 3.5 to 3.6; the highest value is up to 3.62 (Zhang et al 1995a). Phengite show a wide stability field and is stable up to > 7.7 GPa and more than 920^oC for andesitic system (Poli and Schmidt 1995). More recent experiment indicates that phengitic muscovite was found to be stable from 5.5 - 11 GPa at 900 ^oC, and the average phengite content of muscovite increases with pressure from 3.65 Si pfu at 5.5 GPa to 3.81 pfu at 11 GPa (Domanik and Holloway 1996).

Zoisite/epidote and talc coexist with garnet, omphacite, kyanite ± phengite, and Zoisite/epidote also occur as retrograde phase in the Dabie-Sulu eclogites. Zoisite and epidote of peak stage contain inclusions of coesite and/or quartz pseudomorphs after coesite (Zhang et al. 1995a, b). Experimental result in the CaO-Al_2O_3-SiO_2-H_2O system suggests that the maximum pressure stability of zoisite is 6.5-6.8 GPa at 800-1200 ^oC (Poli and Schmidt 1994). Talc with low Al (0.0-0.11 pfu) occurs mainly in Mg-Al rich eclogite and has high Mg/(Mg+Fe) ratios of 0.96 - 0.97. Although no coesite inclusion was found in talc, talc was considered to be a UHP phase based on thermodynamic calculation and coexistence with coesite in eclogitic rocks (Zhang et al. 1995a, b; Liou and Zhang 1995), consistent with some experimental results (e.g., Massonne 1995).

Topaz $Al_2(F,OH)_2[SiO_4]$ was found in kyanite quartzites from several localities of the southern Dabie-Sulu terrane. Topaz-bearing kyanite quartzite includes two representative assemblages: (1) coesite/quartz + kyanite + topaz ± phengite, and (2) quartz + kyanite + topaz + woodhouseite $[CaAl_3(PO_4)(SO_4)(OH)_6]$ ± phengite; both contain minor pyrite and rutile. The quartzite with assemblage (1) occurs as thick layer interbeded with coesite-bearing eclogite within granitic gneiss. Grain size of quartz, kyanite and topaz show a large variation of 0.2-4 mm, but most are ~ 1 mm. Topaz contains abundant inclusions of orintated kyanite in addition to minor phengite, quartz, rutile and rare zircon. Inclusions of quartz pseudomorphs after coesite were found in kyanite; inclusions of coesite with thin palisade quartz rim in kyanite occur nearby quartzite consisting of quartz (~ 80 vol%) + garnet + omphacite + kyanite + epidote. The quartzite with assemblage (2) exhibits inequigranular texture; kyanite (up to 4 mm), topaz and woodhouseite (0.2 to 1.5 mm) are coarser than quartz. The coarser quartz grains (about 0.5-0.8 mm) show kink band and wave extinction. Euhedral woodhouseite contains topaz inclusion. Topaz from quartzite (1) is relatively homogenous in composition, and contains 12-15 wt% F whereas topaz from quartzite (2) contains 11-12 wt% F and shows distinct zoning. The compositional zoning includes (1) prograde zoning with decreasing F content from core (13.3, locally 16.5) through mantle (12.0) to rim (9.5 wt%), and (2) oscillatory zoning with a range of 9.4 to 12.8 wt% F. If topaz formula are calculated based on 3 cations, and F+ OH = 2, the OH/(F+OH) ratios range from 0.35 to 0.55, suggesting the maximum substitution of F by (OH) in the topaz is 55%. This value is the highest so far recognized for natural topaz. Previously reported topaz $Al_2(F,OH)_2[SiO_4]$ in acid igneous rocks and in late-stage hydrothermal vein in pegmatites or in greisen are enriched in F with the maximum substitution of F by (OH) at 30% (Wunder et al. 1993).

Experimental study of topaz-OH indicates that topaz-OH (end-member) is stable at about 5.5 GPa at 700 ^oC and > 9 GPa at 1000^oC (Wunder et al. 1993). The high water-bearing Sulu topaz in equilibrium with kyanite and coesite may have formed at UHP conditions at extremely low geothermal gradient. The presence of abundant kyanite inclusion in topaz records a prograde metamorphic history.

Hydrous phase in garnet peridotites

Garnet peridotites in the Dabie-Sulu UHP terrane were classified into two types based on their mode of occurrence and petrochemical characteristics: type A mantle-derived peridotites and type B crustal peridotite and pyroxenite, that were intruded into continental crust as magmatic cumulates prior to subduction. Both type peridotites were involved into subduction zone and subjected to UHP metamorphism (Zhang et al. 2000). Only minor hydrous phases, such as phlogopite and amphibole, occur in type A mantle-derived peridotites; in contrast considerable amount of hydrous phases and carbonate such as magnesite are present in type B garnet peridotites.

Chlorite is the major aluminous hydrate in harzburgite mantle in the $MgO-Al_2O_3-SiO_2-H_2O$ system and has a large stability field with pressure range of 0.5-5 GPa at the maximum temperature limits of 750-890 ^oC (Ulmer and Trommsdorff 1999). Chlorite often occurs as a retrograde phase in ultramafic rocks. However, minor relatively coarse-grained euhedral chlorite are present as a primary phase in Bixiling websterite and Sulu garnet clinopyroxenite.

Ti-clinohumite is an important dense hydrous magnesium silicate in the Earth's mantle (Thompson, 1992) and may be stable at 150-300 km (5-10 GPa) and 700-1100^oC (Ahrens, 1989). Ti-clinohumite was found as coarse-grained accessory phase in matrix and minute inclusion in garnet, pyroxene, olivine and magnesite in the Dabie ultramafic rocks. Rare Ti-clinohumites occur as mineral inclusions in the Sulu garnet peridotites and as intergranular phase in marble. Ti-clinohumite in Bixiling lherzolite, wehrlite and websterite (± magnesite) is replaced by ilmenite + olivine at its margins during exhumation, and contains TiO_2 and F ranging from 2.98 to 4.75 wt% and from 0.05 to 1.05, respectively (Zhang et al. 1995a). Titanian clinohumite from Maowu garnet orthopyroxenite and harzburgite contains lower TiO_2 (0.2-3.2 wt%) and higher F (0.87-1.34), and shows magnetite lamellae (Okay 1994; Liou and Zhang 1998; Zhang et al. 1999). The stability of Ti-clinohumite was studied at a presure range of 0.1-3 GPa (Engi and Lindsley1980); Weiss (1997) extended the pressure range to 8 GPa. Experimental curves of the breakdown reaction of natural hydroxyl titanian clinohumite (X_{Ti}=0.28, X_{Fe}=0.04 and X_F=O) to olivine + ilmenite + H_2O indicate that the fluorine free Ti-clinohumite is stable at 700^oC with minimum pressure of 2-3.5 GPa, and 800 ^oC with minimum pressure of 3.5-4.8 GPa; F stabilizes clinohumite to much higher temperature (Weiss 1997). P-T calculations of titanian clinohumite-bearing samples yield 4.7-6.7 GPa at 800 ^oC for Bixiling and 4.3-6.9 at 750-800 ^oC for Maowu (Fig. 1). These P-T estimates are consistent with the experimentally determined stability of hydroxyl titanian clinohumite.

In summay, paragenses and P-T estimates of various hydrous phases in Dabie-Sulu UHP rocks imply these hydrous phases are stable in the coesite and even diamond stability fields with very low geothermal gradient. The role of H_2O in subducted oceanic lithosphere and the stabilities of hydrous phases and DHMS have been extensively studied (e.g., Peacock 1990; Thompson; Ulmer and Trommsdorff 1999; Okamoto and Maruyama, 1999). Compared with subducted hydrated oceanic crust, the supracrustal rocks of continental subduction are relatively dry and old. Most volatiles of subducted continental lithosphere include: (a) those released by dehydration reactions incorporated into the overlying mantle wedge, (b) those stored in hydrous phases of the subducted continental slab as incomplete devolatilization, and (c) those in some volatile-bearing melt produced by local partial melting. However the supracrustal rocks at great depths failed to release sufficient fluid flux to cause large scale melting of the overlying mantle wedge + continental crust for formation of coeval magmatic arc (Liou et al. 1997). It is unlikely that there are large volumes of free fluid in deep subduction zone, as rare observation of fluid inclusions in UHP minerals and very limited O-isotopic exchange; probably H_2O will be confined as a component, not a phase, in fluid-deficient condition. The amount of volatiles transported to mantle depths depends mainly on how much volatiles stored in UHP hydrous phases.

Conclusions

Several lines of evidence indicate hydrous phases (phengite, talc, zoisite/epidote, topaz-OH hydroxyl-titanian clinohumite etc.) are stable at least in the coesite stability field; some are only restricted to subduction environments of very low geothermal gradient of ≤ 5 ^oC/km and they are not stable in normal mantle. The common occurrence of minor UHP hydrous phases in UHP rocks from the Dabie-Sulu terrane suggests that H_2O as a component plays an important role in continental subduction-zone UHP metamorphism. The observation of natural parageneses combined with experimental stabilities of phase equilibrium and thermodynamic calculation document that UHP hydrous phases described above are H_2O-carrier to mantle depths of 100-200 km.

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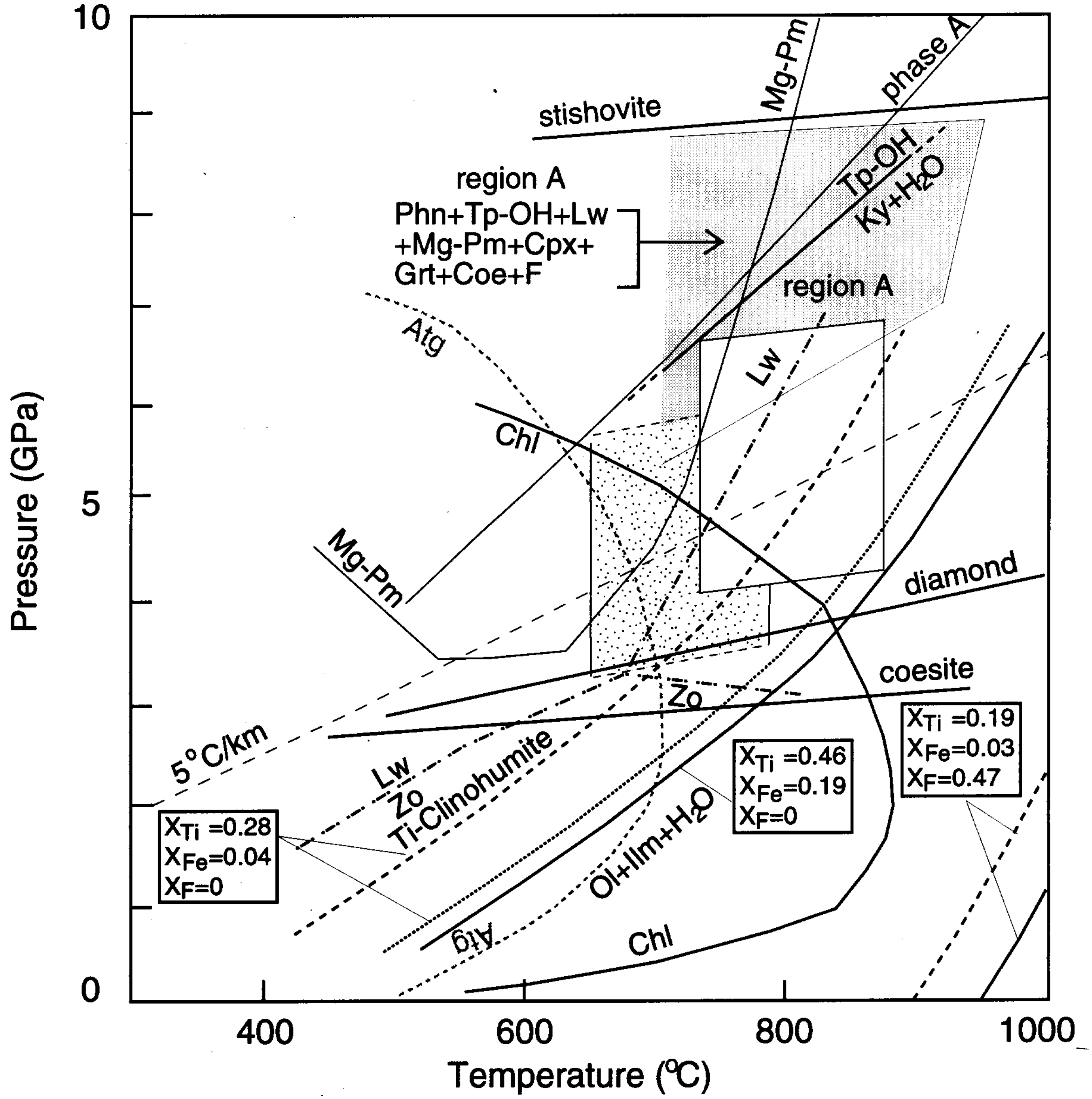

Fig. 1. P-T diagram showing P-T estimated fields for garnet peridotites (white box) and eclogite (sand box) from the Sulu-Dabie terrane (after Zhang et al. 2000). The stabilities of lawsonite (Poli and Schmidt 1995), MgMgAl - pumpellyite (Fockenberg 1998; Schreyer et al. 1991), phase A (Pawley and Wood (1996), antigorite and chlorite (Ulmer and Trommsdoff 1995, 1998), region A phase assemblage (Domanik and Holloway 1996) and Ti-clinohumite with various compositions (Weiss 1997) are also shown. Abbreviations: Atg, antigorite; Coe,coesite; Cpx, clinopyroxene; Chl, chlorite; Lw, lawsonite; Phn, phengite; Pm, pumpellyite; Tp-OH, topaz-OH; Zo, zoisite.

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