

A cold Early Palaeozoic subduction zone in the North Qilian Mountains, NW China: petrological and U-Pb geochronological constraints

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ABSTRACT The north Qilian high-pressure (HP)/low-temperature (LT) metamorphic belt is composed mainly of blueschists, eclogites and greenschist facies rocks. It formed within an Early Palaeozoic accretionary wedge associated with the subduction of the oceanic crust and is considered to be one of the best preserved HP/LT metamorphic belts in China. Here we report new lawsonite-bearing eclogites and eclogitic rocks enclosed within epidote blueschists in the North Qilian Mountains. Five samples contain unaltered lawsonite coexisting with omphacite and phengite as inclusions in garnet, indicating eclogite facies garnet growth and lawsonite pseudomorphs were observed in garnet from an additional 11 eclogites and eclogitic rocks. Peak pressure conditions estimated from lawsonite omphacite-phengite-garnet assemblages were 2.1–2.4 GPa at temperatures of 420–510 °C, in or near the stability field of lawsonite eclogite, and implying formation under an apparent geothermal gradient of 6–8 °C km⁻¹, consistent with metamorphism in a cold subduction zone. SHRIMP U-Pb dating of zircon from two lawsonite-bearing eclogitic metabasites yields ages of 489 ± 7 Ma and 477 ± 16 Ma, respectively. CL images and mineral inclusions in zircon grains indicate that these ages reflect an eclogite facies metamorphism. An age of 502 ± 16 Ma is recorded in igneous cores of zircon grains from one lawsonite pseudomorph-bearing eclogite, which is in agreement with the formation age of Early Ordovician for some ophiolite sequences in the North Qilian Mountains, and may be associated with a period of oceanic crust formation. The petrological and chronological data demonstrate the existence of a cold Early Palaeozoic subduction zone in the North Qilian Mountains.

Key words: Early Palaeozoic; lawsonite-bearing eclogite; North Qilian Mountains; NW China; SHRIMP U-Pb dating.

INTRODUCTION

High-pressure (HP)/low-temperature (LT) metamorphic rocks mainly consisting of blueschists and LT eclogites are considered to be an important indicator of former subduction zones (e.g. Ernst, 1971). Most previously described HP/LT metamorphic rocks formed during the Mesozoic–Cenozoic, and remnants of Palaeozoic HP/LT metamorphic rocks are relatively rare (e.g. Maruyama & Liou, 1998, 2005). The scarcity of older HP/LT metamorphic rocks has been ascribed to the progressive cooling of the earth, or to a preservation problem caused by recrystallization and overprinting during subsequent tectonothermal events (Agard *et al.*, 2005).

Lawsonite-bearing eclogite in HP/LT metamorphic belts is considered to form in a cold subduction zone with a low geothermal gradient (Zack *et al.*, 2004; Tsujimori *et al.*, 2006b). However, eclogite containing unaltered lawsonite is rare in nature (Ghent *et al.*, 1993; Shibakusa & Maekawa, 1997; Och *et al.*, 2003; Altherr *et al.*, 2004; Tsujimori *et al.*, 2005; Clarke *et al.*, 2006; Tsujimori *et al.*, 2006a; Whitney & Davis,

2006) and only two Pre-Mesozoic localities (Port Macquarie, New England fold belt, Australia, and Matalafjella, Western Spitsbergen, Norway) are known (Watanabe *et al.*, 1997; Och *et al.*, 2003; Tsujimori *et al.*, 2006b) although laboratory experiments and thermal models predict that it should be the dominant rock type under *P–T* conditions estimated for typical oceanic subduction zones (Poli & Schmidt, 1995; Schmidt & Poli, 1998; Hacker *et al.*, 2003; Zack *et al.*, 2004). In this contribution, lawsonite-bearing eclogites and eclogitic rocks are reported from the North Qilian orogenic belt, which is regarded as an Early Palaeozoic suture separating the Alashan block to the north and Qilian block to the south (Wu *et al.*, 1993; Xu *et al.*, 1994; Zhang *et al.*, 1997, 1998; Xia *et al.*, 2003). Petrography and mineral chemical data are used to constrain the *P–T* conditions and metamorphic evolution of these rocks. Furthermore, new geochronological data by SHRIMP U-Pb dating on zircon are presented, followed by discussion of the preservation of lawsonite-bearing eclogites, and their protolith and metamorphic ages. Finally, combining petrological and geochronological data, the

implications for a cold Early Palaeozoic subduction zone are discussed.

GEOLOGICAL SETTING

The Qilian orogenic belt is located at the north-eastern margin of the Qinghai-Tibet plateau. It extends in a WNW–ESE direction for ~1000 km, and is bounded

to the north by the Alashan block (ALB) and to the south by the Qaidam block (Fig. 1a). On the basis of geological mapping and lithotectonic characteristics, the Qilian orogenic belt is subdivided into three tectonic units: the North Qilian suture zone (NQLS), Qilian block (QLB) and the North Qaidam subduction–collision complex belt (NQDS) (Fig. 1a). The NQDS is an elongate, NW-trending belt that lies be-

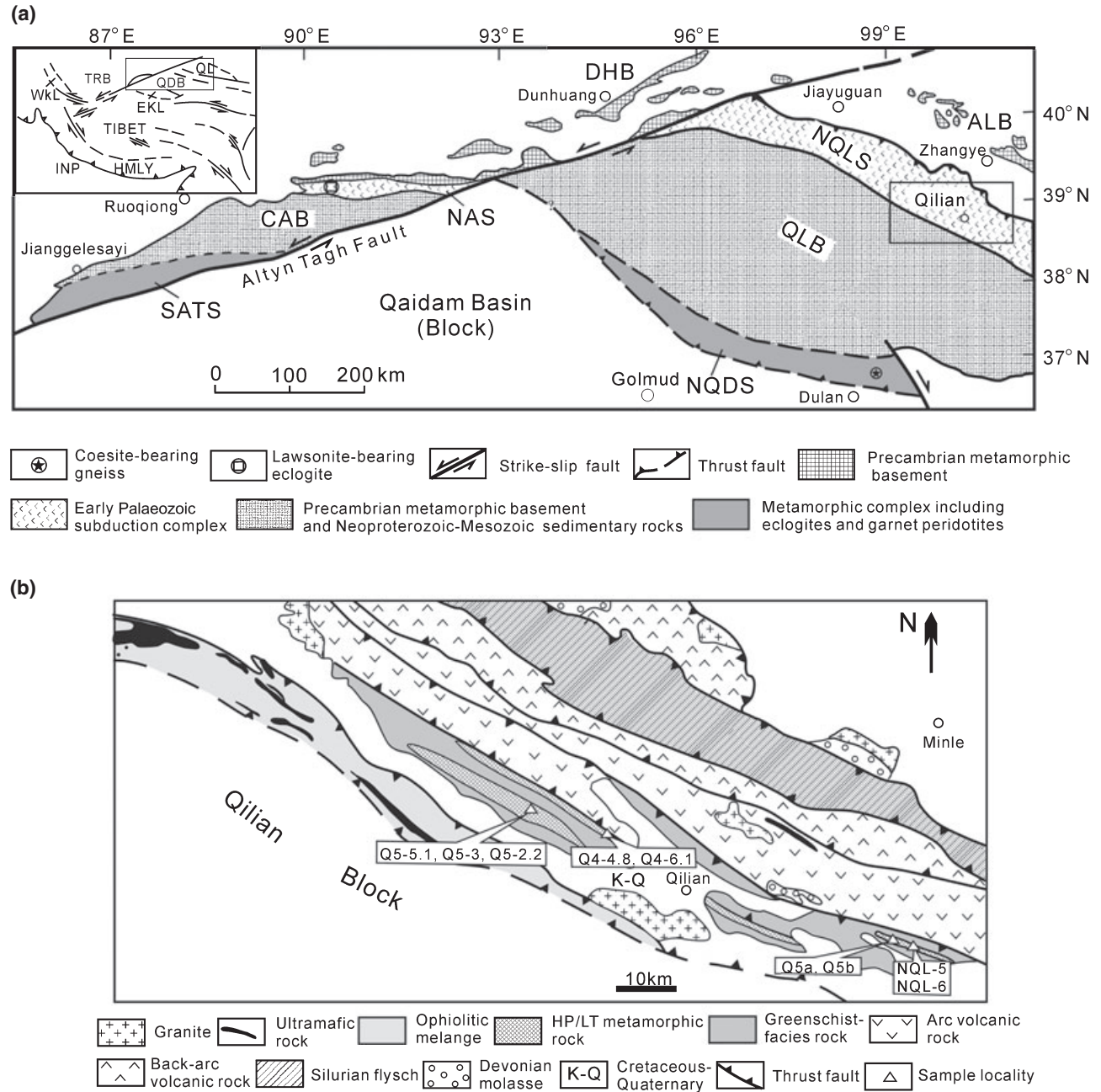


Fig. 1. (a) Schematic map of the Qilian–Altyn Tagh region showing tectonic units; and (b) simplified geological map showing major litho-tectonic units in the North Qilian Mountains and locations of representative samples, modified after Zhang *et al.* (1997, 2005a) and Zhang & Meng (2006). ALB–Alashan block; NAS – north Altyn Tagh suture; NQLS – north Qilian suture; CAB – central Altyn Tagh block; QLB – Qilian block; SATS – south Altyn Tagh subduction–collision zone; NQDS – North Qaidam subduction–collision zone. TRB – Tarim basin; QL – Qilian Mountains; QDB – Qaidam basin; HMLY – Himalaya Mountains; INP – Indian plate; WKL – Western Kunlun Mountains; EKL – Eastern Kunlun Mountains.

tween the ALB to the north and the QLB to the south (Fig. 1a). It is made up of Early Palaeozoic subduction complexes including ophiolitic melanges, high-pressure blueschists and eclogites, island-arc volcanic rocks with granite plutons, Silurian flysch, Devonian molasse, and Carboniferous to Triassic sedimentary cover sequences (Xu *et al.*, 1994; Zhang *et al.*, 1998). The NQLS was regarded to be the product of subduction of an Early Palaeozoic ocean plate between the ALB and QLB (Xiao *et al.*, 1978, 2003; Xu *et al.*, 1994; Zhang *et al.*, 1998). The QLB, located between the NQLS and the NQDS, consists of Precambrian basement overlain by Neoproterozoic to Mesozoic sedimentary sequences. The basement consists of felsic gneiss, marble, amphibolite and localized granulite. The NQDS, located between the QLB and Qaidam Block, consists mainly of paragneiss- and orthogneiss-enclosing blocks of eclogite, garnet peridotite and mafic granulite. These units thrust over, or are overlain by, Lower Palaeozoic volcanic and sedimentary rocks, and are intruded by granites. Eclogites and garnet peridotites in the NQDS record HP/ultrahigh-pressure (UHP) metamorphic conditions, and coesite-bearing paragneisses were also recognized in the Dulan area of the eastern NQDS (Fig. 1a) (Yang *et al.*, 2002; Song *et al.*, 2003). These units are bounded by WNW–ESE-striking shear zones and can be correlated with similar tectonic units in the Altyn Tagh, assuming 350–400 km of left-lateral displacement for the Altyn Tagh fault (Fig. 1a) (Yang *et al.*, 2001; Zhang *et al.*, 2001, 2005a,b,c).

The North Qilian (NQL) HP/LT metamorphic belt lies at the middle segment of the North Qilian Mountains and extends for about 200 km along the NQL suture. The first published record of HP blueschist in the North Qilian Mountains was reported by Xiao *et al.* (1978) and further studies led to the discovery of eclogite blocks in the blueschists (Wu, 1980; Zhang & Liou, 1987; Wu *et al.*, 1993). Recent studies suggest that the NQL HP/LT metamorphic belt may extend to the north Altyn Tagh, where a new HP/LT metamorphic belt has been recognized (Zhang *et al.*, 2005b) (Fig. 1a).

An island arc belt is exposed to the north of the HP/LT metamorphic belt (Fig. 1b). It consists mainly of calcalkaline volcanic rocks and volcanoclastic rocks, as well as 'T'-type granitoids. Whole-rock Sm–Nd isochron and zircon U–Pb TIMS analyses of island-arc-type volcanic rocks gave ages ranging from 486 to 445 Ma (Zhang *et al.*, 1997; Xia *et al.*, 2003). The Middle to Late Ordovician back-arc basin belt is located to the north of the island arc belt (Xu *et al.*, 1994; Zhang *et al.*, 1997; Xia *et al.*, 2003).

The NQL HP/LT metamorphic belt is mainly composed of greenschists, blueschists, eclogites, eclogitic rocks and metasediments with minor slices of ultramafic rocks, representing a deep unit of an accretionary wedge separated from an unmetamorphosed or

lightly metamorphosed ophiolite-bearing sequence (shallow unit of an accretionary wedge) by an overlying Mesozoic–Cenozoic basin (Fig. 1b) (Zhang *et al.*, 1998). Eclogites or eclogitic rocks occur as pods or blocks (0.1–50 m in size) within epidote blueschists, greenschists and metasediments (Fig. 2). Some eclogites are also intercalated with blueschist layers on a centimetre to decimetre scale (Fig. 2c). Available Ar–Ar data on phengite from blueschists and glaucophane-bearing greenschists yield ages of 460–440 Ma, which were interpreted to represent HP/LT metamorphic ages (Liou *et al.*, 1989; Wu *et al.*, 1993; Zhang *et al.*, 1997). Recently, SHRIMP U–Pb dating of zircon from eclogites gave ages of 468–463 Ma, which were regarded as the ages of the eclogite facies metamorphism (Song *et al.*, 2004, 2006).

PETROGRAPHY

More than 30 samples of eclogites and eclogitic rocks were collected in the North Qilian Mountains. Unaltered lawsonite occurs in five samples, but most samples contain lawsonite pseudomorphs (see below). The estimated modal compositions are listed in Table 1. In this paper, the term 'eclogite' is used for rocks with >70% omphacite + garnet, 'eclogitic rock' for the rocks in which the modes of garnet + omphacite is <70%, but are present as an equilibrium assemblage. [Mineral abbreviations are after Kretz, 1983, excepting phengite (Phe).]

Eclogitic metabasite

Eclogitic metabasites consist of garnet, omphacite, glaucophane, phengite, epidote (clinozoisite), quartz and rutile in varying amounts (Table 1). Garnet is idioblastic to subidioblastic and forms inclusion-rich porphyroblasts. Unaltered lawsonite was observed in samples Q5-5.1, Q5-5.3 and Q4-4.8. For samples Q5-5.1 and Q5-3, lawsonite occurs as 5–50 µm inclusions in the rims of garnet porphyroblasts (Fig. 3a–f). Other minerals included in garnet rims are omphacite, phengite, rutile and quartz. From these observations we interpret that the garnet, omphacite, phengite, rutile and quartz coexisted with lawsonite. Actinolite, glaucophane and titanite are restricted to garnet cores, and epidote/clinozoisite occurs in both cores and rims of garnet (Fig. 3a,c,g). In addition, rare lawsonite, together with glaucophane, epidote and titanite, was also observed in garnet core of sample Q4-4.8 (Fig. 3h). All these inclusions are monomineralic, occur well away from fractures and show equilibrium boundaries with their garnet host. By contrast, abundant box-shaped (or rectangular) 'inclusions' consisting of aggregates of Ep (Czo) + Pg ± Ms (Phe) were also observed in garnet of most eclogitic metabasites (Table 1; Fig. 3f). They are located adjacent to fractures, and therefore are inferred to be pseudomorphs after former lawsonite

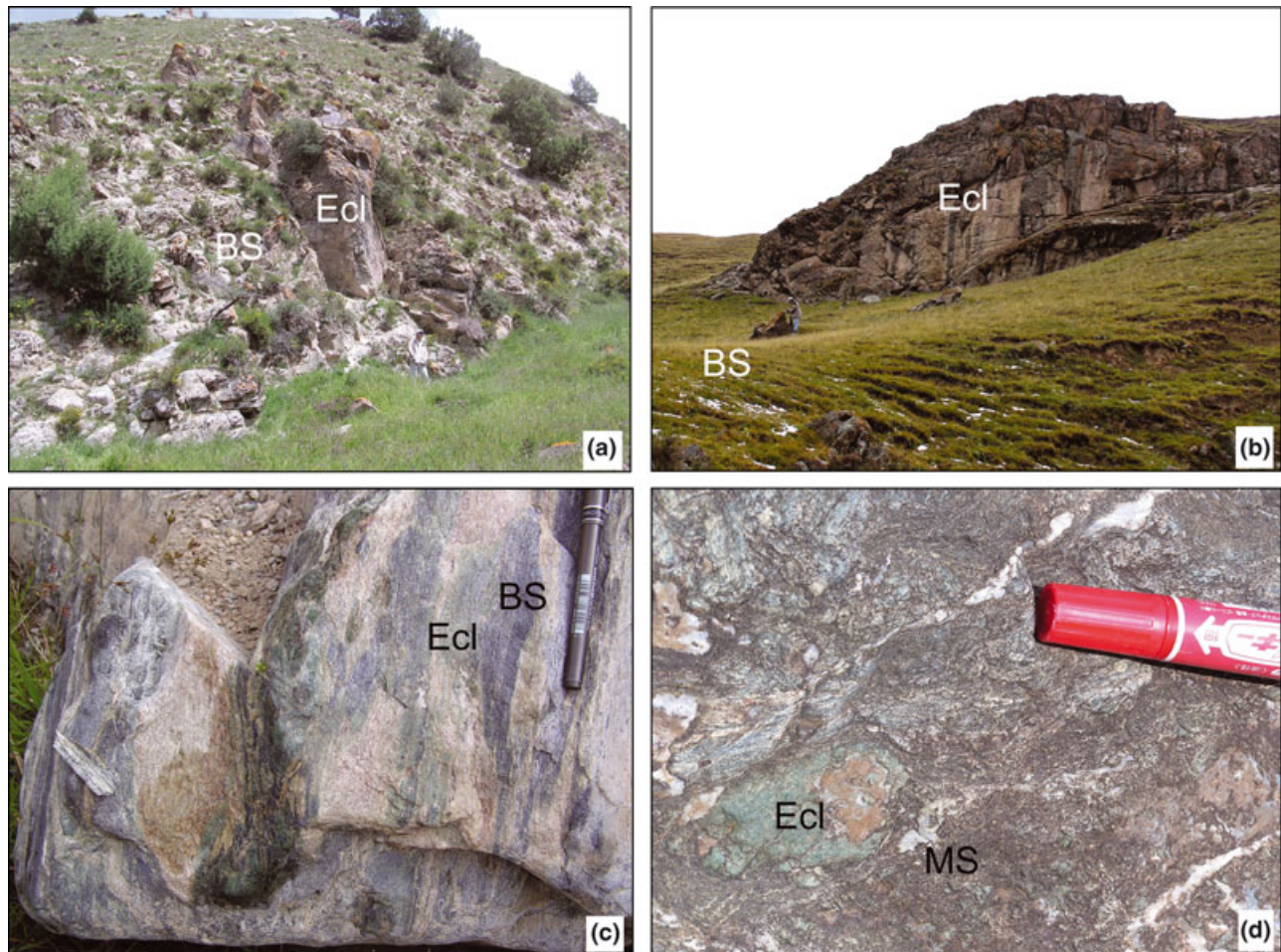


Fig. 2. Photographs showing the field relationships of eclogites and eclogitic rocks. (a) Boudins of eclogitic rocks (Ecl) in blueschist (BS); (b) large eclogite block (Ecl) ($30 \times 50 \text{ m}^2$) in blueschist (BS); (c) eclogite (Ecl) interlayered with blueschist (BS); (d) small eclogite pod (Ecl) within micaschist (MS).

Table 1. Modal contents of representative eclogites and eclogitic rocks from the North Qilian Mountains (vol.%, determined from BSE images).

Sample	Grt	Omp	Lws	Lws-p	Gl	Phe	Ep(Czo)	Qtz	Act	Pg	Ab	Chl	Rt	Ttn	Others	Locality
Eclogites																
Q5-2.2	20–25	40–45	+	+	10–12	3	8	3	2	+	+	+	+	+	Zrn (+), Cc (1)	38°16.55'N, 99°54.98'E
Q2-2.4	15–20	50	–	–	15	5	6	2	2	–	–	1	+	+	Cc (+)	38°16.79'N, 99°55.01'E
Q4-6.1	25	45–50	+	+	5	3	6	3	4	+	+	+	+	+	Ap (+)	38°15.46'N, 100°3.65'E
NQL-5	25	50	–	+	10	5	3	2	1	+	+	+	+	+	Zrn (+)	38°4.30'N, 100°33.84'E
Q1-7.2	20	50	–	+	8	6	5	3	1	+	+	2	+	–	Ap (+)	38°4.32'N, 100°33.72'E
Q1-9.1	22	45–50	–	+	5	3	5	2	6	+	+	2	+	+	Cc (3)	38°4.56'N, 100°35.73'E
Q12-2.4	10	55–60	–	+	10	2	6	1	1	+	+	+	+	+	Cc (+)	38°15.88'N, 99°56.39'E
Eclogitic metabasite																
Q5-5.1	15	10	+	+	30–35	5	10–15	3	10	+	+	2	–	–	Zrn(+), Ap(+)	38°16.89'N, 99°5.51'E
Q5-3	20	5	+	+	45–50	8	5	5	3	+	+	3	+	+	Ap (+)	38°15.28'N, 100°3.87'E
Q5-7.1	15	5	–	+	40–45	10	15	–	–	–	–	–	–	–	Cc (2)	38°16.97'N, 99°54.85'E
Q4-4.8	20	15–20	+	+	30–35	1	15	3	3	+	+	2	–	–	Zrn(+)	38°15.76'N, 100°4.72'E
Q2-2.5	8–10	20–25	–	–	30–35	5	20	8	5	+	+	5	+	+	Ap (+)	38°16.78'N, 99°55.22'E
Q2e	10–12	10	–	+	25–30	3	25	5	10	+	2	4	+	+	–	38°16.65'N, 99°55.41'E
Q2-2.2	10	10–15	–	+	30–35	5	15	3	10	+	1	2	+	+	–	38°16.89'N, 99°55.65'E
Q5-2d	20	10–12	–	+	20–25	10	15	5	5	+	2	4	1	+	Cc(+), Ap(+)	38°16.45'N, 99°56.16'E
Q5a	15	20–25	–	+	30–35	5	12	4	2	+	+	2	+	+	Zrn(+)	38°5.89'N, 100°31.85'E
Eclogitic schist																
NQL-6	20	10	–	+	20–25	15	3	25	1	+	+	+	1	+	Zrn(+)	38°4.10'N, 100°33.75'E
Q1-8.1	15–20	10–12	–	+	20–23	18	2	22	2	1	+	+	1	+	Zrn(+), Ap(+)	38°4.25'N, 100°33.62'E

Lws-p: lawsonite pseudomorph; Cc: carbonates; +: traces; –: no.

that became unstable after cracking of the garnet host facilitated dehydration. Lawsonite relics inside epidote also support such a suggestion (Fig. 3b). In addition, some epidote/clinozoisite grains in lawsonite pseudomorphs appear patchy in back-scattered electron (BSE) images, implying variable compositions (see below). Omphacite outside garnet occurs as porphyroblasts in the matrix, and is surrounded by secondary glaucophane, actinolite, epidote, phengite and paragonite (Fig. 3f), which define the foliation and lineation. Glaucophane and actinolite are intergrown with straight mutual grain boundaries, interpreted to reflect local equilibrium. Coexisting calcic and sodic amphibole grains were described in many studies (e.g. Deer *et al.*, 1997; Schmädicke & Will, 2003). In strongly retrograded domains, large actinolite and epidote porphyroblasts are oblique to the foliation. Garnet is partly replaced by chlorite, and the secondary glaucophane is partially replaced by Act + Ab. Chlorite and albite also occur in the fractures of garnet.

Eclogites

The main constituent minerals of the eclogites are garnet, omphacite, quartz, epidote/clinozoisite, amphibole (glaucophane & actinolite) and white mica (mainly phengite but also locally paragonite) with small amounts of rutile, titanite, chlorite, albite and opaque minerals (Table 1). The idioblastic garnet (2–10 mm) typically contains inclusions of omphacite, epidote/clinozoisite, glaucophane, quartz and rutile (Fig. 4a–d). Unaltered lawsonite, occurring as inclusions within garnet, was only observed in samples Q5-2.2 and Q4-6.1 (Fig. 4c, d), but most eclogites (such as samples NQL-5, Q1-7.2, Q1-9.1 & Q12-2.4; see Table 1) have abundant box-shaped (rectangular) epidote/clinozoisite-paragonite intergrowths as inclusions in garnet (Fig. 4b–d), suggesting the former presence of lawsonite. In contrast to those in eclogitic metabasites (samples Q5-5.1 & Q5-3), these lawsonite or lawsonite pseudomorph inclusions occur mainly in garnet cores and coexist with omphacite, glaucophane, epidote and quartz. The omphacite is fine-grained, subidioblastic, and together with phengite, glaucophane and clinozoisite constitutes the bulk of the rock matrix (such as NQL-5; Fig. 4a). These minerals define the foliation and lineation. Omphacite grains show undulose extinction and the formation of subgrains, indicating dynamic recrystallization related to deformation during eclogite facies conditions. In retrograded domains, omphacite and glaucophane are partially replaced by Act + Ab and garnet is replaced by chlorite. Glaucophane and epidote also occur as porphyroblasts, and are aligned oblique to the foliation, providing evidence to later growth compared with the peak assemblage. These textural characteristics indicate that glaucophane and epidote/clino-

zoisite grew before, during and after garnet and omphacite crystallization.

Eclogitic schist (samples NQL-6 & Q1-8.1)

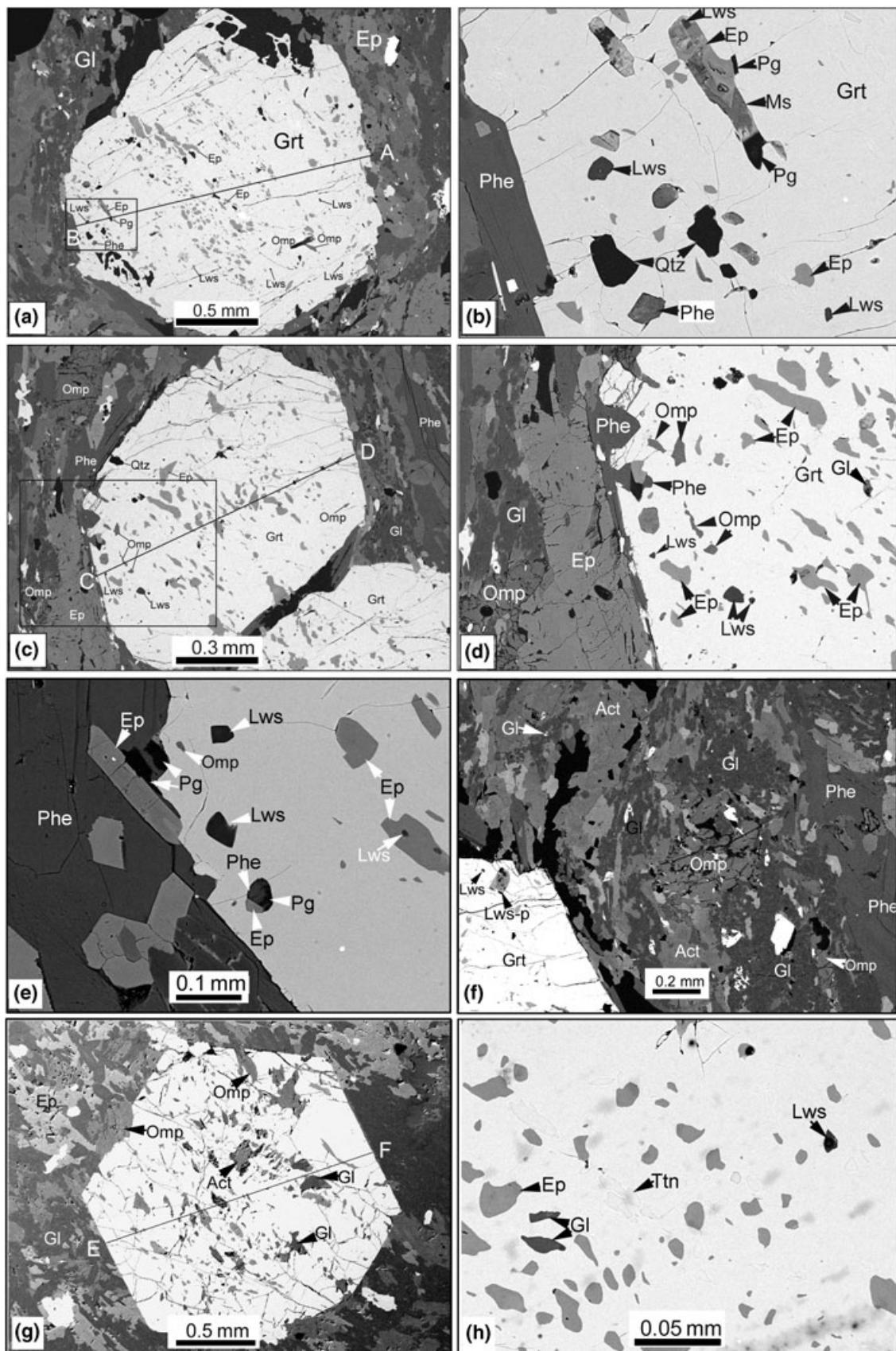
These rocks consist predominantly of garnet, glaucophane, omphacite, phengite and quartz with minor paragonite, rutile, epidote/clinozoisite and chlorite. Compared with eclogitic metabasites, they are rich in quartz and phengite which define the schistosity (Table 1; Fig. 4e, f). Idioblastic garnet (1–3 mm) contains inclusions of epidote/clinozoisite, quartz, glaucophane, omphacite and rutile, and is surrounded by oriented glaucophane, omphacite, quartz and phengite. Rectangular epidote/clinozoisite-paragonite-quartz intergrowths – suggesting the former presence of lawsonite – were also observed in garnet (Fig. 4e,f). In the matrix, oriented omphacite and glaucophane have straight boundaries, indicating a textural equilibrium (Fig. 4e). Chlorite occurs in the fractures or retrograde domains, and coexists with albite.

MINERAL CHEMISTRY

Minerals were analysed at the Institute of Geology and Mineral Resources, Chinese Academy of Geological Sciences, using a JEOL JXA-8800 electron probe with a 20-kV accelerating voltage, 20-nA beam current and a 5- μ m beam. Fine-grained mineral inclusions in garnet and zircon were analysed using 2 μ m beam diameter. Representative mineral compositions are listed in Tables 2–4.

Garnet

Garnet grains in all samples are almandine-rich ($X_{\text{Alm}} = 0.56\text{--}0.70$) with variable amounts of grossular, spessartine and pyrope components, and display a progressive rise in pyrope, a fall in spessartine, and a relatively constant grossular content from core to rim (except for sample NQL-6, see below), suggesting growth zoning (Fig. 5a–e). Garnet grains in eclogite NQL-5 and eclogitic schist NQL-6 have more obvious compositional zoning than those of eclogitic metabasites Q4-4.8 and Q5-5.1. Different almandine zoning patterns are identified: garnet from eclogitic schist NQL-6 exhibits an increase in almandine from core to mantle, then a decrease in almandine towards the outermost rim (Figs 5e & 6); garnet grains from eclogite NQL-5 and eclogitic metabasite Q5-5.1 show relatively constant almandine content (Fig. 4b,d), whereas garnet in eclogitic metabasite Q4-4.8 displays an increase in almandine from core to rim (Fig. 4c). For all samples, $X_{\text{Fe}} [\text{Fe}^{2+}/(\text{Mg} + \text{Fe}^{2+})]$ generally decreases from core to rim. Garnet from sample NQL-6 shows a slight grossular increase at the rim. This may be related to a lawsonite breakdown during the garnet growth (Tsujimori *et al.*, 2006a).



Clinopyroxene

All the analysed clinopyroxene from the studied samples plots in the omphacite field based on the classification of Morimoto *et al.* (1988) (Fig. 7). The jadeite component ranges between 30 and 53 mol.% with varying amounts of aegirine component (Aeg = 0–20 mol.%, calculated by the Droop, 1987 method). Omphacite in eclogitic metabasites Q5-5.1 and Q4-4.8 contains 30–42 mol.% jadeite, whereas omphacite from eclogites (samples NQL-5 & Q1-7.2) and eclogitic schists (NQL-6 & Q1-8.1) has a relatively high jadeite content ranging between 40 and 53 mol.%. Apart from eclogite NQL-5, no apparent variations in compositions between omphacite inclusions in garnet and matrix omphacite have been detected. In samples Q5-5.1 and Q1-7.2, some large omphacite porphyroblasts show compositional zoning characterized by an increase in jadeite content and decrease in aegirine component from core to rim.

Amphibole

Using the classification of Leake *et al.* (1997), amphibole from seven samples is mostly glaucophane and actinolite with minor winchite (Fig. 8). Glaucophane is characterized by Si contents of 7.70–8.00 p.f.u. and Na_B contents of 1.75 to 1.91. Actinolite has Si contents of 7.62–7.95 p.f.u. and Na_B < 0.5 (0.1–0.45). Winchite has Na_B contents of 0.5–0.7, close to the actinolite field (Fig. 8).

Lawsonite

Lawsonite has low FeO content (<1%), and the compositions are very close to the end-member CaAl₂Si₂O₈(2H₂O) (Tables 2 & 3).

White mica (phengite and paragonite)

The Si-values of the phengite from the studied samples range between 3.35 and 3.60 p.f.u. For eclogitic metabasite Q5-5.1, phengite in the matrix contains slightly higher Si contents than those of phengite inclusions. Paragonite has Si-values ranging between 2.93 and 3.06 and Na/(Na + K) values mostly between 0.9 and 0.98. No chemical difference

between matrix paragonite and paragonite inclusions in garnet was observed.

Epidote-group minerals

Cation formulae of epidote-group minerals have been calculated assuming all iron to be Fe³⁺. Epidote/clinozoisite inclusions in garnet show variable Fe³⁺ content (0.11–0.45 Fe³⁺ atoms per formula). Epidote/clinozoisite in the matrix contains higher Fe³⁺ content (0.30–0.65 Fe³⁺ p.f.u.).

METAMORPHIC EVOLUTION

Eclogites and eclogitic rocks commonly display a complex texture and suggest a multi-stage evolution. Based on textural features and mineral compositions, the metamorphic evolution of the eclogites and eclogitic rocks can be subdivided into four probable stages. Stage I corresponds to the prograde evolution and is documented by inclusions of glaucophane, epidote, actinolite, titanite and rare lawsonite in garnet cores of eclogitic metabasites. These inclusions, together with the host garnet core form the earliest recognizable prograde mineral assemblage that probably represents a lawsonite blueschist/epidote blueschist facies condition. Stage II is defined by the assemblage of garnet rim + omphacite + lawsonite + phengite + rutile + quartz in eclogitic metabasites, suggesting a peak lawsonite eclogite facies stage. In addition, for lawsonite-bearing eclogites (samples Q5-2.2 & Q4-6.1) and eclogitic schist (sample NQL-6), the inclusions of epidote, glaucophane, omphacite, quartz and rare lawsonite (or lawsonite pseudomorph) in garnet cores probably represent transitional conditions between those of garnet-lawsonite-epidote-bearing blueschists and lawsonite eclogites (e.g. Shibakusa & Maekawa, 1997; Altherr *et al.*, 2004). Stage III comprises the assemblage of secondary glaucophane + actinolite + phengite + paragonite + epidote which surrounds garnet and omphacite porphyroblasts in the matrix of eclogitic metabasites. This assemblage implies an epidote blueschist condition. Stage IV represents late, greenschist facies retrogression represented by chlorite and albite along the fractures in garnet, replacement of secondary glaucophane by Act + Ab in the matrix of eclogitic metabasite (Q5-5.1) and chloritization of garnet in strongly retrograded domains.

Fig. 3. Back-scattered electron (BSE) images displaying the textural characteristics of lawsonite-bearing eclogitic metabasites (Q5-5.1, Q5-3 & Q4-4.8) in the North Qilian Mountains. (a) Inclusions of lawsonite, phengite and quartz in the rim of a garnet porphyroblast, and epidote concentrated in the core of garnet. A–B is the location of the composition profile shown in Fig. 5a (Q5-5.1). (b) Detail of (a) exhibiting inclusions in the garnet rim. The large inclusion consisting of epidote, paragonite and muscovite (phengite) includes relict lawsonite. It is a pseudomorph after former lawsonite. (c) Lawsonite, omphacite and phengite inclusions in the rim of garnet. The surrounding matrix consists of glaucophane, omphacite and epidote. C–D is the location of the composition profile shown in Fig. 5b (Q5-5.1). (d) Detail of (c). (e) Lawsonite, omphacite and phengite inclusions in the rim of garnet. Epidote includes relict lawsonite (Q5-3). (f) Lawsonite and lawsonite pseudomorph in the rim of garnet; omphacite porphyroblast is surrounded by secondary glaucophane, actinolite, epidote and albite in the matrix (Q5-5.1). (g) Idioblastic garnet with glaucophane and actinolite inclusions in the core and omphacite inclusions in the rim. E–F is the location of the composition profile shown in Fig. 5c (Q4-4.8). (h) Inclusions of lawsonite, glaucophane, epidote and titanite in garnet core (Q4-4.8).

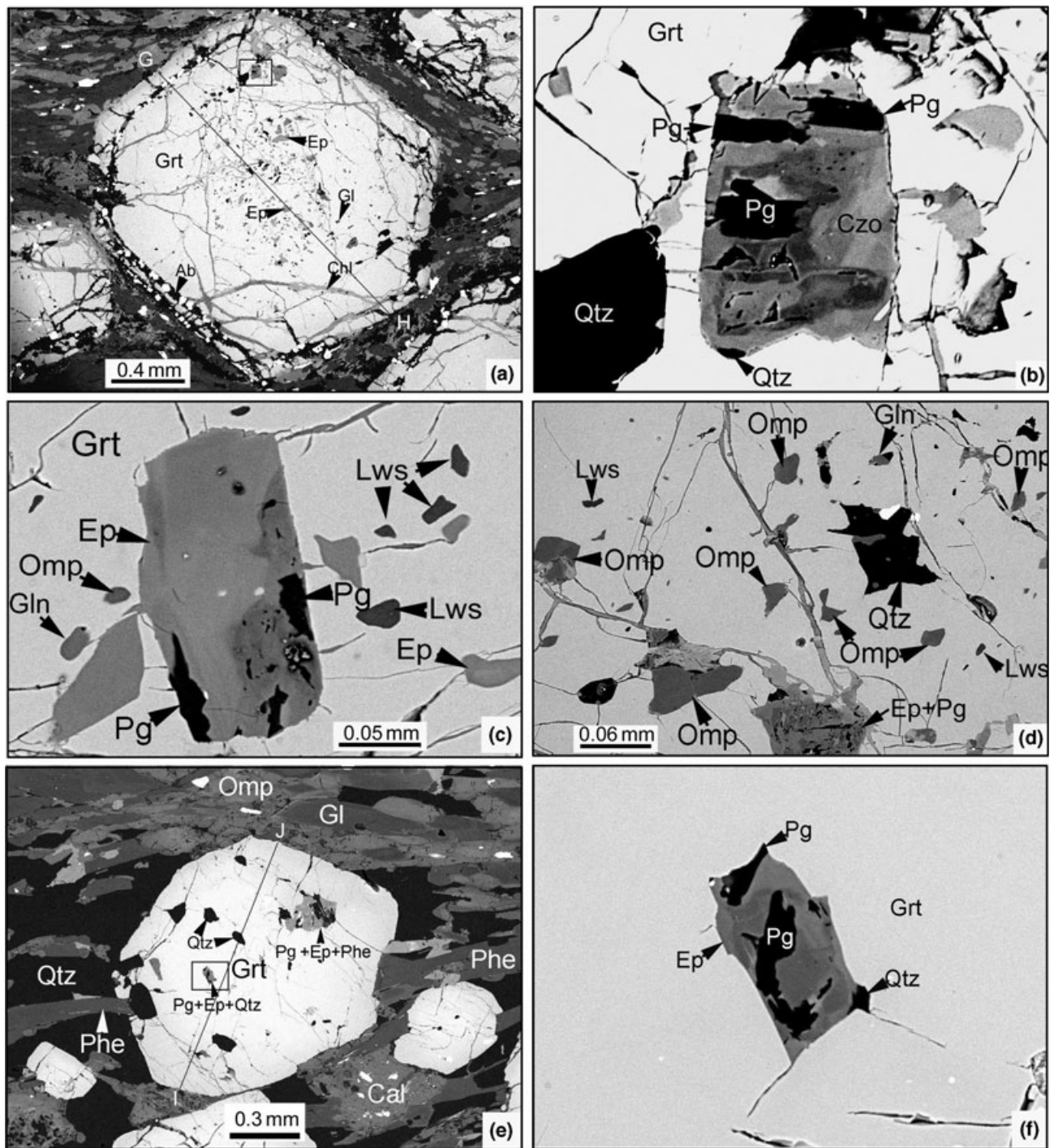


Fig. 4. Microtextures of eclogite and eclogitic schist (BSE images) (a) Fine-grained glaucophane and epidote inclusions in the core of idioblastic garnet (NQL-5). The surrounding matrix consists of oriented omphacite, glaucophane, phengite and clinozoisite. Chlorite and albite grew along cracks in garnet. G–H is the location of the composition profile shown in Fig. 5d (b) Detail of (a) exhibiting the box-shaped epidote (clinozoisite)-paragonite-quartz intergrowth in garnet. (c) Lawsonite and omphacite inclusions in garnet. The rectangular inclusion consisting of epidote and paragonite is a pseudomorph after former lawsonite (Q5-2.2). (d) Omphacite and lawsonite inclusions in garnet (Q4-6.1). (e) Sub-idioblastic garnet surrounded by oriented omphacite, glaucophane, phengite and quartz. In the matrix, omphacite and glaucophane have straight boundaries. I–J is the location of the composition profile shown in Fig. 5e (NQL-6). (f) Detail of (e) exhibiting rectangular, composite inclusion of epidote + paragonite + quartz intergrowth in garnet.

Table 2. Representative microprobe analyses of the minerals for eclogitic rocks.

Sample	Q5-5.1													Q4-4.8										
	Mineral	Grt-c	Grt-r	Omp-m	Omp-in	Phe-m	Phe-in	Gln-in	Gln-m	Czo-in	Ep-in	Ep-m	Lws	Lws	Grt-c	Grt-r	Omp-in	Omp-m	Gln-m	Act-m	Phe-m	Ep-m	s	
SiO ₂	37.89	38.36	56.23	55.61	51.94	49.86	57.69	57.63	39.56	38.38	38.36	37.63	37.60	37.95	38.06	55.66	55.42	57.60	53.85	52.81	38.32	38.37		
TiO ₂	0.08	0.05	0.04	0.03	0.23	0.20	0.13	0.03	0.15	0.26	0.13	0.08	0.02	0.15	0.03	0.03	0.04	0.02	0.04	0.19	0.10	0.05		
Al ₂ O ₃	20.50	21.12	10.48	9.19	27.27	26.79	10.90	11.51	31.32	28.84	26.06	30.75	31.18	20.82	20.73	7.30	6.96	9.55	3.41	24.94	25.40	32.25		
Cr ₂ O ₃	0.03	0.05	0.00	0.03	0.12	0.00	0.03	0.04	0.00	0.00	0.02	0.04	0.02	0.05	0.00	0.03	0.02	0.02	0.05	0.01	0.09	0.00		
FeO	24.36	26.80	4.50	5.28	1.42	1.10	8.66	7.42	1.71	5.90	7.95	0.58	0.70	24.02	26.95	9.15	10.30	13.28	13.03	3.46	8.58	0.46		
MnO	5.04	0.45	0.06	0.06	0.01	0.00	0.00	0.02	0.03	0.05	0.13	0.05	0.02	3.26	0.82	0.02	0.04	0.03	0.05	0.00	0.17	0.02		
MgO	1.75	3.50	8.49	9.03	3.34	3.70	11.31	11.73	0.04	0.14	0.02	0.01	0.07	0.90	1.36	7.60	7.31	9.13	14.67	3.50	0.02	0.01		
CaO	10.51	10.06	13.56	15.10	0.28	0.04	1.53	1.21	24.67	24.16	23.63	17.91	17.76	12.24	11.76	13.65	13.80	0.91	9.69	0.01	23.38	18.05		
Na ₂ O	0.02	0.00	6.97	6.21	0.71	0.79	6.73	7.02	0.00	0.02	0.00	0.00	0.03	0.00	0.02	6.60	6.41	7.09	2.16	0.35	0.00	0.00		
K ₂ O	0.00	0.00	0.00	0.00	10.47	11.26	0.01	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.19	11.25	0.00	0.00		
Total	100.18	100.39	100.33	100.54	95.80	93.75	97.01	96.59	97.51	97.95	96.32	87.04	87.39	99.39	99.73	100.04	100.31	97.65	97.13	96.53	96.87	89.19		
O	12	12	6	6	11	11	23	23	12.5	12.5	12.5	8	8	12	12	6	6	23	23	11	12.5	8		
Si	3.011	3.005	1.988	1.975	3.433	3.389	7.923	7.900	3.039	2.977	3.039	2.014	2.004	3.029	3.031	2.011	2.007	7.999	7.746	3.507	3.047	1.998		
Ti	0.005	0.003	0.001	0.001	0.011	0.010	0.013	0.003	0.009	0.015	0.008	0.003	0.001	0.009	0.002	0.001	0.001	0.002	0.004	0.009	0.006	0.002		
Al	1.919	1.950	0.437	0.385	2.125	2.147	1.965	1.860	2.827	2.638	2.434	1.938	1.957	1.959	1.946	0.311	0.297	1.563	0.578	1.952	2.381	1.978		
Cr	0.002	0.003	0.000	0.001	0.006	0.000	0.003	0.004	0.000	0.000	0.001	0.000	0.000	0.003	0.000	0.001	0.001	0.002	0.006	0.001	0.006	0.000		
Fe ³⁺	0.045	0.031	0.062	0.091	0.000	0.000	0.073	0.060	0.110	0.384	0.527	0.026	0.031	0.000	0.000	0.128	0.136	0.245	0.185	0.000	0.570	0.02		
Fe ²⁺	1.574	1.725	0.071	0.066	0.078	0.063	0.922	0.791	0.000	0.000	0.000	0.000	0.000	1.604	1.795	0.149	0.176	1.297	1.382	0.192	0.000	0.000		
Mn	0.339	0.030	0.002	0.002	0.001	0.000	0.000	0.002	0.002	0.003	0.009	0.002	0.001	0.220	0.055	0.001	0.001	0.004	0.006	0.000	0.011	0.001		
Mg	0.207	0.409	0.447	0.478	0.329	0.375	2.321	2.396	0.005	0.016	0.002	0.001	0.006	0.107	0.161	0.409	0.395	1.89	3.145	0.346	0.002	0.001		
Ca	0.895	0.845	0.514	0.575	0.020	0.003	0.225	0.178	2.033	2.010	2.008	1.027	1.014	1.048	1.003	0.528	0.536	0.135	1.494	0.001	1.994	1.007		
Na	0.003	0.000	0.478	0.428	0.091	0.104	1.792	1.866	0.000	0.000	0.000	0.000	0.003	0.000	0.003	0.463	0.450	1.909	0.602	0.045	0.000	0.000		
K	0.000	0.000	0.000	0.000	0.884	0.977	0.002	0.014	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.035	0.954	0.000	0.000		
Total	8.000	8.000	4.000	4.000	6.978	7.068	15.040	15.075	8.034	8.044	8.027	5.011	5.017	7.980	7.996	4.000	4.000	15.05	15.184	7.007	8.019	5.007		

Notes: Grt-c: Garnet core; Grt-r: garnet rim; Omp-m: Omphacite in the matrix; Omp-in: Omphacite inclusion in garnet; Phe-m: Phengite in the matrix; Phe-in: Phengite inclusion in garnet; Gln-in: glaucophane inclusion in garnet; Gln-m: glaucophane in the matrix; Ep-in: epidote inclusions in garnet; Czo-in: clinozoisite inclusion in garnet; Ep-m: epidote in the matrix. The Droop (1987) method is used to estimate Fe³⁺ in garnet, clinopyroxene and amphibole.

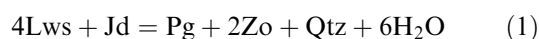
Table 3. Representative microprobe analyses of the minerals for eclogites (NQL-5, Q5-2.2 & Q1-7.2).

Sample	NQL-5							Q5-2.2							Q1-7.2						
	Mineral	Grt-c	Grt-r	Omp-m	Omp-in	Gln-m	Phe-m	Ep-m	Grt-c	Grt-r	Omp-in	Omp-m	Gln-m	Ep-m	Lws	Grt-c	Grt-r	Omp-in	Omp-m	Gln-m	Phe-m
SiO ₂	37.47	38.63	56.04	55.86	58.32	53.20	38.96	37.82	38.59	56.96	57.18	58.54	38.98	38.34	37.47	38.35	54.17	56.62	58.32	53.47	
TiO ₂	0.12	0.03	0.04	0.03	0.03	0.18	0.06	0.20	0.09	0.05	0.05	0.02	0.14	0.02	0.12	0.03	0.04	0.05	0.03	0.22	
Al ₂ O ₃	20.21	21.42	11.61	9.21	10.84	25.31	26.58	20.89	20.99	8.88	9.67	11.05	27.55	31.38	20.21	21.38	9.32	11.24	10.84	27.71	
Cr ₂ O ₃	0.04	0.00	0.01	0.05	0.11	0.06	0.10	0.04	0.12	0.00	0.00	0.02	0.01	0.00	0.04	0.02	0.03	0.09	0.11	0.19	
FeO	27.56	25.46	4.89	6.67	7.17	1.88	7.97	25.79	27.23	4.89	2.55	7.74	6.12	0.51	27.57	27.07	9.80	4.84	7.17	2.07	
MnO	1.34	0.21	0.03	0.02	0.00	0.00	0.00	2.82	0.35	0.02	0.05	0.06	0.04	0.03	1.34	0.30	0.06	0.02	0.00	0.01	
MgO	1.79	6.59	7.14	7.81	12.56	4.02	0.11	1.26	3.46	9.67	8.95	11.89	0.05	0.02	1.79	5.31	6.55	7.76	12.56	3.99	
CaO	10.48	7.44	11.20	12.56	1.06	0.08	23.90	10.88	9.81	14.67	14.49	1.21	23.75	17.25	10.48	7.64	11.82	11.78	1.07	0.12	
Na ₂ O	0.02	0.02	8.12	7.36	7.04	0.51	0.00	0.00	0.03	6.09	6.35	7.03	0.00	0.10	0.02	0.06	7.84	7.95	7.04	0.40	
K ₂ O	0.00	0.00	0.00	0.00	0.02	10.89	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.02	8.23	
Total	99.03	99.81	99.08	99.57	97.15	96.14	97.69	99.71	100.66	100.83	99.30	97.57	96.64	87.52	99.04	100.16	99.63	100.35	97.16	96.41	
O	12	12	6	6	23	11	12.5	12	12	6	6	23	12.5	8	12	12	6	6	23	11	
Si	3.011	2.994	1.997	2.000	7.928	3.513	3.037	3.017	3.018	2.007	2.033	7.953	3.054	2.028	3.011	2.987	1.950	1.993	7.928	3.448	
Ti	0.007	0.002	0.001	0.001	0.003	0.009	0.004	0.012	0.005	0.001	0.001	0.002	0.008	0.001	0.007	0.002	0.001	0.001	0.003	0.011	
Al	1.915	1.957	0.488	0.388	1.737	1.970	2.443	1.965	1.935	0.369	0.405	1.770	2.544	1.955	1.915	1.963	0.396	0.466	1.737	2.107	
Cr	0.003	0.000	0.000	0.001	0.012	0.003	0.006	0.003	0.007	0.000	0.000	0.002	0.001	0.000	0.003	0.001	0.001	0.003	0.012	0.010	
Fe ³⁺	0.049	0.053	0.078	0.120	0.141	0.000	0.519	0.000	0.015	0.031	0.000	0.071	0.411	0.023	0.049	0.066	0.248	0.085	0.139	0.078	
Fe ²⁺	1.804	1.597	0.068	0.080	0.674	0.104	0.000	1.721	1.766	0.113	0.076	0.808	0.000	0.000	1.804	1.697	0.047	0.057	0.676	0.033	
Mn	0.091	0.014	0.001	0.001	0.000	0.000	0.000	0.191	0.023	0.001	0.002	0.007	0.003	0.001	0.091	0.020	0.002	0.001	0.000	0.001	
Mg	0.214	0.761	0.379	0.417	2.545	0.396	0.013	0.150	0.403	0.508	0.474	2.407	0.006	0.002	0.214	0.616	0.351	0.407	2.545	0.383	
Ca	0.902	0.618	0.428	0.482	0.154	0.006	1.998	0.931	0.822	0.554	0.552	0.176	1.996	0.978	0.902	0.638	0.456	0.444	0.156	0.008	
Na	0.003	0.003	0.562	0.511	1.856	0.065	0.000	0.000	0.005	0.416	0.438	1.852	0.000	0.010	0.003	0.009	0.548	0.543	1.856	0.050	
K	0.000	0.000	0.000	0.000	0.003	0.918	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.678	
Total	8.000	8.000	4.000	4.000	15.054	6.984	8.020	7.988	8.000	4.000	3.981	15.052	8.012	4.998	8.000	8.000	4.000	4.000	15.055	6.807	

Notes: Grt-c: Garnet core; Grt-r: garnet rim; Omp-m: Omphacite in the matrix; Omp-in: Omphacite inclusion in garnet; Gln-m: glaucophane in the matrix; Phe-m: Phengite in the matrix; Ep-m: epidote in the matrix. The Droop (1987) method is used to estimate Fe³⁺ in garnet, clinopyroxene and amphibole.

P–T ESTIMATES FOR PEAK CONDITIONS

For lawsonite-bearing eclogitic metabasites (Q5-5.1 & Q5-3) and eclogites (Q5-2.2 & Q4-6.1), the presence of lawsonite coexisting with omphacite constrains the *P–T* condition to the LT/HP side of the following reaction (Fig. 9):



The locus of the reaction was calculated with THERMOCALC (3.1). Jd is the jadeite content in omphacite (assuming Jd = 50 mol.%), and its activity was calculated with AX program of Holland (<http://>

Table 4. Representative microprobe analyses of the minerals for eclogitic schists (NQL-6 & Q1-8.1).

Sample	NQL-6						Q1-8.1					
Mineral	Grt-c	Grt-r	Omp-c	Omp-r	Gln-m	Phe-m	Grt-c	Grt-r	Omp-r	Omp-c	Gln-m	Phe-m
SiO ₂	37.78	39.20	56.34	56.39	57.63	53.52	37.52	38.96	57.14	56.41	58.60	53.39
TiO ₂	0.07	0.03	0.04	0.05	0.01	0.20	0.07	0.03	0.02	0.04	0.02	0.16
Al ₂ O ₃	20.59	21.43	9.84	10.07	10.84	26.85	20.59	21.15	12.39	8.80	10.67	26.77
Cr ₂ O ₃	0.06	0.03	0.08	0.26	0.13	0.21	0.06	0.07	0.05	0.08	0.13	0.17
FeO	25.95	25.40	9.72	10.98	11.67	2.54	25.95	27.48	5.80	10.28	7.50	2.50
MnO	6.88	0.13	0.03	0.02	0.02	0.03	6.88	0.21	0.03	0.01	0.02	0.01
MgO	1.53	6.81	5.43	4.6	9.21	3.38	1.52	5.60	5.92	6.47	12.10	3.34
CaO	7.02	7.19	9.17	7.53	0.51	0.00	7.02	6.89	9.03	10.30	0.78	0.05
Na ₂ O	0.02	0.03	9.15	9.95	7.24	0.78	0.02	0.01	9.32	8.60	7.18	0.75
K ₂ O	0.00	0.01	0.01	0.00	0.02	10.37	0.00	0.00	0.01	0.00	0.02	10.32
Total	99.90	100.26	99.80	99.84	97.28	97.89	99.63	100.40	99.71	100.79	97.02	97.46
O	12	12	6	6	23	11	12	12	6	6	23	11
Si	3.033	3.022	2.015	2.015	7.984	3.470	3.022	3.029	2.018	2.006	7.984	3.425
Ti	0.004	0.002	0.001	0.001	0.001	0.010	0.004	0.002	0.001	0.001	0.002	0.008
Al	1.948	1.947	0.415	0.424	1.77	2.053	1.955	1.939	0.516	0.369	1.714	2.054
Cr	0.004	0.002	0.002	0.007	0.014	0.011	0.004	0.004	0.001	0.003	0.014	0.009
Fe ³⁺	0.000	0.010	0.186	0.225	0.093	0.000	0.000	0.000	0.084	0.192	0.119	0.000
Fe ²⁺	1.742	1.628	0.104	0.104	1.259	0.138	1.748	1.787	0.087	0.113	0.735	0.136
Mn	0.468	0.008	0.001	0.001	0.002	0.002	0.469	0.014	0.001	0.000	0.002	0.001
Mg	0.183	0.782	0.289	0.245	1.902	0.327	0.182	0.649	0.312	0.343	2.457	0.324
Ca	0.604	0.594	0.351	0.288	0.076	0.000	0.606	0.574	0.342	0.393	0.114	0.004
Na	0.003	0.004	0.634	0.690	1.945	0.098	0.003	0.002	0.638	0.580	1.897	0.095
K	0.000	0.001	0.000	0.000	0.004	0.859	0.000	0.000	0.000	0.000	0.003	0.857
Total	7.989	8.000	4.000	4.000	15.05	6.966	7.995	7.999	4.000	4.000	15.041	6.910

Grt-c: Garnet core, Grt-r: garnet rim; Omp-c: Omphacite core; Omp-r: Omphacite rim; Gln-m: glaucophane in the matrix; Phe-m: phengite in the matrix. The Droop (1987) method is used to estimate Fe³⁺ in garnet, clinopyroxene and amphibole.

www.esc.cam.ac.uk/astaff/holland). The other end-member minerals were considered pure phases (activity is 1). In sample Q5-5.1, lawsonite coexists with omphacite and phengite inclusions in garnet rims. Using Grt-Cpx-Phe geobarometry (Ravna & Terry, 2004) and Grt-Cpx geothermometry (Ravna, 2000), coexisting garnet, omphacite and phengite give equilibrium conditions of 420–510 °C and 2.1–2.4 GPa (Fig. 9). The Fe³⁺ contents in omphacite were calculated by $\text{Fe}^{3+} = \text{Na} - (\text{Al} + \text{Cr})$, and total Fe in garnet was considered as Fe²⁺. In addition, for all studied samples, coexisting omphacite, phengite in the matrix and adjacent garnet rims gave conditions of 2.1–2.6 GPa and 430–570 °C (Fig. 9), similar to those obtained by inclusion assemblages in garnet rims of sample Q5-5.1. Therefore, we infer that omphacite and phengite in the matrix also formed during the peak metamorphic stage, and lawsonite may have occurred in the matrix but is no longer preserved.

GEOCHRONOLOGY

Sample preparation and SHRIMP analytical procedures

Zircon grains from lawsonite-bearing eclogitic metabasites (Q5-5.1 & Q4-4.8) and lawsonite pseudomorph-bearing eclogite (NQL-5) were separated using standard heavy liquid and magnetic techniques, hand-picked under a binocular microscope, and mounted in epoxy resin with standard Temora zircon (TEM zircon, 417 Ma; Black *et al.*, 2003). The sample mount was polished to expose the centre of the zircon grains and then gold-coated. Prior to analysis, the mineral inclusions in the zircon were identified by laser Raman

spectrophotometry, and the mineral inclusions polished to the surface were analysed by an electron microprobe (operating conditions as described above, but a 1- μm beam diameter was used). Transmitted- and reflected-light images were taken to get information about the shape of zircon grains and their position in the mount. The zircon was imaged by cathodoluminescence (CL) to reveal their internal structure. The CL images were obtained by scanning electron microscopy (SEM) using a FEI PHILIPS XL30 SFEG instrument with 2 min scanning time at conditions of 15 kV and 120 nA at Peking University.

The dating was carried out on the SHRIMP-II at the Beijing SHRIMP Center, Institute of Geology, CAGS. Operation and data processing follow Williams (1998). The primary oxygen ions were generated in a duoplasmatron at about 4.5 nA, 10 kV. The radius of the ion beam was ~20–30 μm and the mass resolution ~5400 (1% peak height). Standard zircon sample SL13 was measured to calibrate U, Th, and Pb concentrations, and standard zircon TEM was used for element fractionation correction. All the data were analysed with the Isoplot program (Ludwig, 1991), and plotted on the classical Concordia diagram. Common Pb was corrected using the determined ²⁰⁴Pb. Ages were calculated using IUGS-recommended coefficients (Steiger & Jäger, 1977). Uncertainties in Table 5 are given at the 1-sigma level, and uncertainties on weighted mean ages are at the 95% confidence level.

Results of SHRIMP dating

Cathodoluminescence investigations of eclogitic metabasite sample Q5-5.1 reveal three zircon types. The

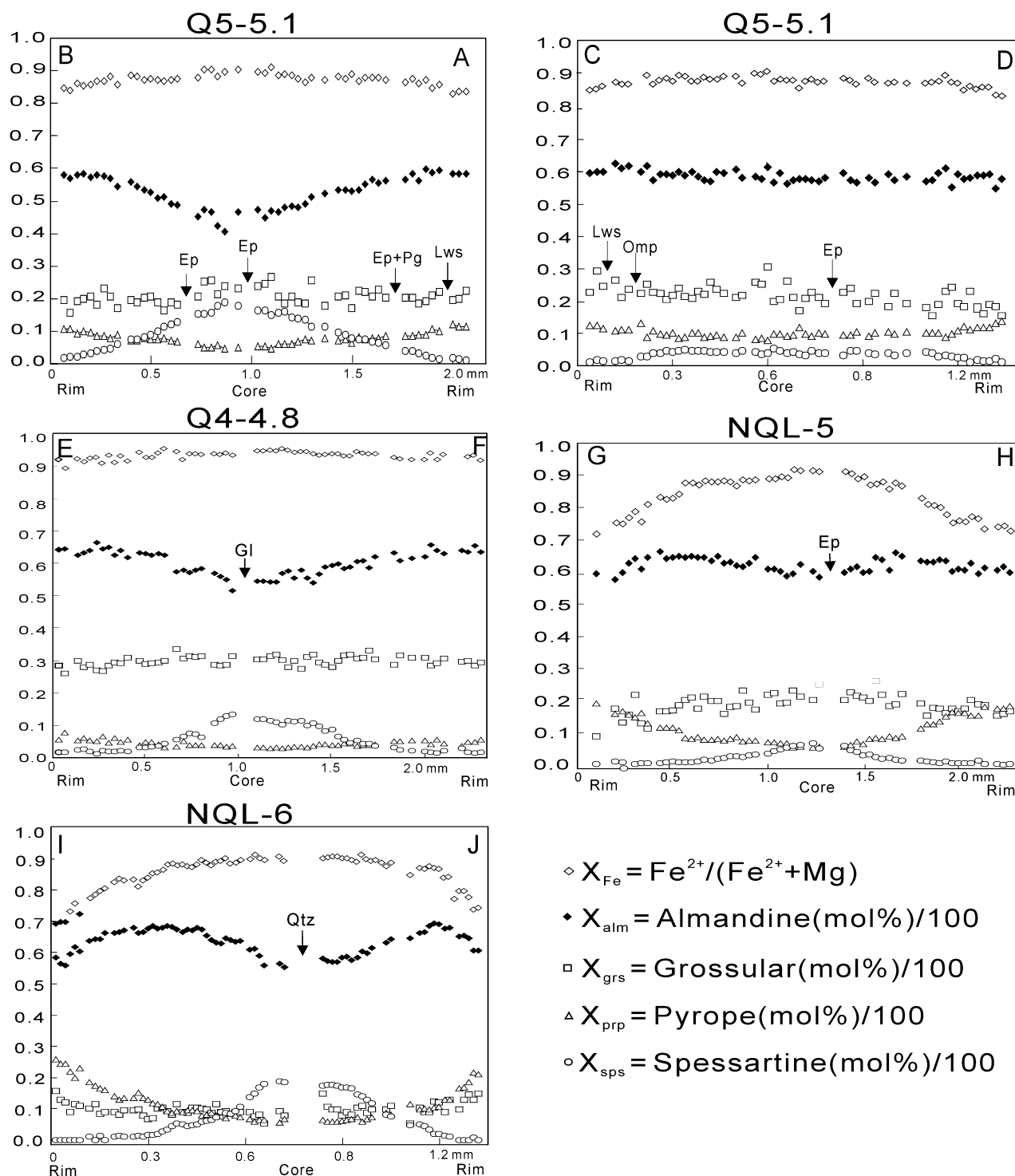


Fig. 5. Garnet compositional zoning profiles for eclogites in the North Qilian Mountains (for profile locations, see Figs 3 & 4).

CL images of type I zircon show a cloudy core or faded fir tree patterns, and are surrounded by thin rims ($< 20 \mu\text{m}$) with dark luminescence (Fig. 10, grains 4 & 9). Rare garnet and rutile inclusions were identified by Raman microspectroscopy and EDS analyses

(Fig. 10). Type II zircon is homogeneous and dark in CL (Fig. 10, grain 8). Type III zircon is euhedral and elongated. In CL they display oscillatory-zoned cores and weakly oscillatory-zoned rims (Fig. 10, grains 3, 10 & 12). Nineteen spots on 15 grains were analysed by

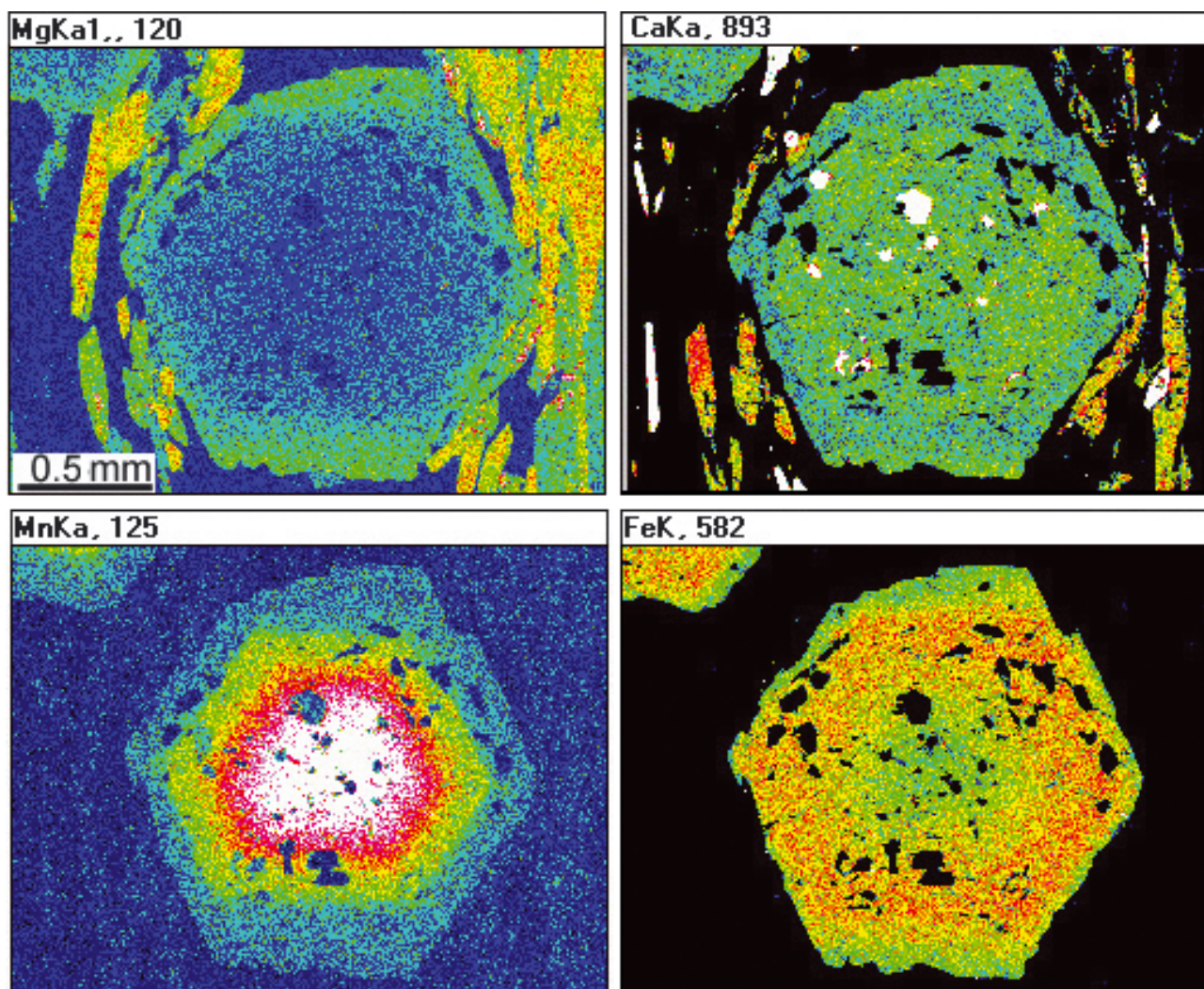


Fig. 6. X-ray compositional maps showing the distribution of: (a) Mg, (b) Ca, (c) Mn and (d) Fe in garnet from eclogitic schist sample NQL-6.

SHRIMP II. Twelve spots including type I zircon with garnet and rutile inclusions, type II zircon and rims of type III zircon gave a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 489 ± 7 Ma (MSWD = 0.64) (Fig. 11a). The rims of type III zircon show oscillatory zoning but have a very low Th/U ratio, consistent with growth from a metamorphic/metasomatic fluid, and gave ages indistinguishable from type I zircon with garnet and rutile inclusions. They were included in the calculation of the weighted mean age. Seven spots were excluded from the calculation of the weighted mean age: three spots from oscillatory-zoned cores of type III zircon yield $^{206}\text{Pb}/^{238}\text{U}$ ages ranging between 710 and 661 Ma (Table 5), which may reflect inheritance from the protolith of the eclogite; two spots gave younger $^{206}\text{Pb}/^{238}\text{U}$ ages (419 & 404 Ma), and may reflect a late thermal event or Pb-loss. Spot 1.1 and 12.2 from a zircon rim gave $^{206}\text{Pb}/^{238}\text{U}$ ages of 517 ± 7 Ma and 533 ± 13 Ma, respectively, slightly older than ages of

other metamorphic zircon domains. This may be the result of minor mixing with core components, and are also excluded from the calculation of the weighted mean age.

Eclogitic metabasite sample Q4-4.8 contains predominantly clear and near-spherical zircon with dark CL intensities (Fig. 12), similar to those of type II zircon in sample Q5-5.1. Of a total of 10 U-Pb analyses, six analyses yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 477 ± 16 Ma (MSWD = 3.4, Fig. 11b). These zircon are characterized by low Th/U ratios of <0.1 (except for spots 7.1 and 10.1; Table 3). Four analyses were excluded from calculation of the weighted mean age: Three analyses gave significantly younger $^{206}\text{Pb}/^{238}\text{U}$ ages (406–424 Ma), and one analysis gave a slightly older age (549 ± 8 Ma).

Eclogite sample NQL-5 contains a relatively homogeneous zircon population. The CL images (Fig. 13)

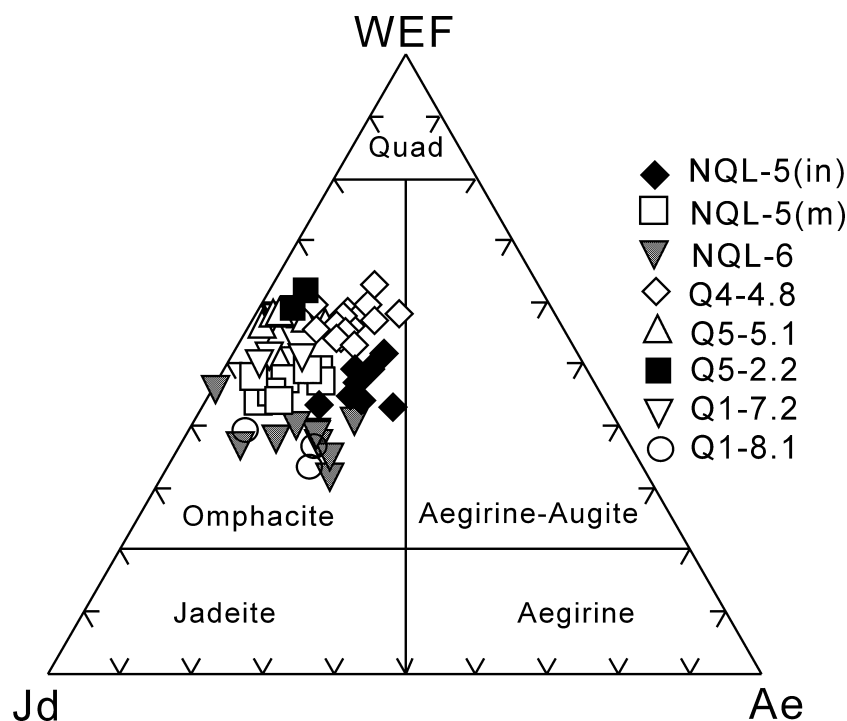


Fig. 7. Omphacite compositions plotted on WEF (Wo, En, Fs)-Jd-Ae ternary diagram. Clinopyroxene classification after Morimoto *et al.* (1988). NQL-5(in): omphacite inclusion, NQL-5(m): omphacite in the matrix. Ferric iron is calculated by the method of Droop (1987).

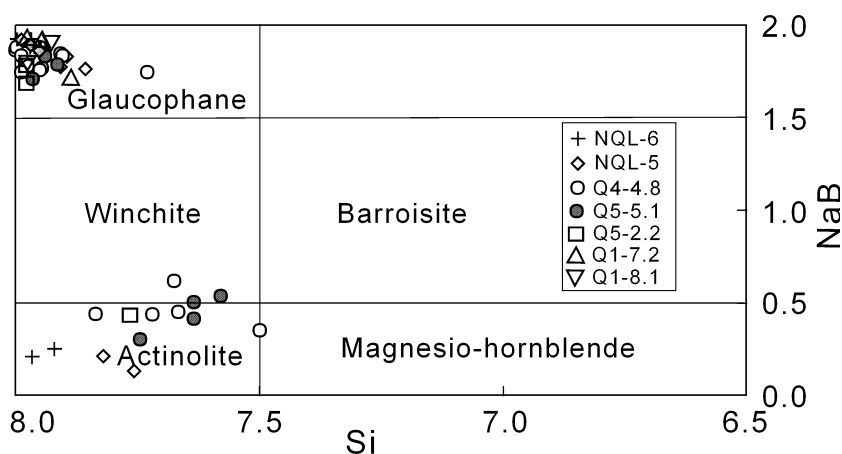


Fig. 8. Na_B v. Si diagram for amphibole in eclogites and eclogitic rocks. The amphibole nomenclature is after Leake *et al.* (1997). The Fe³⁺/Fe²⁺ ratio was calculated assuming a cation total of 13, excluding K, Na, Ca (O = 23).

indicate that all zircon has an oscillatory-zoned domain surrounded by a CL-bright rim. Apatite has been identified as inclusions in some oscillatory-zoned domains, but phengite inclusions lie in CL-bright rims (Fig. 13). Twelve spots were analysed by SHRIMP II, and all of them are from oscillatory-zoned domains. Analysis 7.1 gave a slightly older ²⁰⁶Pb/²³⁸U age (566 ± 38 Ma), which may reflect mixing with an older inherited core, and was excluded from calculation of weighted mean age. The remaining 11 analyses gave a weighted mean ²⁰⁶Pb/²³⁸U age of 502 ± 16 Ma (MSWD = 0.71, Fig. 11c). These analyses correspond to domains with Th/U ratios higher than 0.5 (except for spots 3.1 & 12.1; Table 5), as is typical for magmatic zircon (Rubatto *et al.*, 1998). Therefore, we interpret 502 ± 16 Ma as the protolith age of the

eclogite. In this sample, the age of the HP metamorphism could not be constrained. The CL-bright rims with phengite inclusions may be of metamorphic origin, but they have too low U and radiogenic Pb contents to be dated.

DISCUSSION AND CONCLUSIONS

P-T paths

Although there are no suitable geothermobarometers for the *P-T* estimations of the prograde stage, as mentioned above, petrographical observations and mineral compositions can help delineate qualitative prograde *P-T* trajectories. The inclusions of glaucophane epidote, actinolite and titanite in the cores of

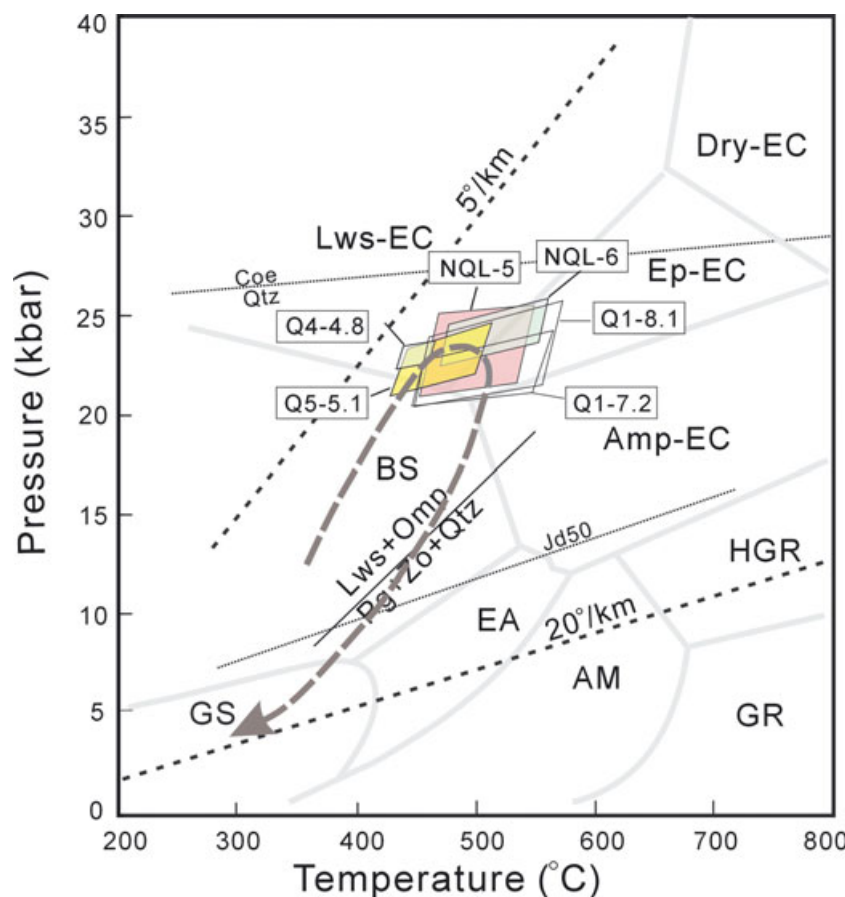


Fig. 9. P - T diagram showing the peak P - T conditions and the qualitative P - T paths for the investigated eclogites and eclogitic rocks in the North Qilian Mountains. The reaction $4\text{Lws} + \text{Omp} = \text{Pg} + 2\text{Zo} + \text{Qtz} + 6\text{H}_2\text{O}$ was calculated using THERMOCALC (3.1) and related data from Powell *et al.*, 1998. The metamorphic facies and their abbreviations are after Liou *et al.*, 1998.

zoned garnet imply that eclogites and eclogitic rocks underwent blueschist-facies metamorphism before eclogite-facies metamorphism (Fig. 9). In some samples (such as samples Q5-2.2 & Q4-6.1), rare lawsonite inclusions together with glaucophane, epidote and omphacite in garnet cores suggest that eclogite and eclogitic rocks underwent a lawsonite blueschist/epidote blueschist facies condition or transitional conditions between those of garnet-lawsonite-epidote-bearing blueschists and lawsonite eclogites.

P - T estimates indicate that the peak conditions of lawsonite-bearing eclogites and eclogitic rocks in the North Qilian Mountains are either within the stability field of lawsonite eclogite or straddle the boundary between lawsonite eclogite and epidote eclogite fields (Fig. 9). Moreover, in sample Q5-5.1, in addition to lawsonite, omphacite and phengite inclusions, epidote inclusions were also observed in garnet rims. Some authors have suggested that lawsonite and an epidote-group mineral can metastably coexist in H_2O -undersaturated systems (Poli & Schmidt, 1997, 2002; Tsujimori *et al.*, 2006a,b). This explanation is not suitable for the present samples considering the ubiquitous occurrence of hydrous phases in the studied rocks. A possible explanation is that the assemblage within the garnet rim of eclogitic metabasite Q5-5.1 represents a transitional condition between lawsonite

eclogite and epidote eclogite field. This is also supported by the results of P - T estimates for peak conditions (see above).

The secondary glaucophane surrounding garnet and omphacite porphyroblasts in the matrix suggests that the retrograde P - T path continues from the eclogite facies to the blueschist facies, and $\text{Ep} + \text{Pg} + \text{Ms}$ (Phe) intergrowths located adjacent to fractures suggest that the retrograde P - T path crossed reaction (1) (Fig. 9). The presence of actinolite and the absence of Ca-Na amphibole (barroisite) associated with the retrograde metamorphism suggest that the decompression P - T path entered the greenschist-facies without passing through the epidote-amphibole facies field (Matsumoto *et al.*, 2003) (Fig. 9). This implies that lawsonite-bearing eclogites have not been heated and stayed relatively cool during decompression. However, the breakdown of lawsonite during exhumation suggests that retrograded P - T path is not cool enough to preserve lawsonite in the matrix (see below).

Preservation of lawsonite-bearing eclogites

As outlined above, petrographical data and P - T estimates for the peak P - T conditions demonstrate that eclogites and eclogitic rocks are formed under an apparent geothermal gradient of about $6\text{--}8\text{ }^\circ\text{C km}^{-1}$.

Table 5. SHRIMP analytical data for zircon of samples Q5-5.1 and Q4-4.8.

Spot name	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	Common Pb (%)	$^{238}\text{U}/^{206}\text{Pb}^*$	$\pm\%$	$^{207}\text{Pb}^*/^{235}\text{U}$	$\pm\%$	$^{207}\text{Pb}^*/^{206}\text{Pb}^*$	$\pm\%$	$^{206}\text{Pb}/^{238}\text{U}$ Age(Ma)	$\pm 1\sigma$
Q5-5.1													
1.1*	1721	357	0.21	139	—	0.0836	0.0012	0.658	0.014	0.0571	0.0008	517	7
2.1	169	7	0.04	12	0.01	0.0789	0.0025	0.593	0.05	0.0545	0.0041	489	15
3.1	509	48	0.09	37	—	0.0787	0.0014	0.587	0.017	0.0541	0.0011	488	8
3.2*	351	110	0.31	41	—	0.1165	0.0013	1.038	0.022	0.0647	0.0011	710	7
4.1	137	4	0.03	10	—	0.0786	0.0019	0.661	0.036	0.0609	0.0028	488	11
5.1	772	22	0.03	55	—	0.0773	0.0027	0.617	0.024	0.0579	0.0009	480	16
6.1*	5662	22	0	333	—	0.0647	0.003	0.496	0.024	0.0556	0.0003	404	18
7.1	686	101	0.15	53	0.01	0.0822	0.0024	0.639	0.029	0.0564	0.0017	509	15
7.2*	1103	82	0.07	69	—	0.0671	0.0017	0.528	0.016	0.0571	0.0008	419	10
8.1	1473	268	0.18	110	—	0.0784	0.0016	0.618	0.014	0.0571	0.0005	487	9
9.1	172	9	0.05	12	0.02	0.0777	0.0017	0.596	0.058	0.0556	0.0051	482	10
10.1*	324	76	0.24	36	—	0.1138	0.0041	1.023	0.046	0.0652	0.0015	695	24
10.2	666	97	0.14	49	—	0.0785	0.0016	0.615	0.02	0.0568	0.0013	487	10
11.1	457	74	0.16	34	0.01	0.0771	0.0022	0.658	0.036	0.0619	0.0026	478	13
12.1*	368	107	0.29	40	—	0.1079	0.0022	0.954	0.029	0.0641	0.0013	661	13
12.2*	407	39	0.10	33	—	0.0862	0.0022	0.661	0.03	0.0556	0.0019	533	13
13.1	1680	323	0.19	130	—	0.0808	0.0022	0.643	0.019	0.0577	0.0005	501	13
14.1	309	53	0.17	23	—	0.0766	0.0027	0.621	0.03	0.0588	0.0017	476	16
15.1	412	20	0.05	31	—	0.0819	0.0022	0.606	0.025	0.0537	0.0016	508	13
Q4-4.8													
1.1*	1651	253	0.15	107	0.01	0.0678	0.0012	0.559	0.017	0.0598	0.0013	423	7
2.1*	844	63	0.07	70	0	0.0889	0.0014	0.693	0.017	0.0566	0.0009	549	8
3.1	244	1	<0.01	18	0.01	0.0789	0.0014	0.666	0.029	0.0613	0.0023	489	8
4.1*	961	163	0.17	59	0.02	0.0649	0.002	0.506	0.031	0.0565	0.0028	406	12
5.1	1479	137	0.09	112	—	0.081	0.0017	0.647	0.021	0.058	0.0013	502	10
6.1	1841	161	0.09	134	0.01	0.0779	0.0018	0.632	0.019	0.0588	0.0010	484	11
7.1	1092	231	0.21	78	0.01	0.0736	0.0011	0.588	0.018	0.0579	0.0018	458	9
8.1*	2492	245	0.10	160	0.01	0.0681	0.0037	0.578	0.041	0.0616	0.0025	424	22
9.1	892	55	0.06	63	—	0.0765	0.0018	0.618	0.017	0.0586	0.0008	475	11
10.1	1562	248	0.16	112	0.01	0.0758	0.0012	0.611	0.018	0.0585	0.0013	471	7
NQL-5													
1.1	117	59	0.51	10	0.01	0.08	0.0047	0.72	0.098	0.0652	0.0075	496	28
2.1	96	91	0.95	9	0.02	0.081	0.0047	0.595	0.079	0.0533	0.006	502	28
3.1	285	39	0.14	21	0.01	0.078	0.0044	0.599	0.076	0.0557	0.0059	484	26
4.1	155	148	0.95	15	0.01	0.0832	0.0045	0.689	0.094	0.06	0.0071	515	27
5.1	249	145	0.58	22	0.01	0.0816	0.0045	0.62	0.053	0.0551	0.0032	505	27
6.1	118	97	0.83	11	0.01	0.0802	0.0046	0.677	0.061	0.0612	0.0038	497	28
7.1*	191	94	0.49	18	0.01	0.0918	0.0065	0.662	0.081	0.0523	0.0048	566	38
8.1	164	107	0.65	15	0.01	0.0855	0.0043	0.665	0.078	0.0564	0.0056	529	26
9.1	128	69	0.54	11	0.02	0.0803	0.0042	0.583	0.12	0.0526	0.0102	498	25
10.1	219	166	0.76	20	0.01	0.0836	0.0046	0.633	0.08	0.0549	0.0059	518	27
11.1	469	279	0.6	39	0.01	0.0786	0.0046	0.611	0.044	0.0564	0.002	488	28
12.1	177	29	0.16	13	0.02	0.0787	0.0052	0.586	0.076	0.054	0.0056	489	31

Notes: Errors are 1σ ; Pb* = radiogenic lead; Common Pb corrected using measured ^{204}Pb . Spots denoted by an asterisk are excluded from the calculation of the weighted mean age.

This is in agreement with formation in a cold, oceanic subduction zone. It is noteworthy that for the lawsonite-bearing eclogites and eclogitic rocks in the North Qilian Mountains, all lawsonite grains occur as inclusions in garnet. No relic lawsonite was observed in the matrix although $\text{Ep} + \text{Pg} \pm \text{Phe}$ intergrowths have been observed in the matrix. These lawsonite inclusions are well away from fractures. By contrast, abundant $\text{Ep} + \text{Pg} + \text{Ms}$ (Phe) intergrowths located adjacent to fractures in garnet are interpreted to be lawsonite pseudomorphs and not primary inclusions (e.g. Balleve *et al.*, 2003). This implies that the cracking of garnet grains may be an important factor controlling the breakdown of lawsonite. In addition, it is interesting to find that the lawsonite pseudomorph is larger than the unaltered lawsonite (Figs 3 & 4). This implies that large lawsonite inclusions in garnet are more likely to be cut by late cracks, and are less likely to be preserved. Altherr *et al.* (2004) considered that the influx of fluids along fractures promotes the breakdown of lawsonite to epidote (clinozoisite).

However, lawsonite-consuming reaction to epidote requires a dehydration. The fractures linking to lawsonite inclusions probably play a role in transmitting ambient conditions to the lawsonite grain and facilitating dehydration rather than fluid ingress.

Some studies also show that the infiltration of aqueous fluid and accompanying deformation related to retrogression can produce secondary hydrous minerals (Whitney & Davis, 2006). Therefore, we infer that most eclogites related to oceanic subduction may enter the stability field of lawsonite eclogite, but lawsonite decomposes readily because of cracking of garnet grains. This may be an important cause why lawsonite eclogite is rare but lawsonite pseudomorphs are frequently reported from eclogites (e.g. Klemd *et al.*, 2002; Schmädicke & Will, 2003; Li *et al.*, 2004). Moreover, in the samples in this study, the absence of relict lawsonite in the matrix indicates that the retrograde P – T path probably crossed the stability field for lawsonite, and retrogression during exhumation ultimately destroyed the lawsonite eclogite assemblage.

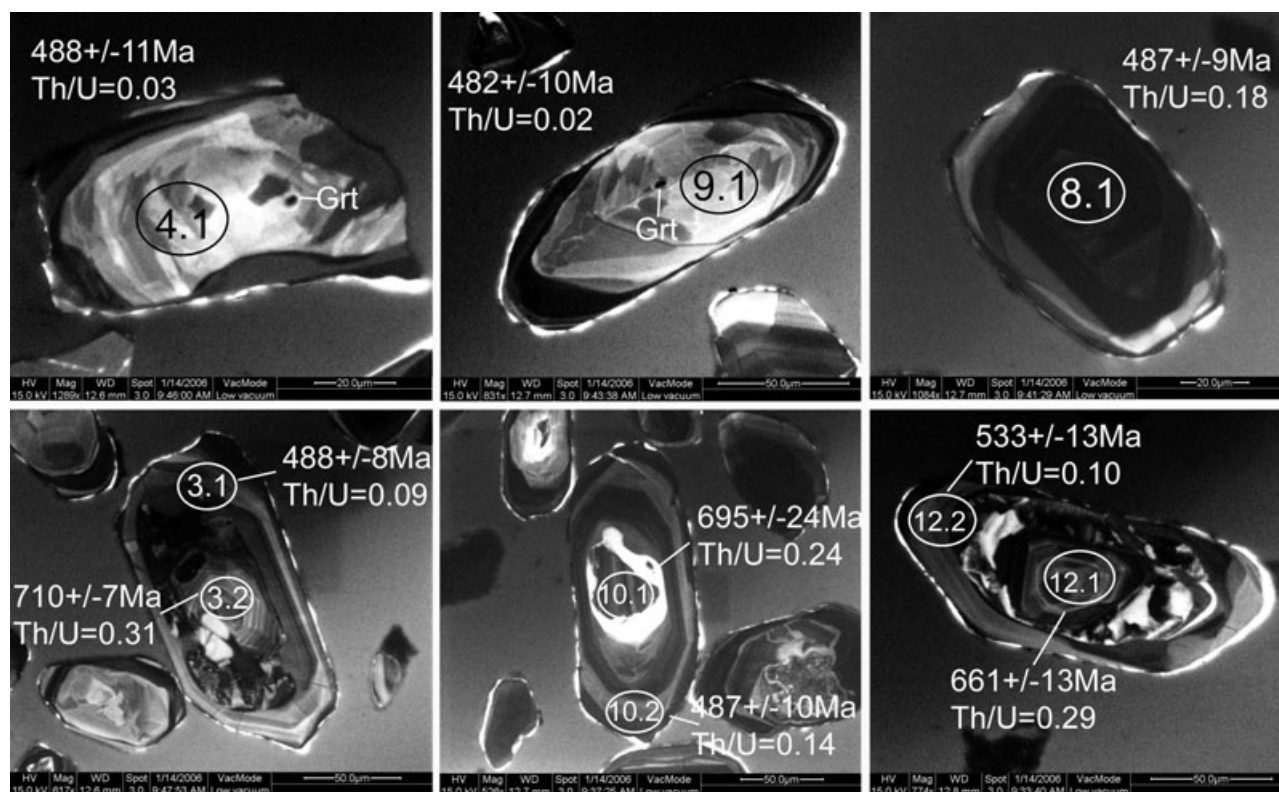


Fig. 10. Representative CL images showing the internal structure of the analysed zircon from lawsonite-bearing eclogitic metabasite Q5-5.1.

even though relatively LT conditions continued during decompression. This may be related to strong deformation in the matrix, hence, indicating that deformation is an important cause resulting in the decomposition of the lawsonite (Whitney & Davis, 2006).

Timing of protolith formation

In eclogite NQL-5, all analysed zircon cores show magmatic oscillatory zoning and have Th/U ratios as well as mineral inclusions typical for magmatic crystals. REE and Sr/Nd isotopic data suggest that the protolith of sample NQL-5 has the characteristics of MORB and mafic cumulate (positive Eu anomaly and positive ε_{Nd} ; Zhang, J. X., Meng, F. C. & Yu, S. Y., unpublished data). Plagioclase-rich cumulates are a common intrusive rock type of the oceanic crust which supports the proposal that the eclogites from NQL represent previously subducted oceanic crust (Wu *et al.*, 1993). The age of 502 ± 16 Ma of igneous zircon cores in NQL-5 therefore may relate to a period of oceanic crust formation. This age is also in agreement with the Early Ordovician formation age of some ophiolites in the North Qilian Mountains, which was obtained from radiolarites in ophiolite sequences (Xiao *et al.*, 1978; Xia *et al.*, 2003).

Eclogitic metabasites Q5-5.1 and Q4-4.8 contain no magmatic zircon with ages of about 500 Ma. In

sample Q5-5.1, several zircon with magmatic oscillatory zoning cores gave an age of about 700 Ma. Recently, a ~ 700 Ma age was reported from granitic gneisses which were considered as continental slices within the North Qilian Mountains (Tseng *et al.*, 2006). Nd isotope and REE data of Q5-5.1 and Q4-4.8 suggest that a possible mixing with a continental crust contaminant has occurred during the formation of the protoliths (Zhang, J. X., Meng, F. C. & Yu, S. Y., unpublished data). Therefore, their protoliths probably formed in a continental/oceanic transitional zone. The age of the protoliths remains unconstrained.

Age of the HP/LT metamorphism

Based on the data above, zircon from sample Q5-5.1 contains inclusions of garnet and rutile. EDS analyses show that the compositions of the garnet inclusions are consistent with that obtained in the thin sections. The presence of inclusions of the eclogite facies assemblage suggests that the zircon dates the HP/LT metamorphism. Therefore, our SHRIMP data combined with petrological data suggest that this age of 477–489 Ma obtained from metamorphic zircon should date the HP/LT eclogite facies metamorphism in the North Qilian Mountains. In the NQL HP/LT metamorphic belt, Ar-Ar data on phengite from

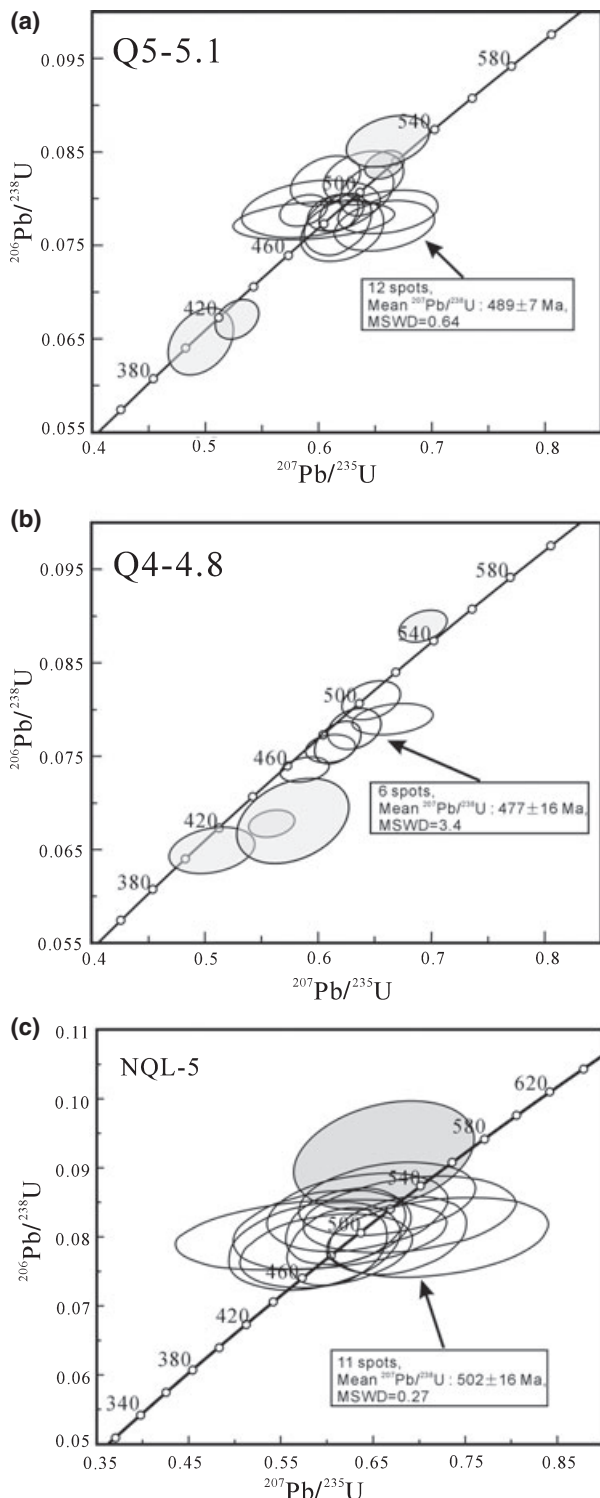


Fig. 11. U-Pb concordia diagrams for samples Q5-5.1, Q4-4.8 and NQL-5. Error ellipses are 1σ , grey-filled ellipses were excluded from the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age ($\pm 2\sigma$).

blueschists and glaucophane-bearing greenschists enclosing eclogite pods yield ages of 460–440 Ma (Wu *et al.*, 1993; Zhang *et al.*, 1997). These ages were

previously interpreted as HP/LT metamorphic ages. In consideration of the fact that the rocks used for Ar-Ar dating contain no eclogite facies assemblages and subsequently experienced a greenschist facies overprint (Zhang *et al.*, 1997), our U-Pb data from eclogites suggest that the Ar-Ar ages of phengite from blueschists may not correspond to eclogite facies stage but to the blueschist facies and subsequent greenschist facies overprinting during exhumation. Moreover, the 489–477 Ma ages of eclogite facies metamorphism obtained in this study are slightly older than the 468–463 Ma U-Pb zircon ages reported by Song *et al.* (2004, 2006) for eclogites for this area. The possible explanation for the age discrepancy is that the eclogites analysed by Song *et al.* (2004, 2006) and the eclogites examined in this study belong to different eclogite blocks that were subducted and exhumed at different times. Further field mapping, petrotextonic and geochronology are required to constrain this scenario.

A cold Early Palaeozoic subduction zone and its geological implication

Maruyama & Liou (1998, 2005) pointed out that a crucial change in subduction zone geotherms from $\sim 15^\circ\text{C}$ to $6\text{--}7^\circ\text{C km}^{-1}$ between 750–540 Ma could have stabilized lawsonite-eclogite assemblages since the Phanerozoic (e.g. Ernst, 1972; Agard *et al.*, 2005; Brown, 2006; Tsujimori *et al.*, 2006b). Up to now, the earliest occurrence of lawsonite-eclogite facies mineral assemblages are in Spitsbergen (475–450 Ma) and the New England fold belts (Ordovician) (Watanabe *et al.*, 1997; Och *et al.*, 2003). Lawsonite eclogites from both areas were considered to form in Ordovician by Ar-Ar or K-Ar dating of phengite (Dallmeyer *et al.*, 1990; Fukui *et al.*, 1995). This study documents a third Early Palaeozoic lawsonite eclogite with ages of 489–477 Ma, and further supports the hypothesis proposed by Maruyama & Liou (1998).

As presented above, eclogite containing unaltered lawsonite is only observed from five samples in the NQL HP/LT metamorphic belt, but abundant pseudomorphs after former lawsonite are recognized from 11 eclogites from different localities (Table 1; Fig. 1b). Therefore, NQL eclogites may record a common lawsonite-eclogite facies metamorphism. In combination with geochronological data, a cold Early Palaeozoic subduction zone is suggested in the North Qilian Mountains.

As mentioned in previous sections, the NQL HP/LT metamorphic belt may extend to the north Altyn Tagh (NAT), where a new HP/LT metamorphic belt has been recognized (Zhang *et al.*, 2005b) (Fig. 1a). Eclogites in the NAT gave equilibrium conditions of 430–540 $^\circ\text{C}$ and 2.0–2.3 GPa (Zhang *et al.*, 2005b), which is similar to those of the NQL lawsonite eclogites. Preliminary radiometric data also suggest that the

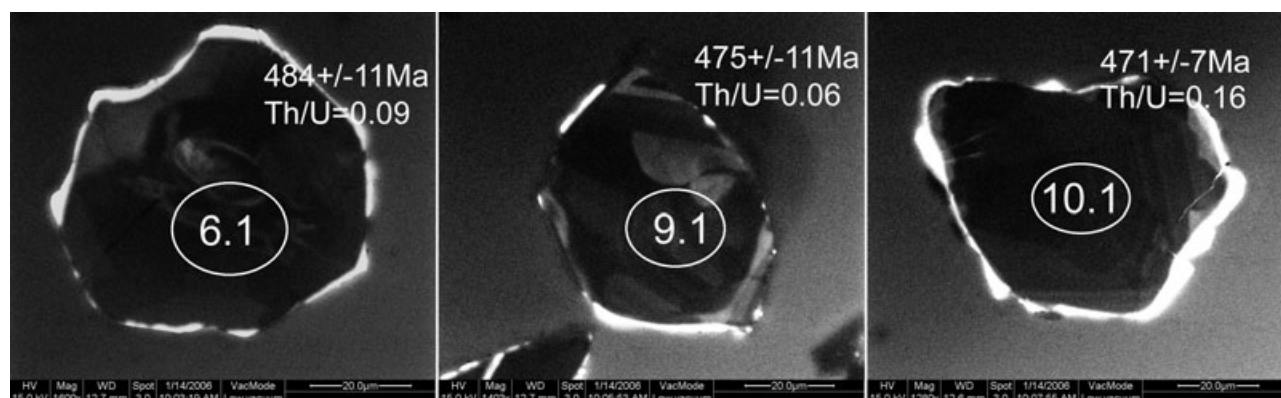


Fig. 12. Representative CL images of the analysed zircon from lawsonite-bearing eclogitic metabasite sample Q4-4.8. Age uncertainties are 1σ .

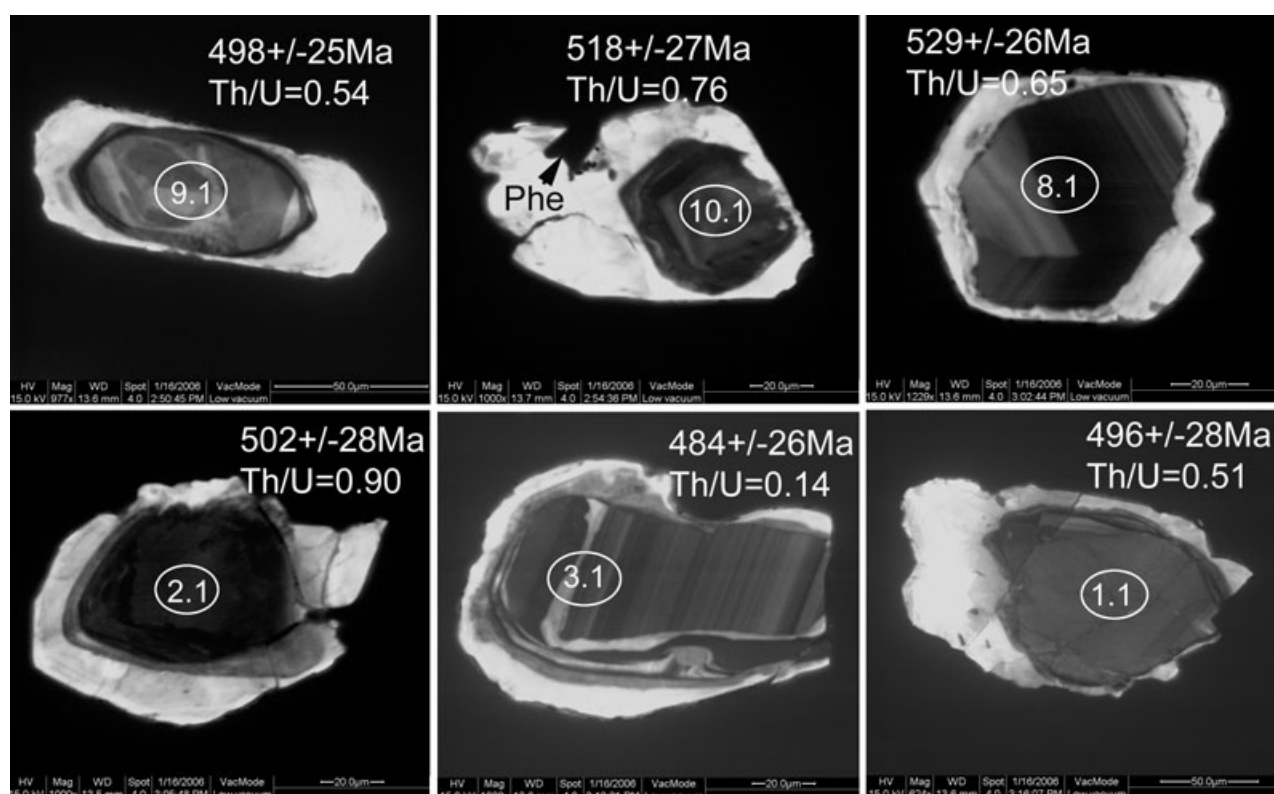


Fig. 13. Representative CL images of the analysed zircon from lawsonite pseudomorph-bearing sample NQL-5. Age uncertainties are 1σ .

metamorphic ages of the NAT eclogites are Early Palaeozoic (Zhang, J. X., Meng, F. C. & Yu, S. Y., unpublished data). In addition, lawsonite-bearing eclogite was also newly reported in the NAT (Fig. 1a) (Zhang & Meng, 2006). The occurrences of lawsonite-bearing eclogites in both NQL and NAT provide new support for the suggestion that the NAT HP/LT metamorphic belt is possibly the north-westward extension of the NQL HP/LT metamorphic belt offset by the Altyn Tagh left-lateral strike-slip fault.

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