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PRESERVATION AND RETROGRESSION OF ULTRA HIGH PRESSURE (UHP) ROCKS: CASE STUDIES OF UHP METAGRANITOIDS IN WESTERN ALPS AND SU-LU REGION

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Abstract: The *in situ* association of ultra high pressure (UHP) rocks and country gneiss, and possible mechanisms to obliterate the UHP metamorphic minerals during exhumation will be discussed for giving a new insight to a debate between *in situ vs.* external origin of UHP rocks. The UHP rocks associated with UHP metagranitoids found in southern Dora Maira massif, western Alps and the Yangkou unit in the Su-Lu region, eastern China are distinct examples of the *in situ* origin. The deformation and accompanied fluid infiltration at low-pressure conditions pervasively erased the precursor UHP evidence without a significant heating in these areas. Granulite facies overprinting on UHP/HP metamorphic rocks is reported in some UHP terranes. Annealing at medium temperature and low-pressure conditions could be another candidate for obliterating the UHP metamorphic minerals pervasively.

key words: ultra high pressure rock, retrogression of metagranitoid, granulite facies over printing

1. Introduction

Since the first find of coesite from metamorphic crustal materials by Chopin (1984) and Smith (1984), and of diamond by Sobolev and Shatsky (1990), the petrology and geochemistry of coesite- or diamond-bearing ultra high pressure (UHP) rocks has become a major topic in the metamorphic geology of this decade. Coesite- or diamond-bearing ultra-high pressure (UHP) rocks have been found in six orogenic belts in the Eurasian and African continents by 1997 (Fig. 1). The tectonics of those areas is closely related to continent-continent collision (CCC) which took place from Late Proterozoic (Mali) to Tertiary (Dora Maira). These facts indicate that the formation of UHP rock is not an exceptional phenomenon in the CCC zone.

The main country rock in the CCC zones that accompanies UHP rocks is quartzo-feldspathic gneiss that has no conspicuous UHP evidence. The principal UHP rock, eclogite, occurs as isolated lenses or intercalated layers in the country gneiss and rarely in garnet peridotite or marble (Fig. 2). The UHP eclogite is commonly rimmed by amphibolite in various degrees of development. The mineral assemblages of the country gneiss are usually isofacial to that of the retrogressed rim of the UHP eclogite. In order

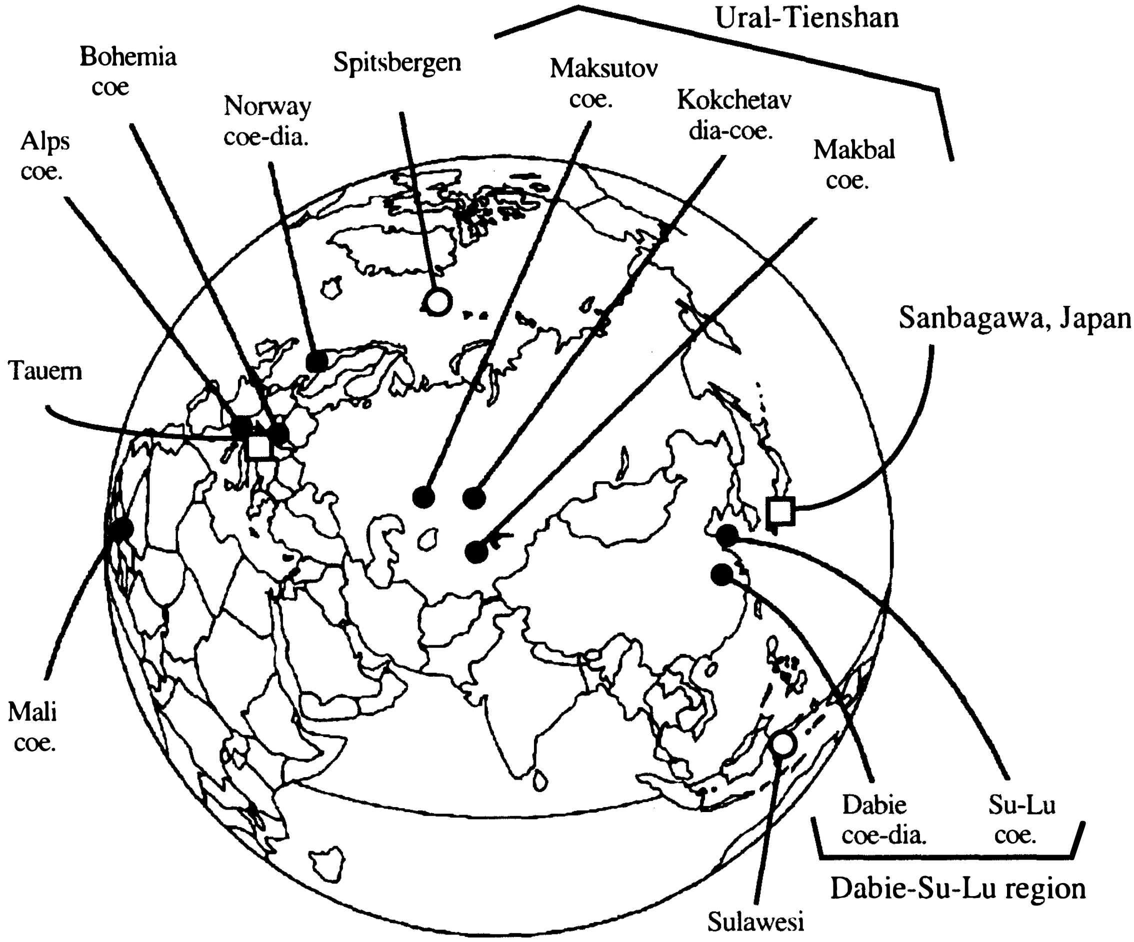

Fig. 1. The distribution of the ultra high pressure (UHP) rocks (●) and of the representative high pressure eclogite (○, □) in the eastern hemisphere (modified from COLEMAN *and* WANG, *1995). coe: coesite, dia: diamond, ○: epidote-glaucophane eclogite, □: kyanite-quartz eclogite.*

to explain the pressure gap between the UHP eclogite and the surrounding rocks, a debate between *in situ vs.* external models still continues.

The *in situ* school insists that both eclogite lenses and the surrounding gneiss suffered the same UHP metamorphism, and the UHP gneiss has completely transformed to the country gneiss with low pressure paragenesis during its uplift to mid-crustal level (Fig. 3). The exotic school insists that the tectonic emplacement of UHP rocks into the country gneiss took place in the middle or lower crust. This is an intuitive interpretation from the field observation, but it is difficult to explain the incorporation of the dense UHP metabasites from the upper mantle to the lower crust.

In this contribution, the author intends to discuss 1) the *in situ* association of UHP rocks and country gneiss and 2) the possible mechanism to obliterate the UHP metamorphic minerals during the exhumation, referring to the following three areas; southern Dora Maira massif in western Alps, Yangkou and Weihai areas in the Su-Lu UHP belt, eastern China.

The first two areas, southern Dora Maira massif and the Yangkou unit, are the

Fig. 2. A typical mode of the occurrence of UHP rocks. Strongly retrogressed eclogite block surrounded by the country Su-Lu gneiss at Weihai area, Su-Lu UHP region.

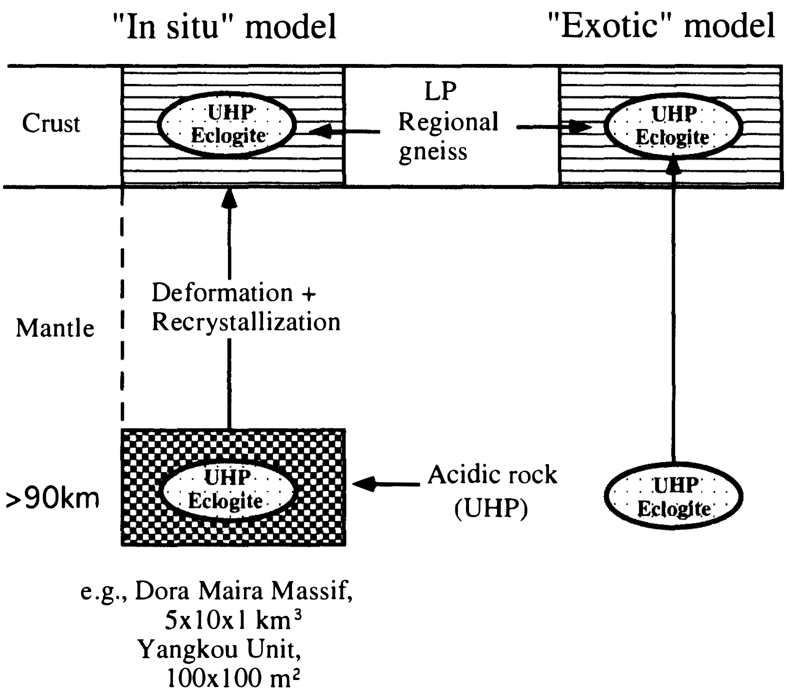

Fig. 3. Cartoon for the in situ and exotic model.

diagnostic example of the *in situ* model, due to the occurrence of UHP metagranitoids. Petrological evidence from these areas indicates that the deformation and accompanied fluid infiltration during the exhumation stage pervasively erased the precursor UHP evidence without a significant heating, and a rock free from this deformation can preserve its UHP evidence. In the Weihai area, a granulite facies overprint on UHP rocks was established (WANG *et al.*, 1993). The precursor UHP evidence is preserved as a scarce inclusion phase in porphyroclastic garnet in granulite which has no distinct deformation texture. Annealing at medium- or high-temperature and low-pressure conditions is another plausible candidate for obliterating pervasively the UHP metamorphic minerals.

2. Dora Maira Massif

2.1. Geological outline

The coesite-bearing UHP rocks occurs in two localities in the western Alps: one in the southern Dora Maira massif (DMM) and the other in a meta-oceanic sequence in the Zermatt-Saas zone.

The DMM is mainly derived from Paleozoic rocks attributed to the passive margin of the European plate, and it consists of a pile of thin thrust sheets, which are characterized by significantly different Early-Alpine recrystallization from blueschist to eclogite facies metamorphism (*e.g.*, COMPAGNONI *et al.*, 1995).

In the southern Dora Maira massif, the $5 \times 10 \times 1$ km^3 UHP rocks only occur in a small nappe shown as UHP in Fig. 4, and are in tectonic contact with an overlying eclogite

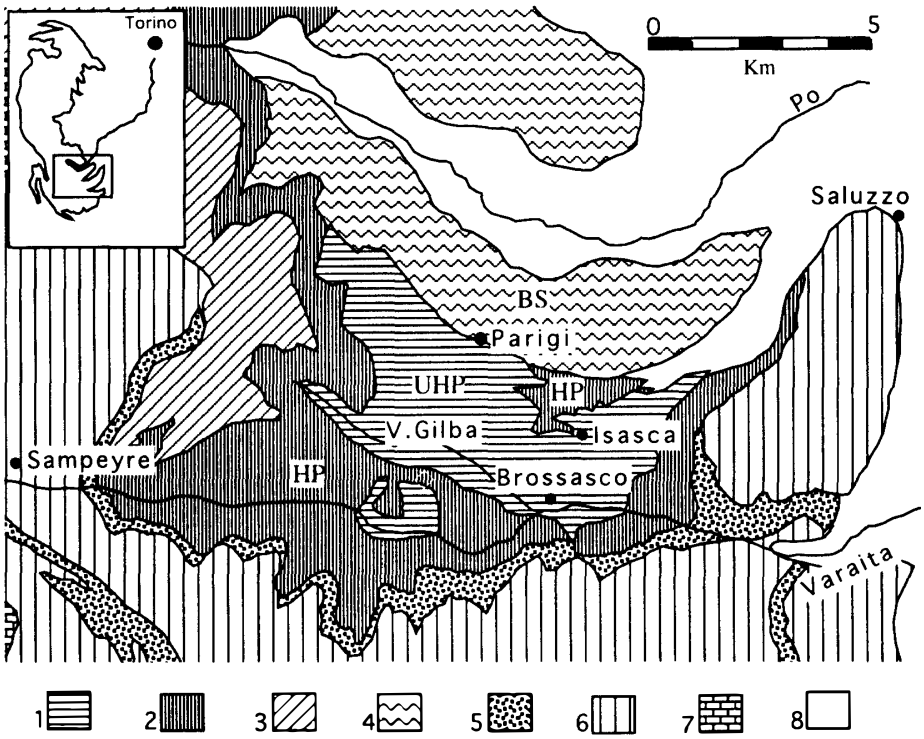

Fig. 4. *Geological sketch map of southern Dora Maira massif. Modified from* COMPAGNONI *et al. (1995) and* MICHARD *et al. (1995).*
1: Ultra high pressure (UHP) unit. 2: Quartz eclogite (HP) unit. 3: Pre-Alpine basement and Permo-Carboniferous + Permo-Triassic cover with low-T eclogite facies overprint. 4: Pinerolo unit epidote-blueschist facies (BS) overprint. 5: Oceanic sediments with blueschist facies overprint. 6: Mesozoic cover and calcschists with blueschist facies overprint. 7: Upper Palaeozoic and Lower Triassic unit with blueschist facies overprint. 8: Postorogenic sediments.

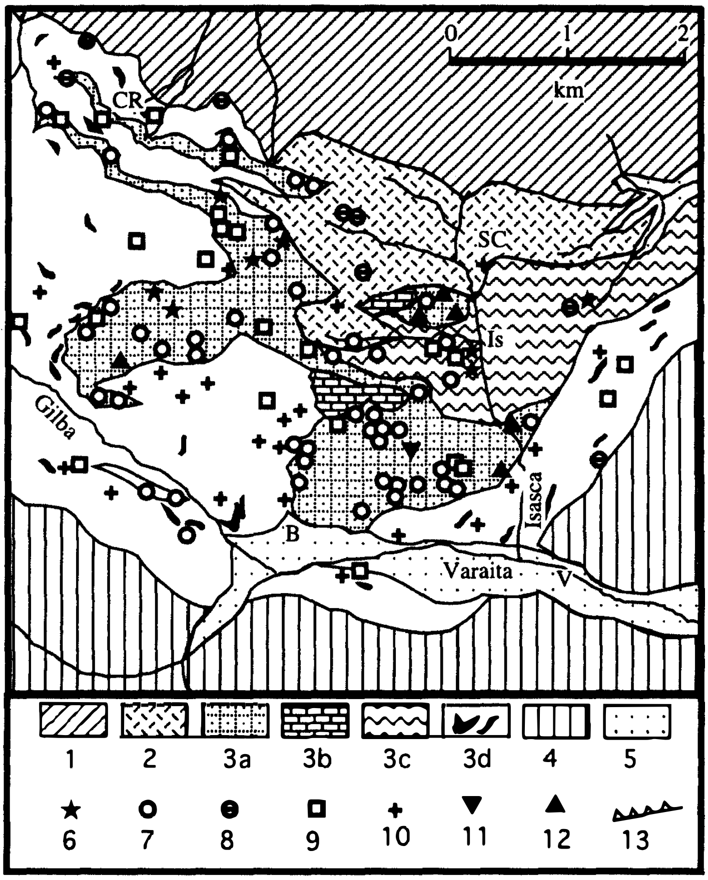

Fig. 5. Detail geological map of the central part of the coesite-bearing "Brossasco-Isasca" unit. 1: Pinerolo unit, blueschist facies. 2: Lower tectonic unit with basement rocks overprinted by Low-T eclogite facies. 3: Coesite-bearing Brossasco-Isasca unit. Polymetamorphic complex; 3a: Paraschists with Middle-T eclogite and marble, 3b: Main marble intercalations, 3c: Fine-grained phengite-rich gneiss. Monometamorphic complex, 3d: Augengneiss grading to medium- to fine-grained orthogneiss with pyrope-bearing whiteschist layer (black lens). 4: Upper tectonic unit with basement rocks overprinted by Low-T eclogite facies. 5: Alluvial deposits. 6: Small marble lens. 7: Fresh eclogite. 8: Retrogressed eclogite. 9: Kyanite-jadeite occurrence, 10: Relic Variscan granitoid. 11: Relic regionally metamorphosed Variscan paraschist. 12: Relic thermally metamorphosed Variscan paraschist. 13: Tectonic contact. B: Brossasco, CR: Case Ramello. Is: Isasca. SC: San Chiaffero church, V: Venasca.

facies nappe (HP), and an underlying eclogite (HP) and blueschist facies nappe (BS).

The UHP rocks are mainly composed of the following two lithological units: a monometamorphic and a polymetamorphic (Fig. 5).

The polymetamorphic unit mainly consists of paraschist (3a), marble (3b), and fine-grained phengite-rich gneiss (3c) with eclogite intercalations (circle).

The monometamorphic unit mainly consists of augen gneiss and medium- to fine-grained mylonitic orthogneiss. The relic of the metagranitoid lithology (+) and the pyrope-bearing whiteschist (black worm) are widely distributed in this unit. The polymetamorphic unit is considered as Hercynian metamorphic basement and the

Table 1. Representative mineral assemblages in the UHP unit of the Dora Maira massif Phn : phengite, Coe : coesite, Nybo : nyboeite, Other abbreviations follow KRETZ *(1983).*

Pock type	Prograde	Climax	Early Retrograde	Late Retrograde
White schist	Phn in Ky	Prp-Coe	Gln-Pg Tlc-Phn	
Sodic White schist		Prp-Gln-Jd		
Jadeite fels		Jd-Grt-Coe*	Omp-Ab-Qtz Fe-Nybo	Agt-Bt
Eclogite		Grt-Omp-Ky Coe-Ep	Pg	Hbl-Ab
Metapelite	Cld-St-Pg-Qtz in Grt core	Jd-Ky-Coe	Pg	Mrg
Metagranite		Grt-Jd-Coe*		Ab-Ms
P-T condition	16 kbr 560°C	32–36 kbr 750±30°C	12–15 kbr 500–570°C	
Reference	1	1, 2, 3	4	

1: SCHERTL *et al.* (1991), 2: CHOPIN *et al.* (1991), 3: KIENAST *et al.* (1991), 4: HIRAJIMA and COMPAGNONI (1993), *: pseudomorph.

monometamorphic unit as a Hercynian intrusive (*e.g.*, CHOPIN *et al.*, 1991; COMPAGNONI *et al.*, 1995).

2.2. *Mineral assemblage and P-T path of the UHP unit*

Representative mineral assemblages of the UHP unit are compiled in Table 1. Abbreviations of minerals mainly follow KRETZ (1983).

Coesite is found from various rock types in the UHP unit. Jd-Ky assemblage in the metapelite is one of the indicators of UHP conditions and is a prograde decomposition product of paragonite

Jd-Prp-Gln assemblage in the sodic whiteschist (KIENAST *et al.*, 1991) and Jd-Tlc assemblage inferred from the Tlc crystal included in a pseudomorph after jadeite in the pyrope whiteschist (CHOPIN *et al.*, 1991) define pressure conditions at the UHP stage by the reaction curve of Gln=Jd+Tlc. The synthetic work and the thermodynamic calculation of relevant phases (*e.g.*, CARMAN and GILBERT, 1983; BROWN *et al.*, 1988) and the Grt-Cpx geothermometry give the *P-T* conditions of the UHP stage as 32–36 kbar and 750°C (Fig. 6).

The prograde path is estimated using inclusion mineral assemblages. The inclusion assemblage of the garnet core in the paraschist is Ctd+Pg+St+Qtz, but that of the rim is Ky and Coe (Table 1). SCHERTL *et al.* (1991) estimated the prograde trajectory passed 16 kbar and 560°C mainly using the phengite composition armoured in a kyanite inclusion

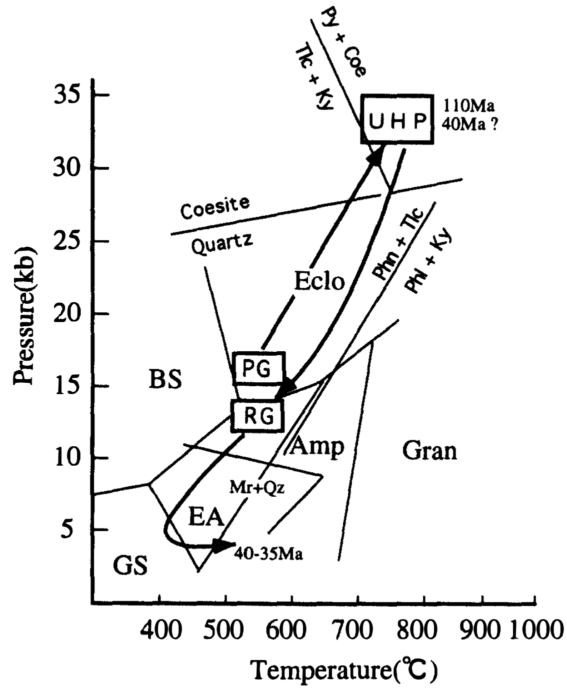

Fig. 6. Prograde and retrograde path of Dora Maira UHP rocks. PG: P-T conditions in prograde stage, RG: P-T conditions in retrograde stage. Metamorphic facies boundaries are modified from Oh *et al. (1988). Gran: granulite facies, Amp: amphibolite facies, EA: epidote amphibolite, GS: green schist facies, BS: blue schist facies, Eclo: eclogite facies.*

in pyrope.

The retrograde path is defined by the decomposition reactions of UHP phases. Two steps of the decompression trajectory are recorded in the alteration of kyanite, which is first replaced by paragonite and later by margarite (COMPAGNONI *et al*., 1995).

P-T conditions of the early decompression stage are estimated as 500–570°C and 12–15 kbar using Fe-Mg distribution between secondary Omp and adjoining Grt, and X_{jd} content of the secondary Omp in the jadeite-fels by HIRAJIMA and COMPAGNONI (1993).

These data give a hair-pin shaped *P-T* path for the Dora Maira UHP rocks (Fig. 6). The steep prograde and retrograde paths are constrained by the occurrence of zoisite from the prograde stage to the climax conditions in eclogite and paraschist, and by the occurrence of Tlc and Phn in the whiteschist (Fig. 6). The Tlc-Phn assemblage developed in the matrix of the whiteschist gives the other constraint for the decompression stage. CHOPIN (1984) reported that the Phl + Ky assemblage developed between pyrope and phengite by the reaction of Phn + Prp = Phl + Ky + Qtz, and it is the higher T-side assemblage of the decomposition of Phn + Tlc (= Phl + Ky + Qtz). CHOPIN (1997) reported a rare occurrence of En and sapphirine along the crack of the pyrope and he ascribed the occurrence of such higher temperature assemblages to the lower water activity along the crack of pyrope. Much still remain to be done, but the proposed *P-T* path in DMM is the most reliable path among the UHP rocks so far reported, because much information is preserved in various rock types.

2.3. The effect of the deformation on mineralogy of orthogneiss

AVIGAD (1992) and MICHARD *et al.* (1995) pointed out that both the UHP unit and neighboring nappe deformed under greenschist facies conditions, and produced a half dome structure in the southern Dora Maira massif. At this stage, the orthogneiss both in

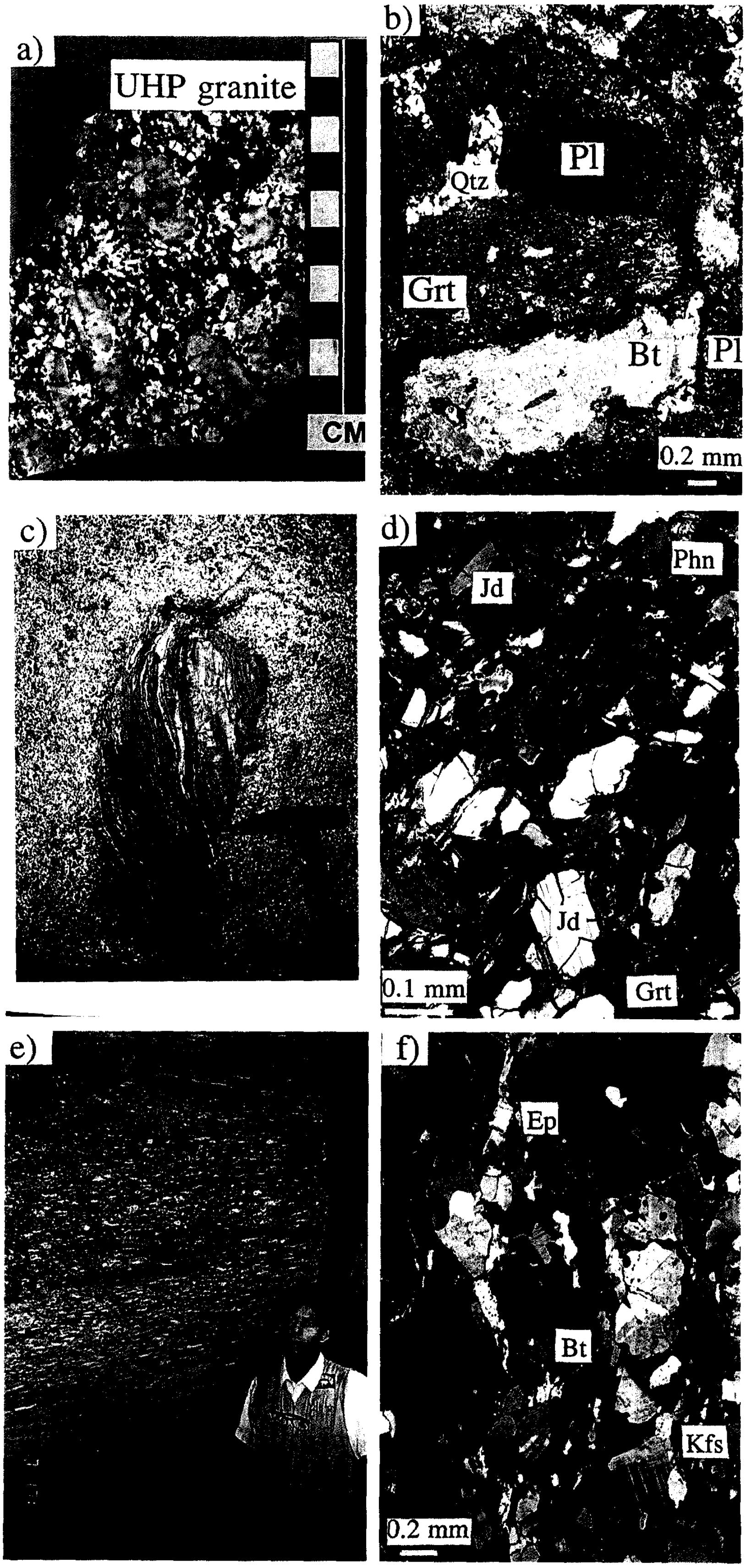
a)
UHP granite
CM
b)
Pl
Qtz
Grt
Bt
Pl
0.2 mm
c)
d)
Phn
Jd
Jd
0.1 mm
Grt
e)
f)
Ep
Bt
Kfs
0.2 mm

Fig. 7

the UHP and HP nappes of the Dora Maira massif were pervasively deformed. Some metagranitoids free from the deformation were found from these units as shown in Fig. 5. In Fig. 7, the author illustrates how a rock free from the deformation has preserved well Hercynian igneous textures and UHP mineral assemblage whereas the acidic rock was easily transformed to Bt-gneiss on account of the development of the deformation.

Figure 7a is the polished surface of less-deformed metagranitoid in the UHP unit. Without microscopic observation, it can hardly be distinguished from a Tertiary granite. Under the microscope, however, biotite and a fine-grained aggregate of albite, white mica and epidote after plagioclase maintain their original idiomorph, although coronitic garnet commonly develops along the grain boundary between plagioclase and biotite (Fig. 7b). Biotite transformed to Si-rich phengite to various extent. The primary quartz changed to a polygonal and polycrystalline aggregate of quartz. Figure 7c is a photomicrograph of the metagranitoid with a pelitic xenolith in the UHP unit. If such a texture was found in a low pressure metamorphic belt, it would be regarded as a paraschist xenolith in granite. This texture was actually formed at 300 Ma (U/Pb zircon dating by Paquette, in Monie and Chopin, 1991), but the xenolith and the host granite suffered Alpine UHP metamorphism as shown in a photomicrograph of the xenolith (Fig. 7d). The xenolith is mainly composed of Jd-Grt-Phn$\pm$Ky, suggesting that it experienced the UHP metamorphism.

However, such UHP assemblages and original igneous textures are easily obliterated by later stage deformation, especially in the orthogneiss. The gradual transformation from the augen gneiss to the fine-grained mylonitic gneiss accompanied by deformation is commonly observed on an outcrop scale in the UHP unit (Fig. 7e). Such deformed gneiss occupies more than 90% of the monometamorphic unit. A photomicrograph of the representative orthogneiss in this unit is shown in Fig. 7f.

The mineral assemblage of the orthogneiss is Qtz-Pl-Kfs with minor Bt, Phn, Ep, Grt and Hbl. This assemblage is the same as that of the regional gneiss in other UHP terrains. However, the geological and mineralogical evidence mentioned above suggests that this orthogneiss of the Dora Maira massif was certainly transformed from the UHP metagranitoid.

The author emphasizes again that later stage deformation in the UHP unit of the southern Dora Maira massif could easily erase the precursor UHP evidence, especially in the acidic rock.

Fig. 7 (opposite). Representative photo/photomicrograph of metagranitoid and orthogneiss in the Dora Maira massif. a) Polished surface of non-deformed metagranitoid in the UHP unit. b) Photomicrograph of the non-deformed metagranitoid (DM989). Thin coronitic garnet (Grt) developed between igneous biotite (Bt), now partly replaced by phengite, and plagioclase (Pl) domain, now aggregate of albite, epidote and mica. Qtz: quartz. Crossed nicols. c) Pelitic schist xenolith enclosed by UHP metagranitoid at Bastoneri. d) Photomicrograph of the pelitic xenolith (DM1361). Jd: jadeite, Grt: garnet. Phn: phengite. Crossed nicols. e) Transitional deformation from the augengneiss to mylonitic orthogneiss in the UHP unit. f) Photomicrograph of the typical orthogneiss in the UHP unit (DM1361). Bt: biotite, Kfs: K-feldspart Ep: epidote. Crossed nicols.

3. Yangkou Unit in the Su-Lu Region, China

The Su-Lu-Dabie UHP belt developed in the continent-continent collision zone between the Sino-Korean and Yangtze cratons, and the Su-Lu region occupies the eastern part of the collision belt (Fig. 8). UHP evidence of the Su-Lu region is found mainly in eclogite and garnet lherzolite which are distributed in the southeastern half of the Shandong Peninsula. The major rock type of the Su-Lu region is orthogneiss with amphibolite facies mineral assemblages, as in the other regional gneiss regions that accompany UHP rocks. However, cooperative studies between Kyoto University and Academia Sinica found a meta-igneous complex including metagranitoids and coesite eclogite at Yangkou, near Qingdao, in the middle of the Su-Lu region (HIRAJIMA *et al.*, 1993; WALLIS *et al.*, 1997).

3.1. Geological and petrological outline of the Yangkou unit

A detail geologic map of the Yangkou beach is shown in Fig. 9. The basement rocks of the Yangkou beach can be divided into two units: the meta-igneous complex (Yangkou unit) and the surrounding Su-Lu orthogneiss. The details of geology of the Yangkou beach are given by WALLIS *et al.* (1997).

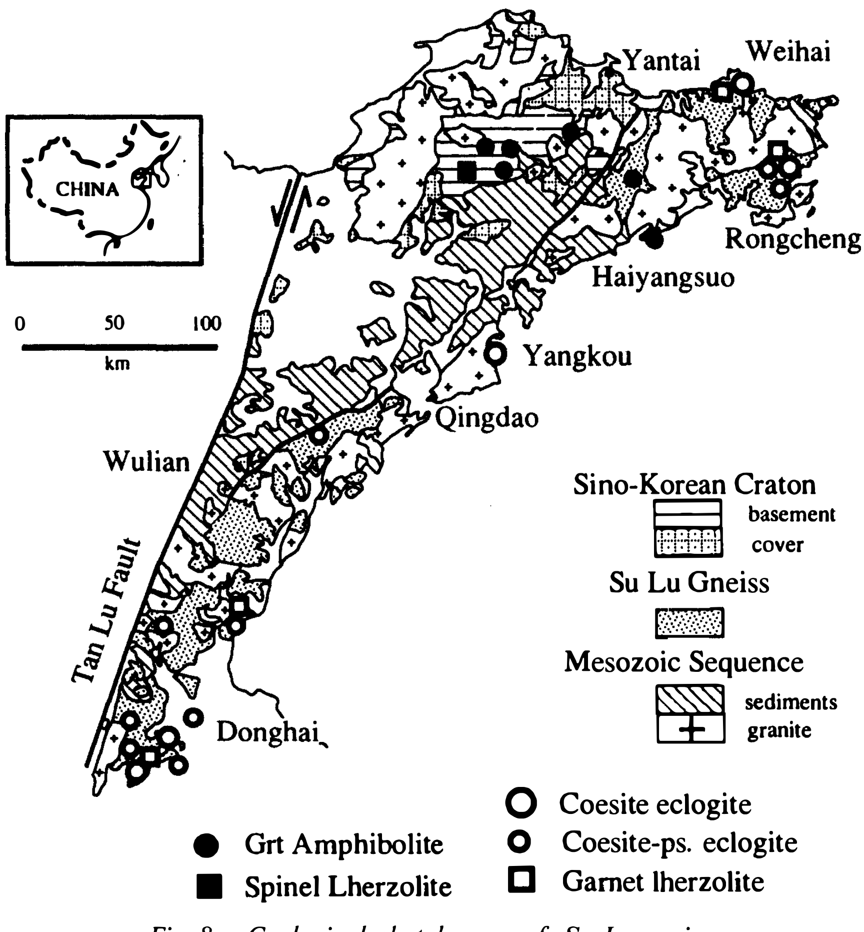

Fig. 8. Geological sketch map of Su-Lu region.

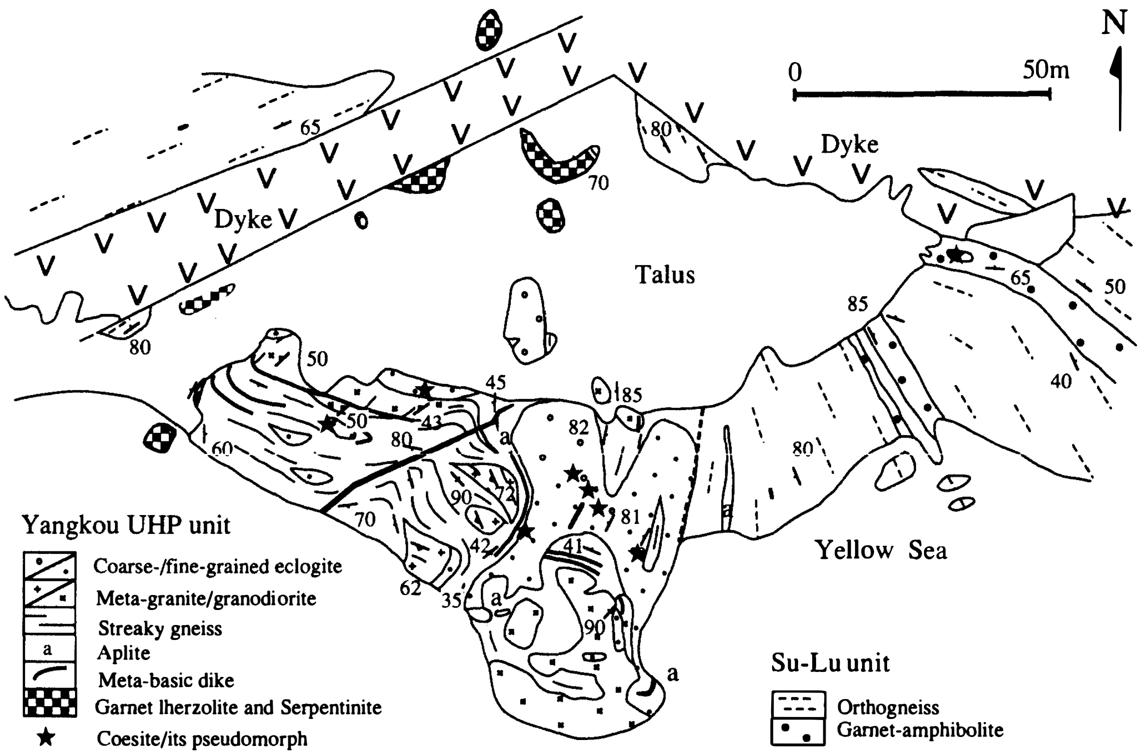

Fig. 9. Detail geological map of the Yangkou unit.

The Yangkou unit (*ca.* $100 \times 100\,m^2$) is mainly composed of metabasite, metagranitoid and streaky gneiss, the last with a prominent stretching fabric. The Su-Lu orthogneiss is characterized by a monotonous foliation which forms an open fold incorporating intercalated garnet-amphibolite layers.

The SiO_2 content of the Yangkou meta-igneous complex ranges from 50 wt% (eclogite) to 70 wt% (metagranitoid) with systematic decrease of CaO, MgO and TiO_2 (max. 1.4 wt%) and it has an almost constant P_2O_5/TiO_2 wt% ratio (*ca.* 0.3) and a uniform light rare earth-enriched pattern (ISHIWATARI *et al.*, 1996). Zircon separates from the eclogite and metagranitoid have similar U-Pb SHRIMP ages of *ca.* 750 Ma (HIRAJIMA *et al.*, in preparation). All major constituents of the Yangkou unit contain UHP evidence, such as coesite in the eclogite and low-Al Opx in metagranitoid and garnet lherzolite (Table 2). These facts suggest that the protolith of the Yangkou unit originated from a calc-alkaline magma in the late Proterozoic probably as a part of the Yangtze cratons and it also suffered the UHP metamorphism. This is one of the best localities to demonstrate the *in situ* origin of the UHP and surrounding rocks.

The Su-Lu orthogneiss at Yangkou, however, has no UHP evidence at all, but relict coesite was found from the eclogite in the core of the amphibolite layer, *ca.* 50 m apart from the Yangkou unit. Temperature estimated using Grt-Cpx geothermometer of POWELL (1985) with a special care for the X_{Jd} effect of Cpx gives 600–650°C at 30 kbar for eclogites in both units, suggesting that the Yangkou unit and surrounding area suffered the same UHP metamorphism (HIRAJIMA, 1996).

WALLIS *et al.* (1997) distinguished three deformation stages, D1, pre-and syn-UHP stage, D2, early decompression stage with high strain rate and D3, later static decompres-

Table 2. UHP evidence observed in the Yangkou unit.

Granitoid	omphacite armouring sodic diopside, low-Al orthopyroxene, coronitic garnet, granoblastic quartz aggregate.
Eclogite	coesite-omphacite-garnet$\pm$kyanite
Ultramafics	low-Al Opx - Mg-rich garnet
Streaky gneiss	remnant of coronitic garnet and rutile

sion stage.

3.2. The representative rocks in the Yangkou unit

The eclogite in the Yangkou unit is composed of coarse- and fine-grained types. Both types of eclogite are mainly composed of Omp-Grt-Phn-Ky$\pm$coesite. The coarse grained-type eclogite free from the deformations during syn- and post-UHP metamorphism still maintains a primary igneous texture (Fig. 10a). The primary igneous minerals, however, are pseudomorphosed by eclogite facies minerals, *e.g.*, igneous augite to omphacite and plagioclase to the aggregate of Jd (at present Ab)-Zo-Ky-Phn. The coronitic Grt garnet develops between the igneous augite and plagioclase domains (Fig. 10b). The fine grained-type eclogite is generally well foliated or folded (Fig. 10c). This type of eclogite commonly contains coesite as an inclusion phase both in omphacite and garnet, but also as a matrix phase (Fig. 10d). One matrix coesite exists near the crest of a fold, suggesting that the tight folding of this eclogite was formed at the D1 stage.

Figure 11a shows a polished surface of the metagranitoid free from D1 and later stage deformations in the Yangkou unit. The mineralogical texture of the metagranitoid is almost identical to those of the UHP metagranitoid in Dora Maira massif (Fig. 11b), *i.e.*, plagioclase and biotite preserve the primary igneous texture, and coronitic garnet developed along the grain boundary between mafic phase and primary plagioclase. The primary quartz changed to a polycrystalline aggregate.

3.3. Effect of later stage deformation on the metagranitoid

The metagranitoid block is gradually transformed to streaky gneiss along its margin (Figs. 11a, c). The polished surface of a specimen showing the gradual transformation (Fig. 11c) is cut perpendicular to the foliation and parallel to the lineation. K-feldspar occurs as augen in the slightly deformed part, but in the streaky part it is distinctly elongated. In the streaky part, the primary igneous structure is completely destroyed (Fig. 11d); Plagioclase domain is completely obliterated and the arrangement of fine-grained garnet, developed between plagioclase and biotite in the metagranitoid, defines a new foliation in the streaky gneiss. Primary K-feldspar is rimmed by fine-grained neoblast or subgrain of K-feldspar. The main constituents of the streaky gneiss is the Kfs-Pl-Qtz, this is identical to that of the Su-Lu gneiss. The fine-grained garnet and rutile armored by titanite are the evidence of precursor UHP conditions.

The Su-Lu gneiss, however, is easily distinguished from the streaky gneiss in the field, by the lack of the prominent stretching fabric and by coarser grain size of the main

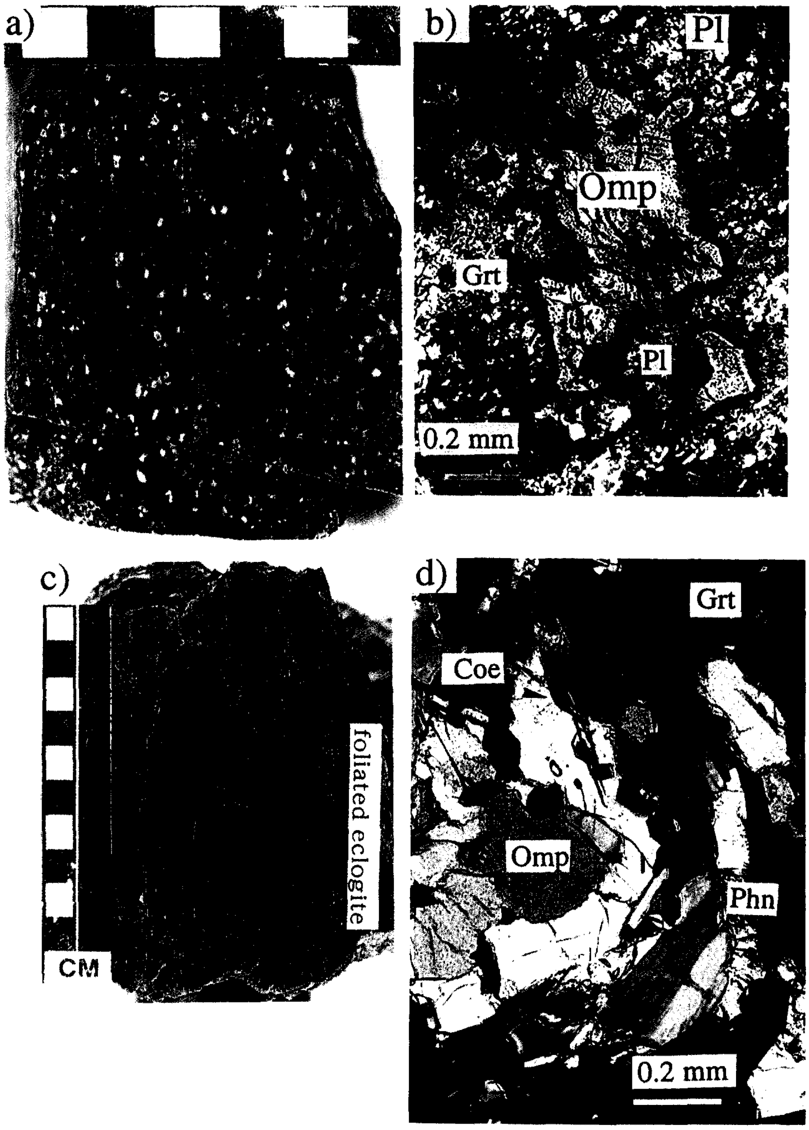

Fig. 10. Representative photo/photomicrograph of eclogite in the Yangkou unit. a) Polished surface of less-deformed coarse-grained eclogite (94YK14D). b) Photomicrograph of the less-deformed coarse-grained eclogite (94YK14E). Thin coronitic garnet (Grt) developed between igneous clinopyroxene, now omphacite (Omp), and plagioclase (Pl) domain, now aggregate of albite, epidote and mica. Crossed nicols. c) Polished surface of folded fine-grained eclogite (94YK15A). d) Photomicrograph of the folded fine-grained eclogite (94YK15A). Partly transformed coesite (Coe) occurs as the matrix phase along with omphacite (Omp), garnet (Grt) and phengite (Phn).

constituent minerals (Figs. 12a, b). The bulk compositions of the Su-Lu gneiss in this region partly overlap with those of the streaky gneiss (WALLIS *et al.*, 1997; ISHIWATARI *et al.*, 1996), thereby suggesting that the Su-Lu gneiss and the streaky gneiss were derived from the same igneous protolith and suffered the same UHP metamorphism. A difficulty with this hypothesis is that the Su-Lu gneiss is composed of distinctly coarser constituent minerals than those of the streaky gneiss. It is possible, however, that the Su-Lu gneiss was

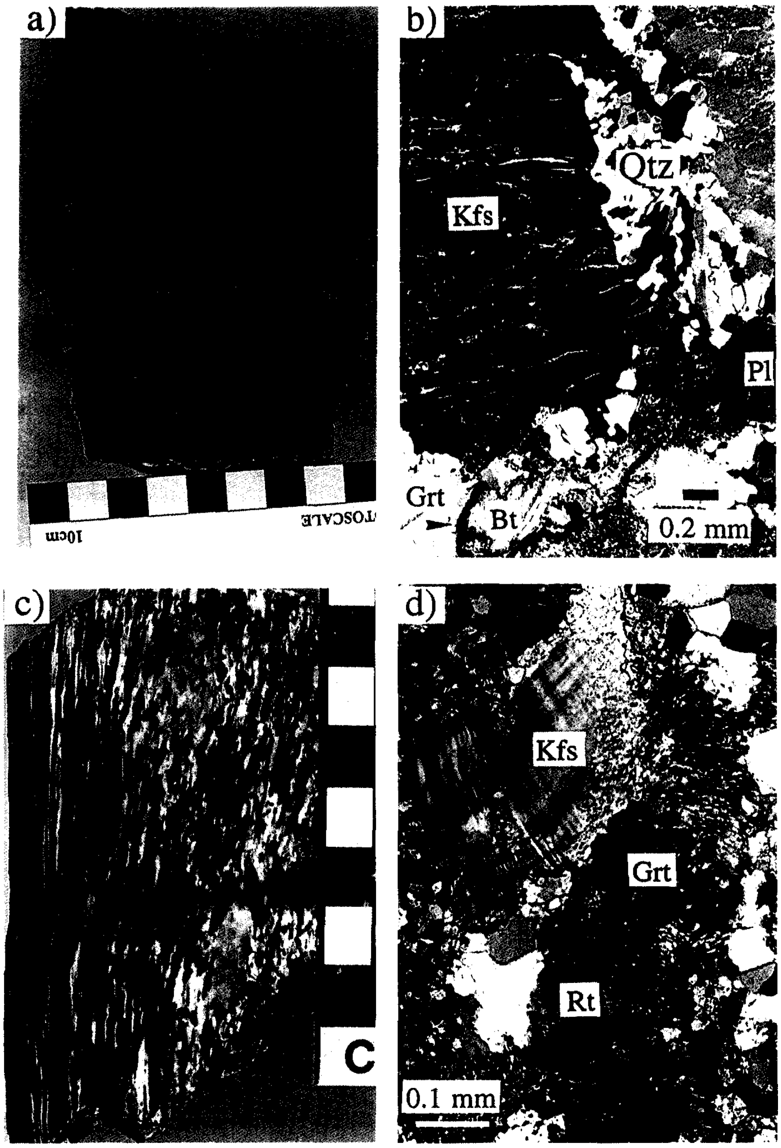

Fig. 11. *Representative photo/photomicrograph of the metagranitoid, the streaky gneiss and the Su-Lu gneiss at Yangkou. a) Polished surface of the less deformed metagranitoid (94YK7A). b) Photomicrograph of the less-deformed metagranitoid (92YK7A). Thin coronitic garnet (Grt) developed between igneous biotite (Bt), and plagioclase (Pl) domain, now aggregate of albite, epidote and mica. K-feldspar still maintains the igneous idiomorphic shape. Crossed nicols. c) Polished surface of the gradual transformation from the metagranitoid to the streaky gneiss, which is commonly observed at the margin of the granitoid lens. d) Photomicrograph of the streaky gneiss (92YK5). Plagioclase domain is strongly elongated and pulverized. Fine-grained Grt and rutile (Rt) are inherited from the UHP metagranitoid. Kfs: K-feldspar. Crossed nicols.*

annealed at wetter conditions than the streaky gneiss, which developed only the margin of the less deformed metagranitoid lens.

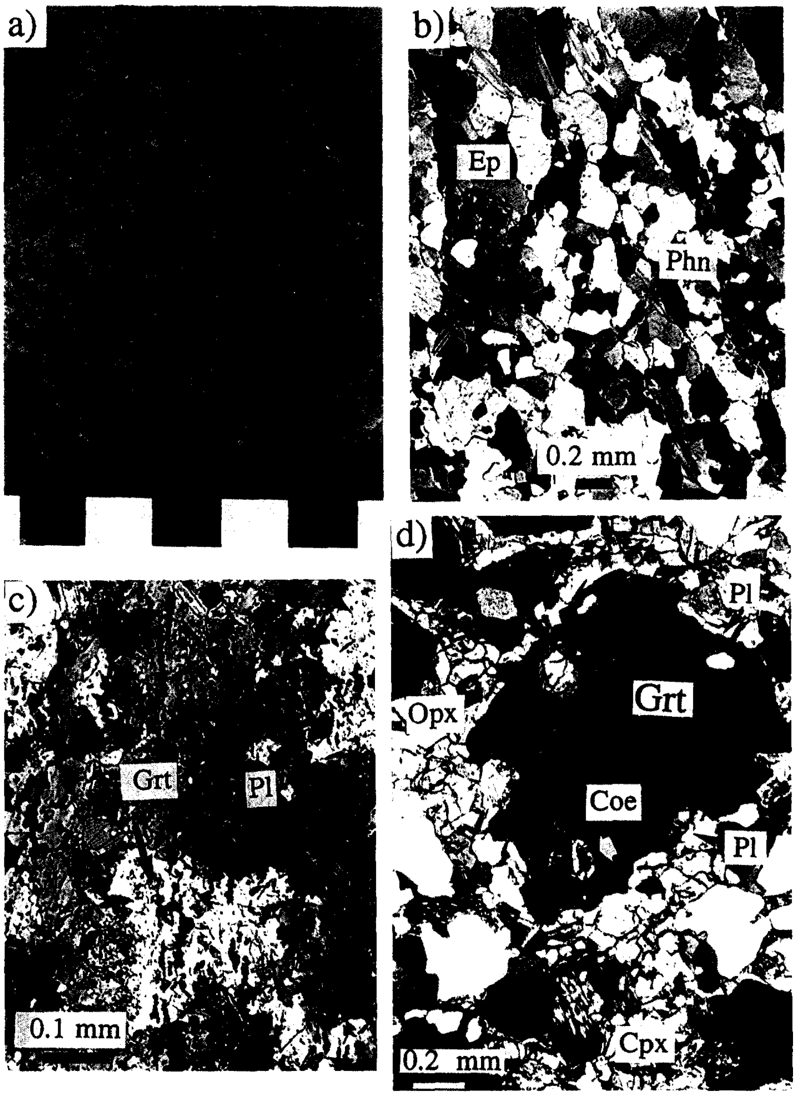

Fig. 12. Representative photo/photomicrograph of the streaky gneiss and the Su-Lu gneiss at Yangkou, and of the coesite-bearing granulite at Weihai. a) Polished surface of the Su-Lu gneiss (94YK32). b) Photomicrograph of the quartz-feldspar- rich layer of the Su-Lu gneiss (94YK32). Phn: phengite, Ep: epidote. Crossed nicols. c) Annealing texture of the streaky gneiss (92YK2). Foliation defined by fine-grained garnet (Grt) is overgrown by plagioclase (Pl). Crossed nicols with test plate. d) Photomicrograph of the coesite (Coe)-bearing Weihai granulite. Cpx: clinopyroxene, Opx: orthopyroxene, Pl: plagioclase.

3.4. Annealing of streaky gneiss

Figure 12c shows that the foliation of the streaky gneiss defined by the preferred alignment of the fine-grained garnet is overgrown by plagioclase which grew during post-deformational secondary annealing. WALLIS *et al.* (1997) considered that the secondary annealing could be related to a dominant regional amphibolite facies metamorphism of the Su-Lu region. The static annealing with sufficient fluid infiltration at crustal depths possibly transformed the streaky gneiss to the medium-grained regional gneiss, completely obliterating UHP evidence.

4. Coesite-bearing Granulite in Weihai, NE Part of the Su-Lu Region

Coesite-bearing granulite in the Weihai area (WANG *et al*., 1993) occurs as a basic lens surrounded by country gneiss in a road side cliff and as a knocker on the sand beach of Weihai. The surrounding country granitic gneiss is tightly foliated along with intercalated amphibolite layers. The margin of the granulite body is altered to foliated amphibolite, but the core of the granulite lens is free from amphibolite overprinting and pervasive deformation.

The coesite-bearing granulite is mainly composed of fine-grained Opx-Cpx-Hbl-Pl-Qtz (0.2–1 mm) in the matrix and porphyroclastic Grt (0.3–1 cm in size), which is usually surrounded by a Pl-Cpx-Opx-Hbl corona. Coesite and sodic pyroxene, however, are found only as rare inclusions in garnet (Fig. 12d). Clinopyroxene in the matrix shows a spongy texture with the irregular shape of albite. This intergrowth might be a breakdown product of omphacite. Quartz in the matrix shows a granular texture and some weak undulatory extinction. Orthopyroxene, clinopyroxene and hornblende in the matrix show polygonal textures. WANG *et al*. (1993) and ZHANG *et al*. (1995) proposed slightly different exhumation paths for this rock. However, it is evident that the UHP rock recrystallized again in the granulite facies condition (*ca*. 800–850°C at 10 kbar) under at least static conditions at Weihai, although it is not certain whether or not a rock was subjected to plastic deformation before the granulite facies overprinting. An annealing at medium- or high-temperature and low-pressure conditions can be another plausible mechanism to erase the precursor UHP evidence.

5. Discussion and Conclusion

The *P-T* path of the decompression with a moderate cooling or an isothermal decompression is considered to be a dominant exhumation path of UHP rocks (*e.g*., COLEMAN and WANG, 1995). The *P-T* path of the UHP rocks in the southern Dora Maira massif is the best example of the former case (Fig. 6). Petrological data from the southern Dora Maira massif indicate the UHP rocks experienced two steps of the retrograde crystallization during the decompression trajectory. The early retrograde recrystallization took place under even higher *P* conditions (12–15 kbar and 500–570°C, HIRAJIMA and COMPAGNONI, 1993), and the second retrograde recrystallization took place under the greenschist or amphibolite facies conditions (Fig. 6). It is not evident whether or not the UHP rocks were subjected to conspicuous plastic deformation during the early retrograde stage. However, the most conspicuous penetrative structure in the orthogneiss both in the UHP and neighbouring nappes is mainly composed of greenschist or amphibolite facies minerals (Fig. 7f). The continuous transformation from the metagranitoid with primary igneous texture and UHP minerals, via augen gneiss, finally to the mylonitic fine-grained orthogneiss was observed in several outcrops in the monometamorphic unit of the UHP nappe (Fig. 7e). This geological evidence suggests that the UHP metagranitoid was pervasively transformed to the country orthogneiss by the later stage deformation at low-pressure conditions without significant heating. The gradual transformation from the UHP metagranitoid to the streaky gneiss with amphibolite facies mineral assemblages is also observed in the Yangkou unit (Figs. 11c, d). MICHARD *et al*. (1995) envisaged that

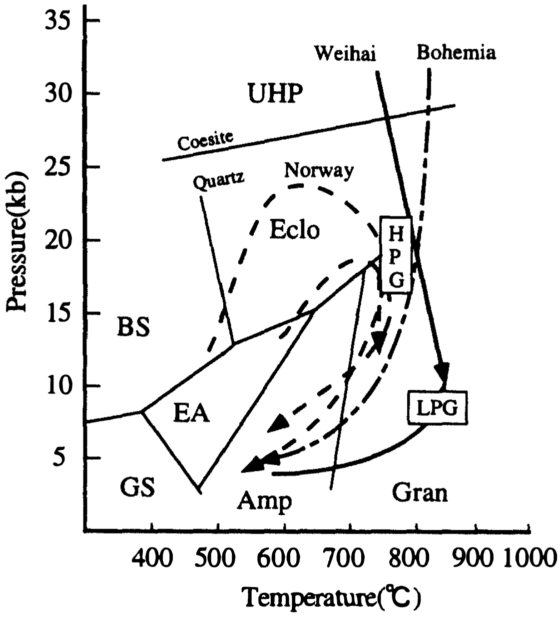

Fig. 13. Reported P-T paths for granulite facies overprinting on the UHP/HP rocks inset metamorphic facies boundaries are same as those in Fig. 6. HPG: high pressure granulite, LPG: low-pressure granulite.

late greenschist facies fabrics form the main tectonic structure at the regional scale as well as the main fabric at the sample scale in every HP-LT region. The deformation with accompanied fluid infiltration under low-pressure conditions is one of the principal mechanisms to obliterate the precursor UHP/HP evidence.

The *P-T* path of the Weihai granulite can be considered as isothermal decompression or decompression accompanied by slight heating. If the UHP rocks, formed under relatively higher temperature conditions (*ca.* >700°C), were uplifted with an adiabatic condition, the UHP rocks came into the granulite facies field at lower- to middle-crustal depths (Fig. 13). If conditions enhancing the metamorphic reactions are satisfied at lower- to middle-crustal depths, *e.g.*, decrease of the exhumation speed and/or the incorporation of some metamorphic catalyzers into the UHP rocks, the UHP rock may begin to transform to the granulite. There is a possibility that the UHP rocks completely transform to the granulite, which is one of the representative lithotypes in the lower crust, if the UHP rocks stay there long time and the metamorphic reactions proceed sufficiently. Recently Nakamura and Hirajima (1997) and Nakamura (1998) proposed that the UHP rocks in the NE part of the Su-Lu region, including the Weihai area, suffered a granulite facies overprinting on a regional scale and followed a rather adiabatic decompression path. An adiabatic *P-T* path and granulite facies overprinting, similar to that we recognized in the Su-Lu region, has been proposed for UHP and HP rocks of Norway and Bohemian massif (*e.g.*, Krogh, 1980; Carswell *et al.*, 1985; Schmadicke *et al.*, 1992). In these areas, granulite facies mineralogy is further retrogressed by amphibolite facies metamorphism. The combination of higher temperature conditions at the UHP stage and the rapid uplift of the UHP rock can most likely transform pervasively the UHP rock to the LP crustal metamorphic rocks.

Before the first report of a UHP rock, the maximum attained depth recorded in metamorphic rocks was considered to be 50–60 km, estimated by the appearance of Jd+Qtz assemblage in an eclogite terrain. Compagnoni and Maffeo (1973) firstly demon-

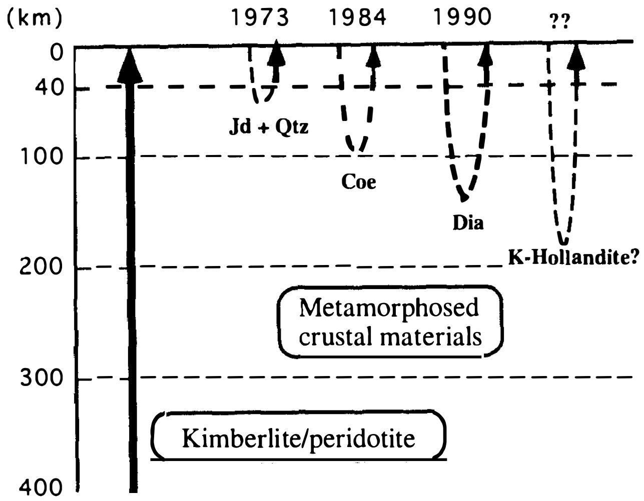

Fig. 14. *The history of the world record of maximum attained depth of the highest pressure metamorphic rocks.*
1973: 50-60 km Jd+Qtz COMPAGNONI and MAFFEO (1973)
1984: >90-100 km Coe. CHOPIN (1984), SMITH (1984)
1990: >140 km Dia. SOBOLEV and SHATSKY (1990)
??: >180 km K-Hollandite

strated that granitoids were subducted to 50-60 km depth at Mt. Mucrone, Sesia zone, western Alps (Fig. 14). However, this world record was replaced by the finding of coesite from metamorphic crustal materials in two orogenic belts in Europe in 1984, and was replaced again by the finding of diamond, from >140 km, in regional gneiss in the Urals in 1990. Is it possible that K-hollandite will be found from orthogneiss in the near future as a further high pressure indicator of a UHP rock ? The author thinks it unlikely at present, because K-hollandite-bearing orthogneiss has higher density than that of the ultramafic and basaltic materials at upper mantle depths and it cannot give a buoyancy force causing its exhumation. The UHP orthogneiss with coesite and K-feldspar is lighter than the eclogite and ultramafic rocks at up to *ca.* 180 km in depth (*e.g.*, IRIFUNE, 1994). High modal amounts of the orthogneiss in the UHP terrain (more than 90 vol%) can give a buoyancy force for the UHP rock intercalated in the orthogneiss.

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