Polyphase Deformation of the Weihai-Rongcheng UHP Unit Rocks, NE Sulu: Insights into the Tectonic Evolution of the Dabie-Sulu UHP and HP Belts, China

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Abstract: Different scales of structural data reveal a complex deformation history of ultrahigh-pressure (UHP) rocks exposed in the Weihai-Rongcheng area, NE Sulu (northern Jiangsu-eastern Shandong), eastern China. Excluding pre-UHP deformations, at least five major sequential deformational stages (D_1–D_5) are recognized. The first deformation (D_1) produced a weak foliation and lineation in massive eclogites. The foliated eclogite with a dominant foliation containing a stretching and mineral lineation was developed during the D_2 deformation. Both the D_1 and D_2 deformations occurred under UHP metamorphic conditions, and are well preserved in the eclogite bodies. D_3 structures which developed shortly after the formation of granulite/amphibolite facies symplectites are characterized by imbricated associations marked by a regional, steeply dipping foliation, compositional layering, eclogite boudinage, isoclinal folds and reverse ductile shear zones. The D_3 deformation was accompanied by decompressional partial melting. A regional, gently dipping amphibolite facies foliation and stretching lineation, low-angle detachments, and dome- and arc-shaped structures formed during the D_4 deformation stage dominate to some degree the map pattern of the Weihai-Rongcheng UHP domain. The last stage of deformation (D_5) gave rise to the final exhumation of the UHP rocks. D_5 is characterized by development of brittle-dominated high-angle faulting associated with emplacement of large volumes of undeformed granite plutons and dykes dated at 134–100 Ma. The deformational and metamorphic sequence followed by the UHP rocks in the Weihai-Rongcheng area is similar to that studied in the entire Dabie-Sulu UHP and HP metamorphic belts from microscopic to mapping scale. Based on structural data, combined with available petrographic, metamorphic and geochronological data, a speculative tectonic evolutionary model for the Dabie-Sulu UHP and HP belts is proposed, involving continental subduction/collision between the Sino-Korean and Yangtze cratons and subsequent polyphase exhumation histories of the UHP and HP metamorphic rocks.

Key words: Weihai-Rongcheng area, ultrahigh-pressure (UHP) metamorphism, tectonic evolution, polyphase deformation, deformation partitioning

1 Introduction

Ultrahigh-pressure metamorphic (UHP) rocks are widely exposed in the Weihai-Rongcheng area, NE Sulu, in the northeastern part of the Shangdong Peninsula, eastern China. They have attracted numerous geochemical, petrological and geochronological studies, and often heated discussion over the past two decades (Enami and Zhang, 1990; Enami et al., 1993; Wang et al., 1993; Zhang et al., 1994, 1995, 2003; Jahn et al., 1996; Ogasawara et al., 1998; Nakamura and Hirajima, 2000; Zhai et al., 2000; Nakamura, 2002; Xu et al., 2003; Yang et al., 2003; Xu et al., 2005). However, no detailed structural analysis associated with petrological observations has been made so far and the deformation

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history of the UHP rocks in the Weihai-Rongcheng area is not well constrained.

The Weihai-Rongcheng area is an ideal one for studying the geodynamic processes for the formation and exhumation of UHP rocks because these rocks show abundant evidence for polyphase deformation. The P-T conditions of the formation of UHP eclogites and other eclogite-facies rocks, dated around 250–230 Ma, are well investigated (e.g., Zhang et al., 1995; Yang et al., 2003). Moreover, deformation partitioning in the UHP rocks, from microscopic to map scale, is especially conspicuous, which provides numerous insights into the geometry and kinematics of structures and related metamorphism developed under different P-T conditions. The purposes of this contribution are: (i) to describe the structural records preserved in UHP rocks in the Weihai-Rongcheng area, on the basis of detailed structural analysis carried out by us over the last four years, and (ii) to discuss the tectonic evolution followed by the entire Dabie-Sulu UHP and HP metamorphic belts, based mainly on our extensive fieldwork and regional analysis of structural events, as well as available geochronological and petrological data (e.g., Ames et al., 1993, 1996; Li et al., 1993, 2000; Okay et al., 1993; Eide et al., 1994; Zhang et al., 1994, 1995, 2003; Liou et al., 1997, 2004; Hacker et al., 1998, 2000; Faure et al., 2001, 2003; Yang et al., 2003; and references therein). The emphasis in this paper is laid on the structural features, at all scales, formed during different tectonometamorphic evolution stages of the UHP rocks.

2 Geological Setting

It is well accepted that the Dabie-Sulu UHP and HP metamorphic belts are attributed to continental subduction/ collision between the Yangtze and Sino-Korean cratons during the Triassic (Okay et al., 1993; Cong et al., 1995; Liou et al., 1997; Hacker et al., 1998, 2000; Yang et al., 2003; and references therein). However, the geometry of the belts exposed at the present erosional surface, on a regional scale, was mainly achieved in the subsequent exhumation history. The overall tectonic framework, which displays some features of Cordilleran-type metamorphic core complexes (Davis, 1983; Ames et al., 1993; Suo et al., 2000, 2001, 2002), was formed by an extensional ductile process mostly between 200 and 170 Ma. In the Dabie region, the Balifan-Mozitan-Xiaotian fault (BMXF) is regarded as a significantly modified roof-boundary of the Triassic tectonic suture zone or the northern limit of UHP and HP metamorphic rocks (Suo et al., 2003, 2004). To the south of the BMXF, five major superposed petrotectonic units can be distinguished, namely, in ascending order, the core complex (CC), the UHP, the HP, the epidote-blueschist (EB), and the non-metamorphic or slightly metamorphic sedimentary cover (SC) units. These units are commonly bounded by shallow-dipping extensional detachment zones with different extensional directions. They are, from base to top, the lower detachment zone (LDZ), the middle detachment zone (MDZ), the upper detachment zone (UDZ), and the top detachment zone (TDZ), respectively (see Fig. 1 of Suo et al., 2001). So, all the units are tectonically stacked, showing overall normal-sense metamorphic breaks. In the Sulu region, the Wulian-Yantai fault (WYF) separates the Sino-Korean craton to the northwest from the UHP and HP metamorphic belts to the southeast (Fig. 1). The WYF zone, made up by mylonitic rocks with an average width of 1000 m, also represents the strongly reworked tectonic boundary between the Yangtze and Sino-Korean cratons (Zhang et al., 1994; Wallis et al., 1999, 2005; Suo et al., 2000, 2001, 2005). More recently, however, Faure et al. (2001, 2003) proposed that the whole Shandong Peninsula belongs to the Yangtze craton or the South China Block. This idea is highly controversial and has not been supported by observed structural, petrological and geochronological data (Zhang et al., 1994; Suo et al., 2000, 2001; Xu et al., 2003). A detailed discussion regarding the case is beyond the scope of this paper.

The Weihai-Rongcheng area is situated in the northeastern part of the Shangdong Peninsula. In this area, UHP rocks exhibiting polyphase tectonometamorphic evolution are well exposed, penetrated by Late Mesozoic plutons, and unconformably overlain by Cretaceous sedimentary rocks (Fig. 1). The LDZ crops out clearly along the seacoast near Haiyangsuo, separating the CC unit below from the UHP unit above. As in the Dabie region, the CC unit is dominated by mylonitized granite, amphibolite, biotite plagioclase-gneiss, quartzite and banded magnetite quartzite (banded iron formation) of granulite/upper amphibolite facies metamorphism (Fig. 2). This unit, belonging to part of the Yangtze craton basement, was subjected to a protracted pre-Triassic tectonothermal history. The rocks, however, lack evidence for UHP and HP eclogite-facies metamorphism. The UHP unit consists of eclogite, retrograded eclogite, amphibolite, kyanite quartzite, marble, biotite-hornblende gneiss, garnet-bearing gneiss, foliated garnet-bearing granite (orthogneiss), and a small amount of garnet peridotite (Zhang et al., 1995; Ogasawara et al., 1998). Commonly, the eclogite and retrograded eclogite occur as boudins, pods, lenses and blocks with different sizes in gneisses, marbles and ultramafic rocks. Coesite and quartz pseudomorphs after coesite are widespread as minor fine-grained inclusions in garnet, omphacite, kyanite and epidote in many eclogites and kyanite quartzites (Wang et al., 1993; Zhang et al., 1995), recording UHP metamorphism within the coesite

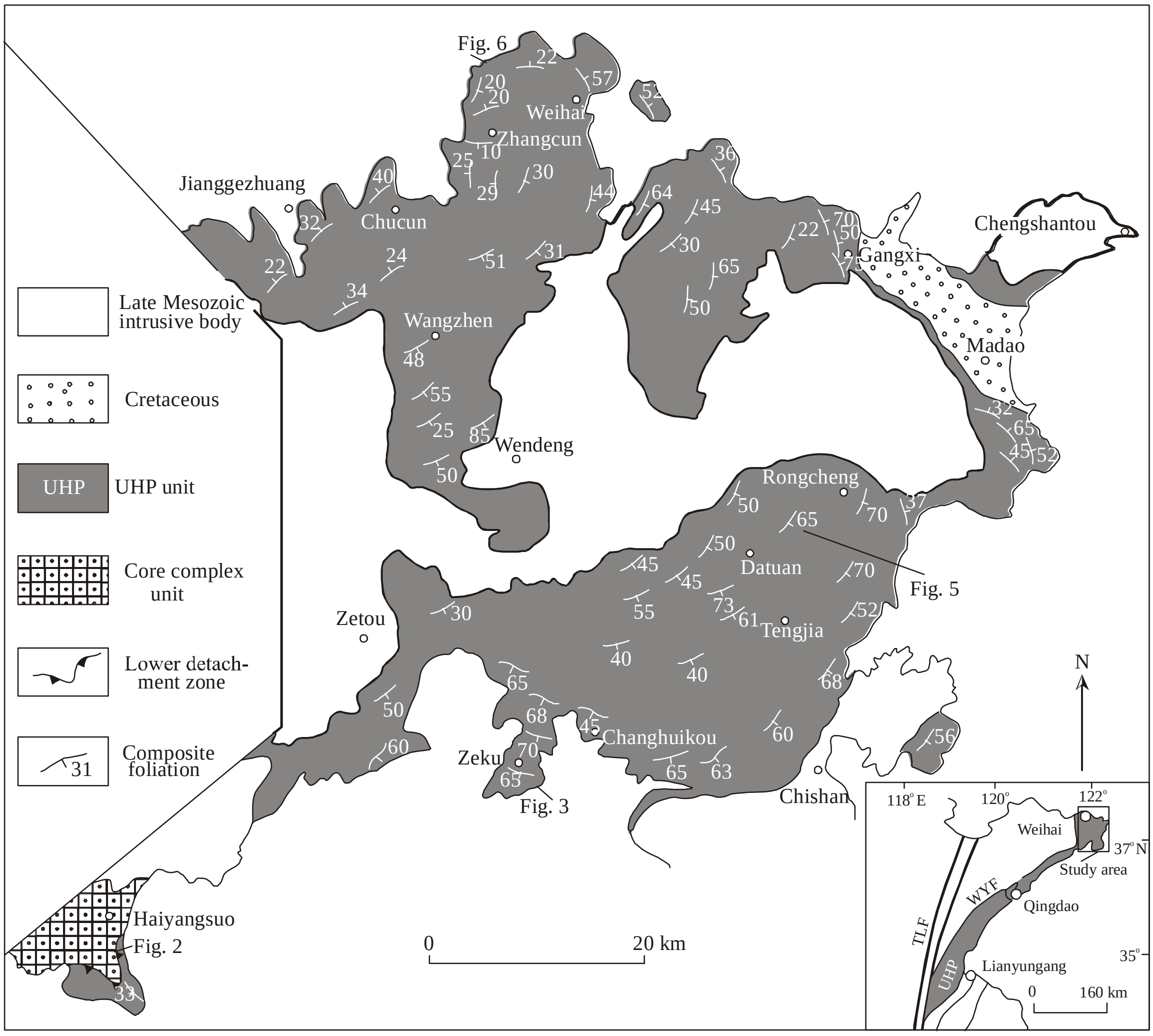


Fig. 1. Simplified structural sketch map of the Weihai-Rongcheng area, NE Sulu, eastern China, with emphasis on extensional structures mainly formed during the D_4 stage.
Eclogites and their early structures are not shown in this map. Locations of Figs. 2, 3, 5 and 6 are indicated. Inset map shows location of the Weihai-Rongcheng area in the Sulu region. TLF – Tancheng-Lujing (Tanlu) fault; WYF – Wulian-Yantai fault.

stability field (>28 kbar). For a more complete description of the geological setting and petrography of UHP rocks in the Weihai-Rongcheng area, see Wang et al. (1993), Zhang et al. (1995), Ogasawara et al. (1998) and Faure et al. (2003).

3 Deformation Stages and Related Structures

Excluding pre-UHP deformations, five major at least sequential deformational stages (D_1–D_5) that affect the UHP rocks in the Weihai-Rongcheng area are recognized based mainly on structural records, especially thin-section to outcrop scale structural relations of mineral assemblages and overprinting criteria. Although a carefully tested, detailed chronology of these various stages is difficult to determine, their relative chronology is well constrained (Fig. 3). Characteristic features for each stage are briefly described below.

3.1 D_1 Deformation

The main structures formed during the D_1 deformation stage are a weakly developed foliation (S_1) and mineral lineation in the massive eclogites, which are dominantly expressed by the rough shape preferred orientation of omphacite. The massive eclogites, with a metamorphic inequigranular and granoblastic texture (Fig. 4a), are enclosed in foliated eclogites (Fig. 3), garnet peridotites and marbles as lenses or pods of 0.1 m to 10 m thick. The fresh massive eclogite with little retrograde alteration contains a simple assemblage of garnet + omphacite + rutile + coesite/quartz pseudomorphs after coesite. According to Xu et al. (1992), Okay (1993) and Okay et al. (1993), most of minute diamond inclusion discoveries come from these eclogites in the Dabie region. The peak P-T conditions for

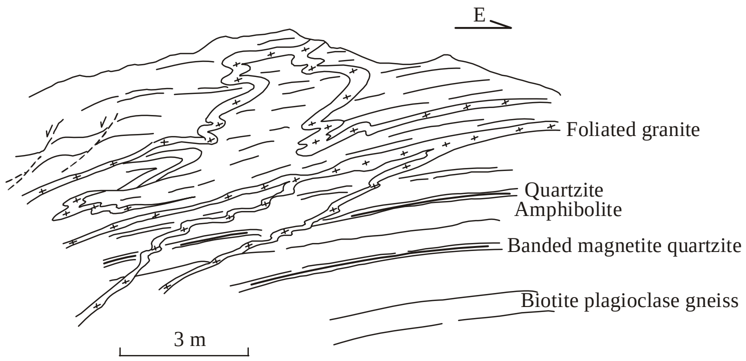


Fig. 2. Schematic cross-section showing the CC rocks well-exposed along the coast near Haiyangsuo, northeastern Shangdong.
For location see Fig. 1.

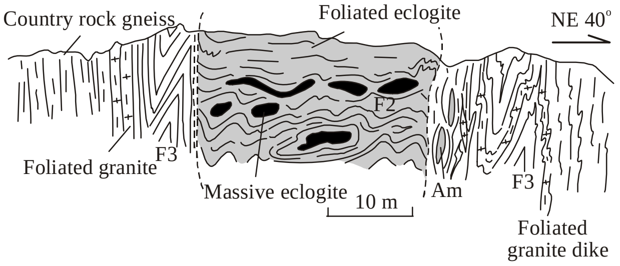


Fig. 3. Vertical cross-section near Zeku, northeastern Shangdong, illustrating the overprinting relationships between D_1, D_2 and D_3 structures seen in a small area.
The D_1 and D_2 structures occur in massive eclogite and foliated eclogite, respectively. F_2 – D_2 folds; F_3 – D_3 folds; Am – Amphibolite. For location see Fig. 1.

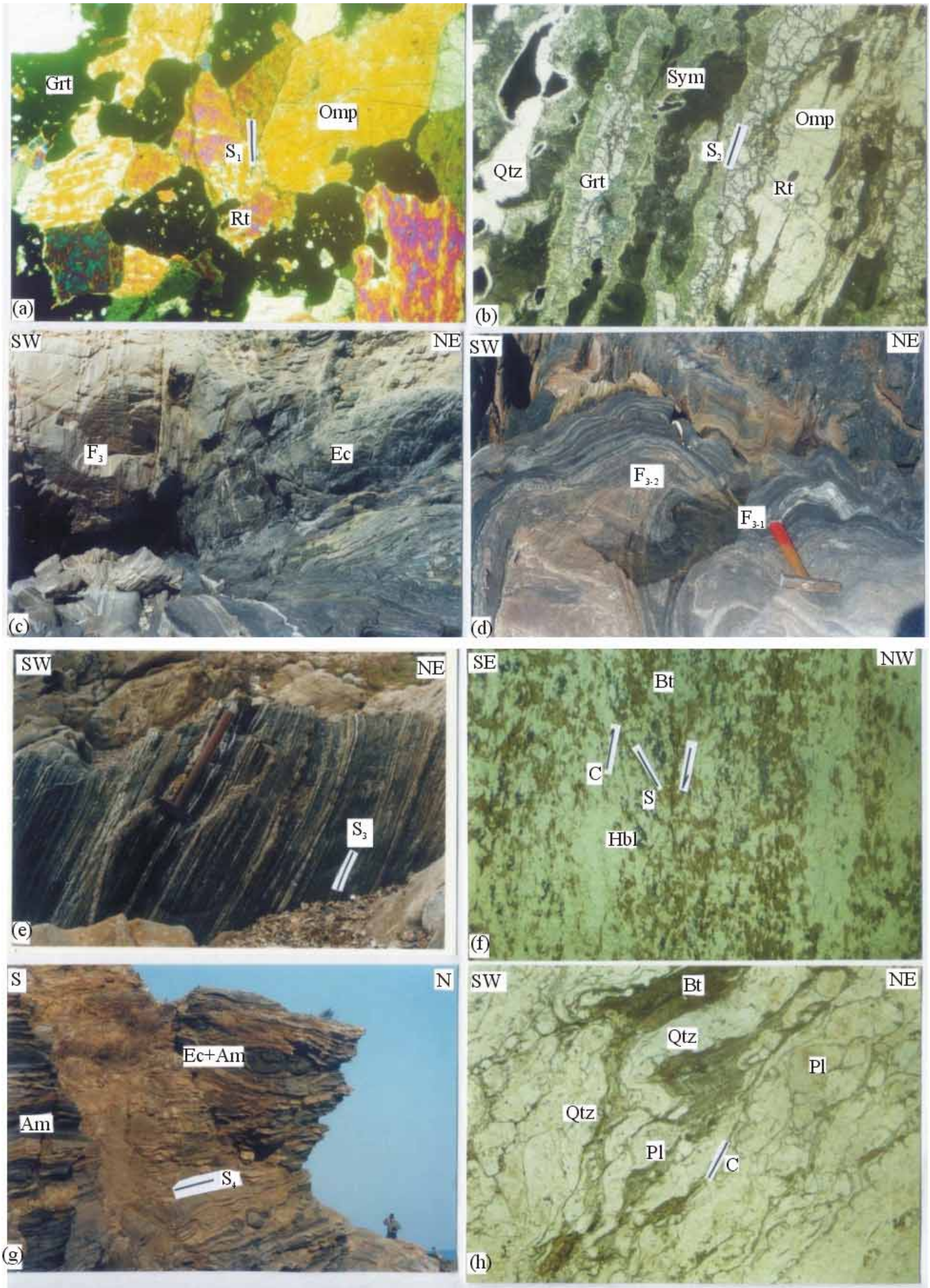
the production of massive eclogite, thus, are about 800±50°C and >3.8–4.0 GPa within the diamond stability field (Okay, 1993).

The best exposures of massive eclogites occur at Chijiadian and Dazhuji near Datuan, Fengshan and Yujiazhuang near Rongcheng, and Shanjia near Tengjia. Locally, for example at Yujiazhuang, the weak foliation dips at 60–75° to the west. However, the attitudes of both the foliation and the lineation are very difficult to measure in the field. At the microscale, garnets form anhedral or subhedral crystals of 0.5–2.0 mm and up to 3.0 mm in diameter, and locally contain irregularly shaped inclusions of omphacite, rutile and quartz, indicating a prograde metamorphism. In general, the garnet grains with inclusions have a round inclusion-rich core and a relatively thick inclusion-free rim, which is thicker in the direction of the lineation, and thinner elsewhere (Fig. 4a). On the other hand, the omphacite crystals (0.65×2.0 mm in size) with a rough shape preferred orientation exhibit some solid-state plastic deformation features, such as weak undulatory extinction, subgrain occurrence and serrated crystal boundaries. Omphacite boundaries oriented subparallel to the weak foliation commonly are straight, whereas those highly oblique or perpendicular to the foliation are irregular, and exhibit a serrated form. These features indicate that omphacite is the main framework-supporting mineral in the massive eclogite. Crystal plasticity of omphacite is one of the main factors controlling the D_1 deformation of eclogites at low differential stress conditions. However, the kinematics of the D_1 stage are as yet unknown at any scale.

3.2 D_2 Deformation

The most typical structure associated with D_2 is the widespread development of anastomosing UHP eclogite-facies shear zones hosting massive eclogite lenses or pods. Rocks in the shear zones are dominated by foliated eclogites that contain the common assemblage garnet + omphacite + rutile + phengite+ kyanite ± coesite/quartz pseudomorphs after coesite. Compared with the massive eclogite, clearly, the foliated eclogite bears relatively abundant hydrous minerals. The metamorphic conditions of > 2.8 GPa and 840±50°C were obtained from the eclogite near Weihai (Zhang et al., 1995).

The eclogite-facies shear zones are mainly preserved in large eclogite bodies exposed at Datuan, Fengshan, Tengjia, and along the coast near Zeku (Fig. 3). They are generally several hundred meters in length and up to 50 m wide, and are expressed in a steep–dipping, penetrative dominant foliation (S_2) containing mineral and stretching lineation. At hand specimen and outcrop scales, a compositional layering or banding characterized by an alternation of garnet-rich and omphacite-, phengite- and kyanite-rich layers, several millimeters thick, is often present. It is geometrically concordant with the foliation. The orientation of both the foliation and lineation varies between different eclogite blocks in the Weihai-Rongcheng area. The foliation, for example, dips at 55–70° to the east at Datuan, 70–76° to the north at Fengshan, and 65–80° to the southeast at Tengjia, respectively. In addition, reclined, intrafolial mesoscopic folds, with their axes parallel to the lineation, are developed in a few places. One example, with a steep north-plunging axis, is observed in the eclogite body near Datuan. The variation of the planar and linear fabric orientation is tentatively interpreted as being related to passively variable rotation of eclogite bodies during subsequent deformational phases. However, it is unknown to what extent the eclogite facies fabrics have been rotated. The regional geometry of D_2 structures, thus, has not yet been elucidated. The three-dimensional relationship between the massive and foliated eclogites is well displayed in the large eclogite lenses. The most striking features are their anastomosing structural patterns with lens-shaped massive eclogite bodies of low strain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surrounded by foliated eclogite zones of intense shear strain. This type of structural pattern was mainly produced by progressive deformation partitioning during UHP metamorphic conditions (Bell et al., 1986; Suo et al., 2000, 2001, 2005; Terry and Robinson, 2003, 2004). In addition, local reverse shear with a dextral or sinistral strike-slip component in different outcrops can be deduced from the geometric and kinematic relationships between the lenses of the massive eclogite and the surrounding foliated eclogites or shear zones.

Intense plastic deformation of eclogite minerals in the foliated eclogite, responsible for forming the penetrative foliation and stretched lineation at the outcrop scale, is very conspicuous at the microstructural level. The shape-preferred orientation of garnet, omphacite, kyanite, phengite and rutile is well developed (Fig. 4b). In most cases, their shape fabrics have long to short axis ratios in XZ sections that vary between 6 and 20, 8 and 15, 10 and 15, 4 and 10, and 4 and 6, respectively. In particular, strongly elongated garnets of 3–4 mm and up to 7 mm long usually retain a residual ribbon texture. However, a systematic strain analysis of D_2 structures and fabrics has not yet been carried out in this area. In a few cases, the foliated eclogite has preserved a composite planar fabric formed by S-surface and C-surface/bands (Berthe et al., 1979). The angle between the two sets of planar structures, in general, ranges from 15° to 20°, yielding a magnitude for the shear strain in the range of 2.4 to 3.5 in the studied sections. The smallest measurable angle between the C- and S- surfaces is 5° to 10°, implying shear strain higher than 5.5 to 11. With increasing strain, the angle decreases until the two sets of planar structures became completely parallel to each other. Consequently, we interpret the foliated eclogite as an eclogite-facies mylonite, which was formed by non-coaxial ductile deformation under UHP metamorphic conditions. The microstructures of the foliated eclogite also indicate that the rheological contrasts among the main minerals of the eclogite became very low, and their plastic deformation behavior was quite similar at high differential stress conditions.

It is clear that much of the D_2 finite strain experienced by the eclogite bodies was largely accommodated in the foliated eclogites and UHP shear zones. They recorded the main D_2 tectonometamorphic event, which probably took place at a minimum age of 228 ± 29 Ma (Yang et al., 2003).

3.3 Intermediate structure

Various kinds of thin (0.025–0.05 mm and up to 0.5 mm wide) granulite/amphibolite facies symplectites and coronas occur in the retrograded massive and foliated eclogite. The very fine-grained symplectitic aggregates with palisade structure and fibrous crystals grown perpendicularly to their host mineral grain boundaries (Fig. 4b) have been interpreted as representing a strain-free decompression and dynamic process (Carswell, 1986; Suo et al., 2002, 2005). The symplectitic assemblages and reaction structures are widespread but only preserved in the eclogite and retrograded eclogite bodies. Textural relationships identified in thin sections suggest that the ductile deformation of both the massive and the foliated eclogite occurred before the formation of symplectites and coronas. Hence, the symplectites also define a reference system to describe the sequential deformation stages. They are considered as the intermediate structures (Hopgood, 1984) or markers for the end of the UHP metamorphism and the onset of the retrogression of the UHP assemblages. Detailed studies of microstructures of a variety of symplectite assemblages in the Weihai-Rongcheng area were carried out by Zhang et al. (1995) and Banno et al. (2000). Estimated P-T conditions for the formation of the granulite/amphibolite facies symplectite and corona are 0.7–1.4 GPa at 750–800°C and 1.0 GPa at 700±30°C, respectively.

3.4 D_3 Deformation

D_3 structures developed during and closely after the formation of various kinds of symplectites and coronas. They are characterized by subvertical, imbricated structural associations in which strongly dismembered and boudinaged eclogites and retrograded eclogites are

Fig. 4. Representative photomicrographs and field photographs of UHP rocks from the Weihai-Rongcheng area, NE Sulu, showing structural features formed during the distinct tectonometamorphic events.

(a) Coarse-grained massive eclogite with inclusions of omphacite, rutile and quartz in garnets (Sample Z-20-1, cross polarized light; long axis of photograph represents ~ 5 mm); (b) XZ-section of foliated eclogite with a UHP eclogite facies foliation (S_2) defined by a shape-preferred orientation of omphacite, garnet and quartz etc. Note granulite/amphibolite facies symplectites with palisade and reticulate structures surrounding the host minerals. The symplectites developed during a subsequent strain-free decompression process (Sample S-R-19-3, plane polarized light; long axis of photograph represents ~ 5 mm); (c) outcrop-scale, vertical F_3 folds, near Zeku, width is 10 m; (d) photograph of the outcrop viewed along the fold axes, showing isoclinal $F_{3\text{-}1}$ folds refolded into tight $F_{3\text{-}2}$ folds, displaying type 3 interference pattern, near Zeku; note hammer for scale; (e) steeply SW-dipping layered amphibolite with pegmatitic granite dykes parallel to foliation (S_3) displaying a banded structure, immediately above the lower detachment, near Haiyangsuo; note hammer for scale; (f) photomicrograph of D_3 structures, showing top-to-the-NW S-C structures in layered mylonitic amphibolite, south of Zeku (Sample S-r-17-4, plane polarized light; long axis of photograph represents ~ 5 mm); (g) symmetric meter-scale eclogite and garnet-amphibolite blocks or boudins in ductile layered gneisses, developed due to subvertical flattening across S_4 during D_4, Xiaoshido of Weihai; people for scale; (h) the asymmetrical microfold quartz ribbon and mica fish structures in the mylonitized gneiss indicate a top-to-SW extensional shearing, near Haiyangsuo (Sample Z-9-5-2, plane polarized light; long axis of photograph represents ~ 5 mm). Abbreviations: Bt – biotite; Qtz – quartz; Hbl – hornblende; Grt – garnet; Omp – omphacite; Rt – rutile; Sym – symplectite; Ec – eclogite; Am – amphibolite; see text for S_1, S_2, S_3, S_4, C-, S-, F_3, $F_{3\text{-}1}$ and $F_{3\text{-}2}$.

enclosed in country rock gneisses. The domainal behavior features with lens-shaped or retrograded eclogite bodies surrounded by gneisses are well displayed at the outcrop and map scales.

Eclogite and retrograded eclogite bodies located within the domains of low strain were weakly deformed during the D_3 stage. An array of retrograde shear zones or bands with a sparse spacing occurred only in these bodies. The symplectitic assemblages and retrogressive reaction structures in the shear zones or bands were intensely reworked and recrystallized. Barroisitic hornblendes occur in several of the retrograded eclogites, showing an elongated shape and a shape-preferred orientation subparallel to the foliation within the shear zones and boundaries of the eclogite bodies.

The most prominent D_3 structures and fabrics are a strongly developed pervasive, steep-dipping foliation (S_3) or compositional layering and stretched lineation in the country rock gneiss (Fig. 4c, d, e and f). It is stressed that the term "country rock gneiss" here includes only layered garnet-bearing amphibolite, amphibolite, biotite gneiss, mica amphibole gneiss and schist. The relict UHP mineral assemblages (e.g., garnet, rutile and clinozoisite), in general, have been identified in these layered rocks. However, the original UHP and symplectite microstructures were completely destroyed. In most cases, the layers exhibit a continuous mineral assemblage and textural transition from less altered through partially and extensively retrograded eclogite to gneissic rock of amphibolite facies (Cong et al., 1995; Zhang et al., 2003; Suo et al., 2005). Therefore, the country rock gneisses are, at least in part, strongly retrograde products of previous eclogites.

In the Weihai-Rongcheng area, volumetrically, perhaps approximately 40–60% of the UHP unit rocks consist of deformed garnet-bearing granites (orthogneisses) and associated leucocratic dykes. They have the common assemblage plagioclase + K-feldspar + quartz + hornblende + biotite + minor garnet, epidote, zircon and apatite. The granitic bodies and leucocratic dykes, in some cases, are clearly intrusive, as they often contain enclaves of the retrograded eclogite and country rock gneiss. Their margins, crosscutting eclogite bodies and layered country rock gneisses, can also be observed in a few outcrops. Both the deformed garnet-bearing granite (orthogneiss) and the dyke bear the same well-developed D_3 foliation and associated lineation as the country rock gneiss, and were together overprinted or reworked by the D_4 deformation. Recent U-Pb dating on zircon extracted from the garnet-bearing granite and strongly deformed granitic dyke gives ages bracketed between 230 and 200 Ma (Zhang et al., 2001; Wallis et al., 2005). These data suggest that temperatures during D_3 were probably high enough to cause rapid decompressional partial melting of the country rock gneiss, responsible for forming garnet-bearing granites and dykes. The partial melting, displaying an important reheating event, was roughly coeval with the late stage of the progressive D_3 deformation (Zhong et al., 1999).

The D_3 deformation was heterogeneous. Some of country rock gneisses and orthogneisses, with progressive or episodic deformation partitioning due to the contrasted rheology of the rocks and strain localization (Handy, 1990) were transformed into interlayered amphibolite mylonites and quartzofeldspathic mylonites with a well-developed S-C composite planar fabric (Fig. 4f). The mylonites or ductile shear zones of meter to decameter scale in width constitute a network geometry, and subdivide the UHP rocks into a series of slices or lenses of lower strain. Highly sheared, isoclinal meso-scale D_3 folds (F_3) are widespread in the layered country rock gneiss and orthogneiss (Fig. 4c). In general, they exhibit a remarkable sheath-like form. Especially, the folds formed by the foliated granite dykes during D_3 are commonly tight and reclined, with steep-dipping axial planes and moderate to steeply plunging axes. The cross-section form is dominated by strongly attenuated limbs and a thickened hinge (Figs. 3 and 4c). The D_3 folds are best developed near Zeku, Wendong, where coastal exposure and sea cliffs allow D_3 nearly 100% display of meso-scale folds within the layered country rock gneiss and orthogneiss (Fig. 4c). Moreover, two generations of folds and their overprinting relationship can be seen at the outcrop scale. An outstanding example is shown in Fig. 4d. It is clear that the early generation of isoclinal folds (F_{3-1}) were refolded into the late generation of tight folds (F_{3-2}), forming a complex interference pattern, type 3 of Ramsay (1967). The late generation of folds has an axial planar foliation dipping steeply to the southwest and steep-plunging axes parallel to the D_3 lineation. However, regional structural observations indicate that the similar overprinting relationship and transposition by folding (Williams, 1983), seen in small areas of the outcrop, might have resulted from local mechanical instabilities rather than being correlatable as two regional deformation phases (Burg, 1999). Also there is little evidence for D_3 large-scale folding within the UHP unit in the Weihai-Rongcheng area.

Associated kinematic indicators are a variety of asymmetric structures (Fig. 5) and fabrics (e.g., S-C mylonite) (Fig. 4f). They supply a consistent reverse sense of shear with a local dextral or sinistral strike slip component along D_3 foliations (S_3). The D_3 structural features noted above, including penetrative foliation, compositional layering, eclogite boudinage, partial melting of the country rock gneiss and subsequent strain

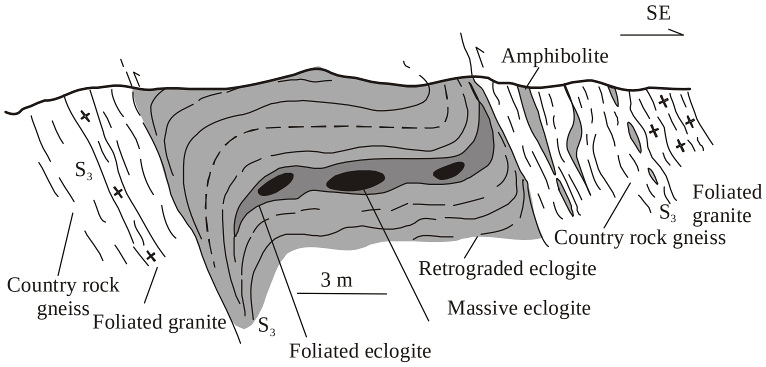

Fig. 5. Schematic cross section of the outcrop showing D_3 reverse sense-of-shear indicators, such as the deflection of S_3 foliation towards shear planes between retrograded eclogite and country rock gneiss, drag folds and asymmetric amphibolite boudins.
For location see Fig. 1.

localization in the shear zones at different scales, are considered to be an integral part of a major phase of tectonism linked to crustal shortening and thickening. The D_3 deformation finally led to tectonic juxtaposition or imbricate stacking of the steeply dipping, ductile shear zone-bounded UHP rock slices as a whole. Microstructures observed in thin-section reinforce that during the D_3 stage, amphibole, feldspar, biotite and quartz are strain accommodating phases, whereas garnet, rutile and clinozoisite remain rheologically passive or less active as porphyroclasts. The D_3 structures, thus, are thought to have formed under HP amphibolite or upper amphibolite-facies conditions (Cong et al., 1995).

3.5 D_4 Deformation

The commonest D_4 structures include a regionally, shallow–dipping dominant foliation (S_4) containing mineral and stretching lineations, low-angle extensional ductile shear or detachment zones, and meso-scale recumbent/reclined folds, as well as dome- and arc-shaped structures at the map scale (Fig. 1). The foliation and lineation are defined by amphibolite/upper greenschist-facies minerals including plagioclase, microcline, amphibole, quartz, biotite, muscovite, epidote with minor amounts of chlorite and titanite, and their assemblages in the country rock gneiss and orthogneiss. Most of eclogite or retrograded eclogite bodies of different sizes are distributed in country rock gneisses and orthogneisses. Volumetrically, they now constitute perhaps 5–10% of the rocks within the UHP unit, and display a “block- in- matrix” fabric (Handy, 1990; Suo et al., 2000, 2001, 2005).

In the Weihai-Rongcheng area, although a few large eclogite or retrograded eclogite bodies of several hundreds of meters in length can be seen at Datuan, Tenjia and Fengshan, a large amount of eclogites or retrograded eclogites only occur as pods, lenses, and boudins ranging in size from a few centimeters to several meters long. This feature can be interpreted as the result of the further dismembered pre-existing larger eclogite or retrograded eclogite bodies during D_4. The most typical feature of D_4 deformation in less-strained eclogite or retrograded eclogite bodies is the development of an array of ductile-brittle shear zones. These shear zones, which cross-cut previously formed structures at high angle, generally have a thickness of a few millimeters to several centimeters. In some cases, the shear zones were filled by quartz veins or chlorite-bearing quartz veins.

D_4 deformation is the most intense in the surrounding country rock gneiss and orthogneiss, and is represented by the development of a new compositional layering parallel to S_4 (Fig. 4g). All the country rock gneisses and orthogneisses are transformed into interlayered boudinaged amphibolites, epidote two-mica gneisses and mylonites. The newly formed compositional layering and foliation (S_4), in some places, are somewhat similar to D_3 foliation in attitude, where both sets of foliation are hard to distinguish in the field. They, therefore, are termed $D_{3/4}$ composite foliation (Fig. 1). In most cases, they are easily distinguished by their different geometries, overprinting nature, especially, metamorphic mineral assemblages and microstructures observed at the thin-section scale. The D_3 foliation and compositional layering have often been thrown into a set of outcrop/meso-scale recumbent/reclined folds with subhorizontal axial planes (S_4) and shallow-plunging axes (Fig. 6).

D_4 ductile shear zones characterized by low-angle mylonite zones, ranging from centimeters to several decameters in thickness were mainly developed along the contact zones between different lithologies in country rock gneisses and orthogneisses. The mylonite, in general, has a typical S-C composite planar fabric, in which all quartz grains were deformed predominantly by plastic deformation to produce a well-developed ribbon structure. Therefore, quartz was the main strain-accommodating mineral during the D_4 deformation stage. By contrast, plagioclase, biotite and amphibole etc. in the form of porphyroclasts are rheologically less active or passive phases in the deforming rocks.

The lower detachment zone (LDZ), >500 m in thickness, is particularly well exposed along the coast near Haiyangsuo (Fig. 1). The rocks within the detachment zone have undergone extremely ductile shear flow deformation, forming a shallow-dipping mylonitic foliation. Detailed observations at the coast near Haiyangsuo show that the shortening of the detachment zone, marked by folded

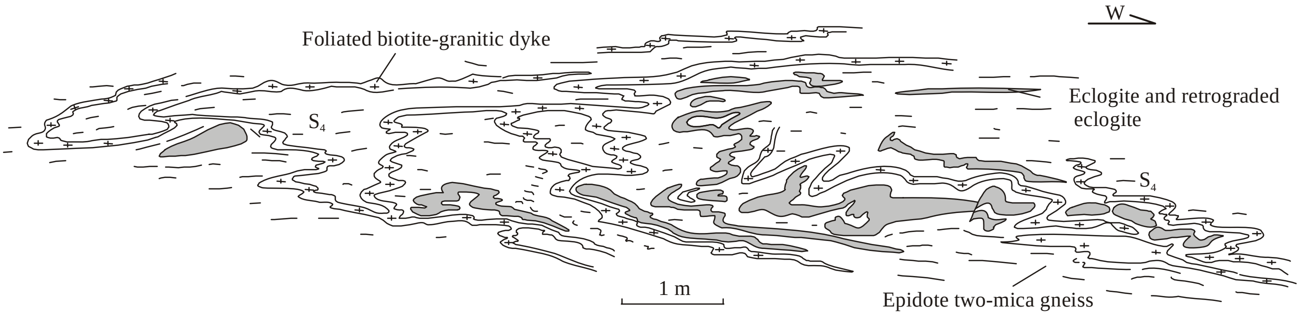

Fig. 6. Schematic E-W cross-section from the core of the Weihai structural dome, showing deformation features of foliated biotite-granitic dykes and discontinuous eclogite or retrograded eclogite layers of 10–15 cm thick in the epidote two-mica gneiss.
Note that the dykes developed at high angles to S_4 in the gneiss were folded due to vertical ductile shortening across S_4 during dome formation. For location see Fig. 1.

granite dykes across the mylonitic foliation, reached a value of 60% (Fig. 2). The kinematic criteria in the mylonitic rock, for example the asymmetrical microfold quartz ribbon, rhomboidal shaped "mica fish" and mantled plagioclase porphyroclasts (Fig. 4h), indicate a SW-side-down shear during D_4.

The D_4 foliation (S_4) and compositional layering, in the entire Weihai- Rongcheng area, delineate a dome-shaped structure, the Weihai structural dome in the north, and an arc-shaped structure in the south with an apex pointing SE (Fig. 1). As seen in Figs. 1 and 6, the D_4 foliation and fold axial plane are subhorizontal at the core of the dome (Figs. 4g and 6). Foliated biotite-granitic dykes parallel and at right angles to the dominant S_4 foliation in the country rock gneisses were boudinaged and folded, respectively, due to subvertical flattening across S_4 during dome formation. The recumbent folds with subhorizontal axial planes and symmetric boudins or pinch-and-swell structures indicate that the deformation in the core is mostly coaxial. It is characterized by nearly vertical shortening, with values up to 85% and a main south-north stretching (Figs. 4g and 6). The dominant S_4 foliation at the dome flank dips gently outward. All the kinematic criteria at the flank, including asymmetrical meso-scale folds, boudins, and the S-C fabric of the mylonitic rocks within the ductile shear zones (Fig. 4h), confirm a general normal sense of shear along the S_4 foliation. Hence, it is evident that the D_4 deformation might have occurred within a regional extensional strain field. This inference is also demonstrated by the D_4 stretching lineations with a multi-direction in the studied area. According to Zhang et al. (1995), the D_4 deformation took place at T~650°C and P<0.8 GPa.

3.6 D_5 Deformation

The D_5 deformation is characterized by the development of brittle-dominated high-angle faults of different trends as well as the Madao faulted basin. It was associated with the intrusion of large volumes of undeformed granitic plutons and dykes of 134 to 100 Ma age. The granitic plutons comprise about 30–40% of the surface exposure (Fig. 1). These tectonothermal events record post-orogenic extensional collapse and tectonic unroofing at shallower crustal levels (Dewey, 1988; Malavieille, 1993). The field relationships show that both the faults and granitic bodies crosscut the D_4 foliation and the previous D_4 stack of rock slices, but have not affected the principal structural framework formed during D_4 (Wallis et al, 1999, 2005; Suo et al, 2001, 2005). The D_5 structures largely control the geomorphology of the Weihai- Rongcheng area. The last stage of deformation gave rise to the final exhumation of the UHP rocks to the surface.

4 Regional Structural Evolution

A regional structure study of UHP and HP rocks in the Dabie-Sulu region has revealed that well recognizable deformation phases (D_1–D_5) and the related structures in the UHP rocks, as noted above, are not restricted to the Weihai-Rongcheng area. They are also observed in the whole Dabie-Sulu UHP and HP belts (Suo et al, 2002, 2003, 2004, 2005). Consequently, the structural data, combined with the available petrographic, metamorphic, geochemical and geochronological ones (e.g., Ames et al., 1993; Li et al., 1993, 2000; Okay et al., 1993; Liou et al., 1997, 2004; Zhang et al., 1995, 2003; Hacker et al., 1998, 2000; Faure et al., 2003; Xu et al., 2003; Yang et al., 2003; Zhong et al., 2003; Liu and Jian, 2004 and references therein) have allowed us to develop a tentative structural evolution model for the Dabie-Sulu UHP and HP belts, schematically depicted in Fig. 7. In this model, five major deformation events (D_1–D_5), excluding pre-UHP/HP events, are involved in the geodynamic processes responsible for the creation and exhumation of UHP/HP rocks in the Dabie-Sulu region. In Triassic times (250–230 Ma), there was a northward continental deep subduction of the Yangtze Craton to depths of about 100 km or more

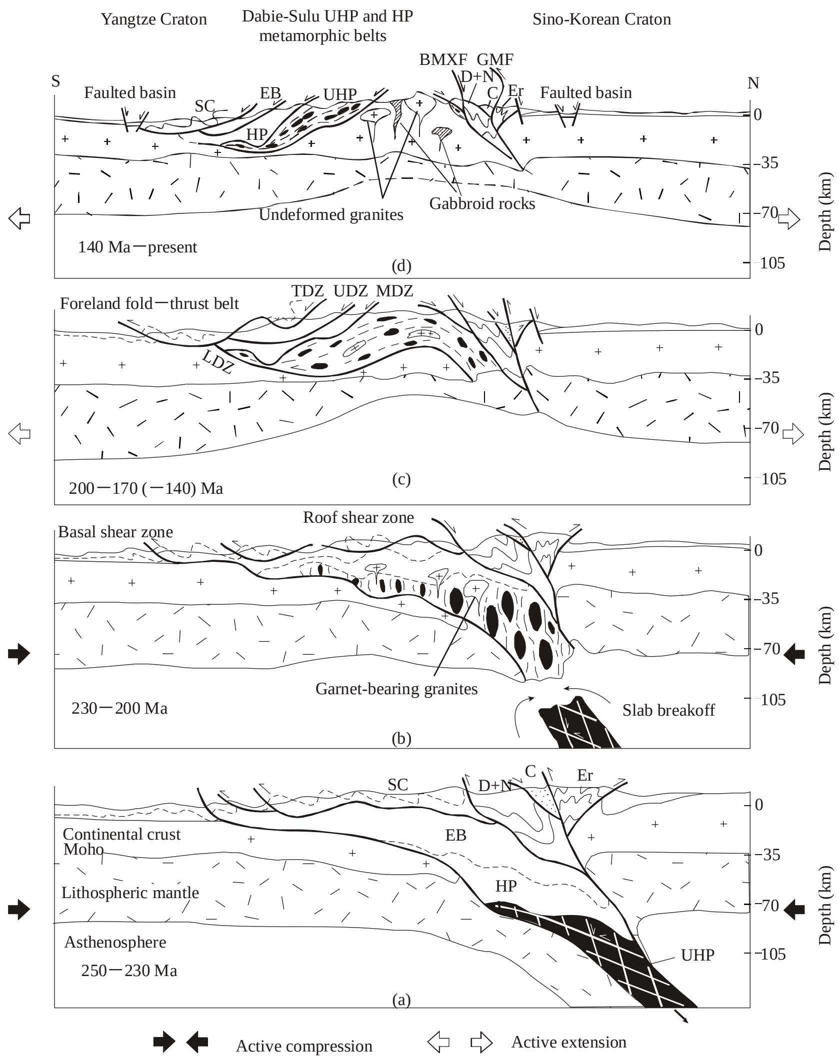

Fig. 7. Model for the regional structural evolution of the Dabie-Sulu UHP and HP metamorphic belts mainly inferred from geological constraints (not to scale, location of structures is only indicative), modified after Suo et al. (2005).

(a) Continental subduction and collision responsible for the formation of UHP and HP metamorphic rocks and associated D_1 and D_2 structures; (b) first exhumation stage (D_3) of UHP and HP rocks at crustal level, indicating that they were exhumed from near the Moho to the lower crust as an extruded wedge, bounded below and above by a gently N-dipping basal thrust shear zone and a moderately N-dipping roof shear zone with a down-dip sense of shear, respectively, and associated with the intrusion of garnet-bearing granites and decompressional partial melting of the country rock gneiss under upper amphibolite facies conditions; (c) subsequent exhumation stage, the D_4 deformation, characterized by post-collisional ductile extension and crustal ductile thinning, forming a regional-scale extensional framework similar to metamorphic core complexes; and (d) differential uplift of faulted blocks, faulted basin development and the intrusion of large volumes of granite, suggesting a post-orogenic collapse and tectonic unroofing during the last stage (D_5). GMF – Guishan-Meishan Fault; BMXF – Balifan-Mozitan-Xiaotian Fault; UHP – Ultrahigh-pressure unit; HP – High-pressure unit; EB – Epidote-blueschist unit; SC – Sedimentary cover; LDZ – Lower detachment zone; MDZ – Middle detachment zone; UDZ – Upper detachment zone; TDZ – Top detachment zone; Er – Erlangping Group; C – Carboniferous; D+N – Dingyuan and Nanwan formations.

beneath the Sino-Korean Craton with collision taking place over the Dabie-Sulu. The massive eclogites record this process, which occurred at the peak UHP metamorphic conditions within the diamond/coesite stability field. The microstructural signatures such as weak foliation and lineation are thought to have developed under low differential stress conditions. We infer that the differential stress, probably, was too low to produce notable deformation in the eclogites during the D_1 stage (Suo et al., 2005). The second stage of deformation (D_2) took place at high differential stress conditions. The pre-existing massive eclogites are intensely sheared to create anastomosing eclogite facies ductile shear zones. They are marked by mylonitic, foliated eclogites hosting relict massive eclogite lenses or lozenge-shaped blocks of different sizes (Fig. 7a). The D_2 deformation occurred immediately after the peak of UHP eclogite–facies metamorphism but was still in the coesite stability field. This inference is better demonstrated by the widespread coesite inclusions or their pseudomorphs in the foliated eclogite. On the other hand, minimum pressures between 1.5 GPa and 2.0 GPa were obtained for foliated eclogites in the Bixiling area, Dabie Mountains by Xiao et al. (1995). The D_2 stage, thus, is assumed to indicate compressional deformation related to subduction/collision between the cratons, which continued to exhume initially the UHP rocks from UHP depths to the depth near the Moho (Walsh and Hacker, 2004). Both the D_1 and D_2 ductile structures and fabrics have been strongly modified by post-eclogite deformations. Consequently, these early structures and fabrics are only preserved in eclogite, retrograded eclogite bodies and other UHP bodies. The detailed chronology of D_1 and D_2 is difficult to test. We assume that the stages are diachronous, illustrating a progressive increase in deformation toward the eclogite-facies shear zones.

The tectonic exhumation history of the UHP rocks at crustal levels can be divided into three main stages. The first exhumation stage (D_3) began with the development of granulite/amphibolite facies symplectites and coronas. During this stage, between about 230 Ma and 200 Ma, the

UHP rocks together with the HP rocks, constituting a subducted wedge, were rapidly extruded from near the Moho to lower crustal depths (Maruyama et al., 1994; Suo et al., 2002, 2005). Subsequently, the extruded wedge thrust further and eventually transported southward over the Yangtze Craton basement and foreland unit along the basal shear zone (Fig. 7b). Eclogites in the extruded wedge were further dismembered and boudinaged. A significant part of the eclogites was usually retrograded and transformed into steep-dipping, layered country rock gneisses. These layered rocks exhibit a different mineral assemblage and texture transition from eclogite, slightly retrograded through extensively retrograded eclogite to gneissic rocks of amphibolite facies. The country rock gneisses, thus, at least in part, are retrograde products of previous eclogites (Cong et al., 1995; Zhang et al., 2003). Slab breakoff of the subducted wedge probably provided sufficient heat to cause decompressional partial melting of the country rock gneisses (Davies and von Blanckenburg, 1995; Zhong et al., 1999; Labrousse et al., 2002; Wallis et al., 1999, 2005). Mechanical and thermal instabilities induced by crustal thickening and reheating due to the emplacement of volumes of garnet-bearing granites and dykes have led to the inversion from a contractional to extensional regime. The partial melting of the country rock gneiss is thus thought to play an important role in the tectonometamorphic evolution history of the UHP and HP belts in the Dabie-Sulu region.

The second exhumation stage of UHP rocks (D_4) occurred about between 200 Ma and 170 Ma, and probably lasted until 140 Ma (Fig. 7c). The exhumation of the UHP rocks up to the middle-upper crust was accomplished by a combination of subvertical shortening in the petrotectonic units and shear flow along the low-angle extensional detachment zones. The overall tectonic framework of the Dabie-Sulu UHP and HP belts formed during this stage displays some features of metamorphic core complexes (Davis, 1983; Ames et al., 1993; Suo et al., 2000, 2001, 2002, 2005). It resulted mainly from a post-collisional crustal ductile extension and thinning process, and dominates the map pattern of the Dabie-Sulu region to some degree. Cretaceous and Cenozoic (~140 Ma to present) post-orogenic collapse and tectonic unroofing (D_5), associated with intrusion of large volumes of granitic plutons, occurred after the regional ductile extension (D_4), belonging to the third exhumation stage of the UHP rocks at crustal levels (Fig. 7d). The D_5 tectonothermal event, to a certain degree, controls the present-day geomorphology of the Dabie-Sulu region. It is seen thus that the model is in reasonable agreement with the structural situation in the Dabie-Sulu UHP and HP metamorphic bells. Naturally, further study will eventually lead to a better understanding of the dynamic processes responsible for the formation and exhumation of the UHP rocks.

5 Conclusions

1. The UHP rocks exposed in the Weihai-Rongcheng area, NE Sulu, eastern China have a polyphase deformation history, in which, excluding pre-UHP events, five major stages of deformation (D_1 to D_5) have been distinguished at all scales. The first two stages of ductile deformation (D_1 and D_2) occurred under UHP metamorphic conditions, and are mainly preserved in large eclogite or retrograded eclogite bodies, while D_3 and D_4, characterized by intense ductile deformation are developed mostly within the country rock gneiss and orthogneiss, and belong to post-UHP eclogite facies contractional and extensional structures, respectively.

2. D_4 structures dominate the map pattern of the UHP rocks in the Weihai-Rongcheng area, whereas the D_5 tectonothermal events caused the final uplift of part of the UHP rocks to the surface, and thus largely control the geomorphology of the area. The overall geometry and kinematics for D_1 and D_2 at the studied area scale remain unknown.

3. The geometric pictures produced during the different stages show that shearing is the normal behavior if even the bulk regional strain is flattening or stretching, which is often progressively localized in anastomosing patterns of shear zones. The resulting structural domainal behavior, with lens-shaped domains of low strain enclosed by shear zones of high strain, reflects strong deformation partitioning at different scales, generally exhibiting a typical “block-in-matrix” fabric.

4. The structures and deformation sequence similar to those occurring in the Weihai-Rongcheng area are also well known from the whole Dabie-Sulu UHP and HP metamorphic belts. A speculative tectonic evolution model of all the belts, thus, can be proposed, inferred mainly from geological constraints, in which D_1 and D_2 are related to continental deep subduction and collision between the Sino-Korean and Yangtze cratons, while D_3, D_4 and D_5 present a three-stage exhumation process of the UHP and HP metamorphic rocks at crustal depths. These conclusions need to be tested and verified by further field and experimental investigations.

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