Eclogite and carpholite-bearing metasedimentary rocks in the North Qilian suture zone, NW China: implications for Early Palaeozoic cold oceanic subduction and water transport into mantle

S. G. SONG^{1,2}, L. F. ZHANG¹, Y. NIU², C. J. WEI¹, J. G. LIOU³ AND G. M. SHU¹

¹MOE Key Laboratory of Orogenic Belts and Crustal Evolution, School of Earth and Space Sciences, Peking University, Beijing 100871, China (sgsong@pku.edu.cn, shuguang.song@durham.ac.uk)

²Department of Earth Sciences, Durham University, Durham DH1 3LE, UK

³Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305-2115, USA

ABSTRACT Low-temperature eclogite and eclogite facies metapelite together with serpentinite and marble occur as blocks within foliated blueschist that was originated from greywacke matrix; they formed a highpressure low-temperature (HPLT) subduction complex (mélange) in the North Qilian oceanic-type suture zone, NW China. Phengite-eclogite (type I) and epidote-eclogite (type II) were recognized on the basis of mineral assemblage. Relic lawsonite and lawsonite pseudomorphs occur as inclusions in garnet from both types of eclogite. Garnet-omphacite-phengite geothermobarometry yields metamorphic conditions of 460-510 °C and 2.20-2.60 GPa for weakly deformed eclogite, and 475-500 °C and 1.75-1.95 GPa for strongly foliated eclogite. Eclogite facies metasediments include garnet-omphacitephengite-glaucophane schist and various chloritoid-bearing schists. Mg-carpholite was identified in some high-Mg chloritoid schists. P-T estimates yield 2.60-2.15 GPa and 495-540 °C for Grt-Omp-Phn-Gln schist, and 2.45-2.50 GPa and 525-530 °C for the Mg-carpholite schist. Mineral assemblages and P-T estimates, together with isotopic ages, suggest that the oceanic lithosphere as well as pelagic to semi-pelagic sediments have been subducted to the mantle depths (≥75 km) before 460 Ma. Blueschist facies retrogression occurred at c. 454-446 Ma and led to eclogite deformation and dehydration of lawsonite during exhumation. The peak P-T conditions for eclogite and metapelite in the North Qilian suture zone demonstrate the existence of cold subduction-zone gradients (6-7 °C km⁻¹), and this cold subduction brought a large amount of H₂O to the deep mantle in the Early Palaeozoic times.

Key words: eclogite; eclogite facies metapelite; lawsonite and carpholite; North Qilian suture zone; oceanic subduction and exhumation.

INTRODUCTION

High-pressure (HP) low-temperature (LT) rocks including blueschist and eclogite in Pacific-type subduction complexes recorded a complete process of ancient oceanic lithosphere consumption and closure at an active convergent margin. These rocks are thus considered to be the key markers for a palaeosuture zone within orogenic belts and have received a great deal of attention from geoscientists for their tectonic significance (e.g. Ernst, 1970, 1988; Ernst & Liou, 1995; Maruyama et al., 1996). Differences in protoliths and in metamorphic assemblages between oceanic-type subduction zones and continental-type ultra-high-pressure (UHP) metamorphic belts enable us to unravel the evolution of a subduction zone from oceanic subduction to continental collision (e.g. Chopin et al., 1991; Ernst & Liou, 1995; Guillot et al., 1997; Agard et al., 2001; Ernst, 2001; Song et al., 2006).

The North Qilian Mountains are considered to be a typical Pacific-type subduction zone in China (e.g. Xiao

et al., 1978; Wu et al., 1993) as it comprises ophiolite suites, calc-alkaline volcanic and granitic rocks, and subduction-zone complexes including HPLT rocks and mélange. Recent studies revealed that this belt is an Early Palaeozoic suture zone (c. 460 Ma) between the North China Craton (NCC) and the Qilian-Qaidam microcontinent, a fragment of the Rodinia supercontinent (Wan et al., 2001; Song et al., 2006). Wu et al. (1993) reported occurrences of high-grade blueschist with the assemblage Grt + Gln + Ep + Phn +Ab + Qtz and a low-grade blueschist characterized by Gln + Lws + Pmp + Ab + Chl + Arg + Qtz in two distinct areas (Fig. 1a), and gave P-T estimates of \sim 340 °C and 0.8 \pm 0.1 GPa for eclogite lenses within high-grade blueschists. Mineral abbreviations are after Kretz (1983).

In this paper, we report a new discovery of Mgcarpholite + Mg-chloritoid-bearing metapelite and document in detail petrological characteristics and their metamorphic P-T conditions for various protoliths of the subduction complex in the high-grade



Fig. 1. Geological maps of the middle part of the North Qilian suture zone (a) and specified maps with sample locations (b,c). Legends in (b) are the same as in (a).

blueschist sub-belt. These data, together with available radiometric ages (e.g. Liou *et al.*, 1989; Zhang *et al.*, 1997; Liu *et al.*, 2006; Song *et al.*, 2006) allow us to

constrain the P-T-t path of this cold and deep subduction complex in the North Qilian Mountains, NW China.

GEOLOGICAL BACKGROUND

The North Qilian Suture Zone is an elongate, NWtrending belt that lies between the Alax Block, the western part of the North China Craton, to the north, and the Qilian–Qaidam Block to the south (Fig. 1a), and is cut by the Altyn-Tagn Fault, the largest leftlateral strike-slip fault system in western China. It is made up of Early Palaeozoic subduction complexes including ophiolitic mélanges, blueschists and eclogites, Silurian flysch formations, Devonian molasse, and Carboniferous to Triassic sedimentary cover sequences (Song, 1996; Fig. 1a). The continental-type North Qaidam UHP belt (CNQ) is subparallel to the North Qilian Suture Zone (Fig. 1a, for details, see Song *et al.*, 2003a,b, 2005, 2006).

The high-grade blueschist sub-belt, including blueschist and eclogite, is mainly distributed in the middle part of the North Qilian suture zone around Qilian county-town. The low-grade lawsonite-bearing blueschist sub-belt is located in an area ~ 20 km west of the Sunan county-town (Fig. 1a).

Some high-grade rocks along the Qingshuigou (Fig. 1b) and the Baijingsi (~30 km east to Qilian town) (Fig. 1c) traverses have been dated: Ar–Ar dating of phengitic mica from blueschists yields plateau ages of 448 \pm 11 Ma (Liou *et al.*, 1989) and 454–446 Ma (Liu *et al.*, 2006) and 489–450 Ma with retrograde overprint at 420–410 Ma for phengitic mica and glaucophane (Zhang *et al.*, 1997). More recently, Song *et al.* (2004, 2006) reported zircon SHRIMP U–Pb ages of 463 \pm 6 Ma and 468 \pm 13 Ma from two eclogite samples in Xiangzigou (~30 km west of Qilian town) and Baijingsi sections respectively. These ages suggest that HP metamorphism in the North Qilian suture zone happened in the Late Ordovician.

FIELD OCCURRENCE AND PETROGRAPHY

As shown in Fig. 1, the high-grade blueschist sub-belt occurs as three NW-trending slices A, B and C within arc-type siliceous volcanic rocks. Protoliths are similar in the three slices and consist of various blocks and lenses of limestone and ophiolitic fragments including serpentinite, basalt and pelagic chert within the greywacke matrix, which are composed of typical subduction-zone mélange (Fig. 2a–d). Blueschist facies meta-greywacke predominates in the high-grade blueschist sub-belt.

More than 200 samples, including eclogite and eclogite facies metapelite from the high-grade blueschist sub-belt have been examined. Characteristic assemblages of representative samples are listed in Table 1.

Eclogite

All mafic eclogites occur as variably sized blocks or lenses within felsic blueschists (Fig. 2e). Based on mineral assemblages, two types of eclogites were recognized. Type I is the phengite-eclogite with a peakstage Grt + Omp + Phn + Rt assemblage with minor epidote and is strongly overprinted by blueschist facies retrogression (Fig. 3a,b). Geochemical analyses of type I eclogite suggest E-type MORB or ocean island basalt (OIB) protoliths (Song et al., 2006). Type II is the epidote–eclogite with a Grt + Omp + Ep/ $Cz + Gln + Rt \pm Qtz$ assemblage and minor phengite and paragonite (Fig. 3c,d). Most type II eclogites are strongly deformed, and show elongated epidote/clinozoisite, omphacite and phengitic mica oriented along the foliation (Fig. 3d). A number of eclogites with coarse-grained granoblastic assemblages and weak mineral orientation also suffered retrograde glaucophane overprinting. Geochemical analyses suggest that type II eclogite protoliths resemble N-type MORB.

Lawsonite inclusions have been reported in some porphyroblastic garnet from eclogites in this belt (Zhang & Meng, 2006). In our samples, inclusions of lawsonite and lawsonite pseudomorphs were also identified in some porphyroblastic garnet (Fig. 3e,f) from both eclogite types. Lawsonite pseudomorphs show rectangular and triangular shapes and consist of aggregates of $Cz + P \pm Phn \pm Omp$ defining a possible reaction as Lws + Jd (Omp) = Cz + Pg + H_2O . The numerous lawsonite pseudomorphs in garnet suggest that lawsonite was ubiquitous during the peak stage of eclogite facies metamorphism associated with oceanic subduction.

Eclogite facies metasedimentary rocks

Most pelitic schists occur as country rocks or are interlayered with eclogites. However, field relations between pelitic schists and metagreywackes are rather ambiguous. According to the mineral assemblages, two kinds of pelitic schist were recognized.

Chloritoid-glaucophane (Cld-Gln) schist

Chloritoid–glaucophane schists are widespread as inter-layers with eclogites and other schists in the North Qilian high-grade blueschist belt; these schists contain four discrete mineral assemblages: (i) Cld–Gln schist with a Cld + Gln + Phn + Ep + Dol + Qtz assemblage without garnet (Fig. 4a); (ii) Grt–Cld–Gln–Pg schist with a Grt + Cld + Gln + Pg + Ep + Rt + Qtz assemblage; (iii) Grt–Cld–Gln–Phn schist with a Grt + Cld + Gln + Phn + Ep + Rt + Qtz; and (iv) Car–Cld schist with a Grt + Car + Cld + Gln + Phn + Rt + Qtz assemblage. The former two types mainly crop out in the Qingshuigou–Xiangzigou area (Fig. 1b), and the later two types occur together as a ~200-m-thick layer in the Baijingsi section (Fig. 1c).

Chloritoid in weakly foliated garnet-free Cld–Gln schist occurs as porphyroblastic crystal (Fig. 4a). The



Fig. 2. Photographs showing rock assemblage of the North Qilian high-pressure low-temperature complex. (a) Serpentinite block within felsic blueschist (meta-greywacke); (b) blocks of meta-chert and mafic rocks within felsic blueschist; (c) blocks of limestone (LS) and meta-basalt (MB) within glaucophane-bearing meta-greywacke, showing mélange accumulation near trench; (d) mafic blueschist with relic pillow structure; (e) outcrop of large eclogite block; (f) eclogite with weak foliation.

types (ii) and (iii) Grt–Cld–Gln schists are strongly deformed (Fig. 4b) but have different composition of white mica (paragonite *v*. phengite) and chloritoid (see below).

Mg-carpholite was discovered in three samples (2Q34, 2Q35 & 2Q44) and is the first reported

occurrence in China. The Car–Cld schist mainly consists of Mg-carpholite (15–20%), garnet (\sim 5–8%), Mgchloritoid (\sim 10–15%), phengite (10–15%) and quartz (30–40%) with minor tourmaline. Rare glaucophane grains occurs in the matrix, or as inclusions in garnet. Coarse-grained prismatic Mg-carpholite crystals of
 Table 1. Representative samples with their localities and mineral assemblages in the North Qilian suture zone.

Sample	Locality	Rock type	Mineral assemblage
2Q19	Baijingsi section (Fig. 1c)	Type II eclogite	Grt, Omp, Ep/Cz, Phn, Gln, Qtz
2Q22	Baijingsi section	Type II eclogite	Grt, Omp, Ep/Cz, Phn, Gln, Qtz
2Q24	Baijingsi section	Type II eclogite	Grt, Omp, Ep/Cz, Phn, Gln, Rt
2Q25	Baijingsi section	Type II eclogite	Grt, Omp, Cz, Phn, Gln, Rt
2Q27	Baijingsi section	Type II eclogite	Grt, Omp, Cz, Phn, Gln, Lws inclusion, Rt
2Q28	Baijingsi section	Meta-pelite	Grt, Omp, Ep/Cz, Phn, Gln, Rt
2Q32	Baijingsi section	Meta-pelite	Grt, Omp, Ep/Cz, Phn, Gln, Qtz, Rt
2Q33	Baijingsi section	Meta-pelite	Grt, Omp, Ep/Cz, Phn, Gln, Qtz, Rt
2Q34	Baijingsi section	Meta-pelite	Grt, Car, Cld, Gln, Phn, Qtz, Rt, Tur
2Q35	Baijingsi section	Meta-pelite	Grt, Car, Cld, Gln, Phn, Qtz, Rt, Tur
BJ17	Baijingsi section	Meta-pelite	Grt, Cld, Gln, Phn, Qtz, Chl, Ep/Cz, Rt
Q04	Qingshuigou (Fig. 1b)	Type I eclogite	Grt, Omp, Phn, Gln, Ep, Lws inclusion, Qtz, Rt
QS35	Qingshuigou	Meta-pelite	Cld, Gln, Phn, Dol, Qtz, Chl
QS45	Xiangzigou (Fig. 1b)	Type I eclogite	Grt, Omp, Phn, Gln, Ep, Lws inclusion, Qtz, Rt
Q67	Xiangzigou	Type I eclogite	Grt, Omp, Phn, Gln, Ep/Cz, Qtz, Rt
Q68	Xiangzigou	Type I eclogite	Grt, Omp, Phn, Gln, Ep/Cz, Qtz, Rt
Q70	Xiangzigou	Type II eclogite	Grt, Omp, Phn, Gln, Ep/Cz, Qtz, Rt
XZ07	Xiangzigou	Meta-pelite	Grt, Cld, Pg, Gln, Ep, Qtz, Rt, Chl
2Q63	Qingshuigou (Fig. 1b)	Cld-bearing quartzite	Cld, Qtz, Phn

Mineral abbreviations are after Kretz (1983) except for Phn for phengite and Car for carpholite.

0.1–0.4 mm occur in the matrix (Fig. 4c,d), and as small inclusions in chloritoid. Mg-chloritoid occurs as porphyroblastic crystals in equilibrium with Mg-carpholite, garnet and phengite. Some chloritoid crystals are retrogressed into chlorite and pyrophyllite at low P-T (< ~400 °C, Deer *et al.*, 1992) conditions from the reaction chloritoid + quartz + H₂O \rightarrow pyrophyllite + chlorite.

Garnet–omphacite–phengite–glaucophane (Grt–Omp–Phn–Gln) schist

As shown in Fig. 1c, the Grt–Omp–Phn–Gln schist occurs as a \sim 100-m layer in the Baijingsi cross-section and is bounded by a large block of eclogite to the north and the Car–Cld schist to its south. This schist consists of garnet porphyroblasts set in a foliated fine-grained matrix of omphacite, phengite, glaucophane, rutile, epidote and quartz (Fig. 4e,f).

Meta-greywacke

The mélange matrix containing blocks of serpentinite, eclogite, meta-chert, marble and meta-pelite is metagreywacke thought to represent materials from the accretionary wedge (see Fig. 2a–c). Most of the greywacke is foliated, has undergone blueschist facies metamorphism and contains a mineral assemblage of glaucophane, phengite, paragonite, epidote, albite, quartz with or without garnet.

Meta-chert

Meta-cherts occur as blocks or layers (~50 m in maximum thickness) in the meta-greywacke (Fig. 2b). Some occur interlayered with the various pelitic schists described above. Most meta-cherts consist predominantly of recrystallized quartz with minor phengitic mica, yet some samples contain additional minor garnet and glaucophane. Mn-ore has been exploited in

the Mn-bearing meta-chert, suggesting a protolith of pelagic sediment.

MINERAL CHEMISTRY

Electron microprobe analyses of minerals were performed on a JEOL JXA-8100 at Peking University. operated at 15 kV acceleration voltage, with 20 nA beam current and 1–5 μ m beam spot. Routine analyses were obtained by counting for 20 s at peak and 5 s on background. Synthetic silica (Si) and spessartine (Mn), natural sanidine (K), pyrope (Mg), andradite (Fe and Ca), albite (Na and Al) and rutile (Ti) served as standards. Ferric iron in garnet and clinopyroxene was determined based on the scheme of Droop (1987) and $Fe^{3+} = Na - (Al + Cr)$ (Cawthorn & Collerson, 1974) respectively. Normalized pyroxene end-member components were calculated on the basis of jadeite $(X_{\rm Jd}) = {\rm Al^{VI}}/({\rm Na + Ca})$, aegirine $(X_{\rm Ae}) = ({\rm Na - Al^{VI}})/({\rm Na + Ca})$ and augite $(X_{\rm Au}) = ({\rm Ca + Mg + Fe^{2+}})/2$ (Morimoto, 1988). The Fe³⁺ in sodic amphibole was estimated on the basis of structural formulae of 23 oxygen following the charge balance method of Robinson *et al.* (1982). Total Fe is reported as Fe^{2+} in white mica, and as Fe^{3+} in epidote. Representative analyses are listed in Tables 2-4.

Garnet

Garnet zonation in the two eclogite types is defined by both inclusions and chemical patterns, which is a common feature for garnet in all HPLT rocks from orogenic belts (e.g. Clarke *et al.*, 1997). Garnet is rich in inclusions of zoisite/epidote, quartz and rare albite in the core, and contains inclusions of omphacite, phengite, lawsonite and its pseudomorph in the mantle part and rim (Fig. 4f). A porphyroblastic garnet from a type I eclogite (2Q27) was chosen for zoning profile analyses. As shown in Fig. 5, the garnet possesses pronounced bell-shaped zoning profiles with antithetic



Fig. 3. Photomicrographs of two types of eclogite from the North Qilian suture zone. All are cross-polarized light except (f). (a) Phengite-eclogite (Type I) with assemblage Grt + Omp + Phn + Rt (Q04); (b) blueschist facies overprinting on the phengite-eclogite (Q67); (c) epidote–eclogite (type II) with assemblage Grt + Omp + Cz + Phn + Rt (2Q27); (d) strongly foliated epidote–eclogite (2Q22); (e) lawsonite pseudomorphs (Pg + Cz) in eclogitic garnet (2Q27); (f) back-scattered image showing lawsonite + omphacite + lawsonite pseudomorphs in garnet (2Q27).

zoning of spessartine relative to almandine, grossular and pyrope contents; $X_{\rm sps}$ [=Mn/(Mg + Fe + Ca + Mn)] decreases from the core of ~0.2 to the rim of

less than 0.01, whereas X_{alm} [=Fe/(Mg + Fe + Ca + Mn)] increase from the core ~0.46 to the rim ~0.60, and X_{prp} [=Mg/(Mg + Fe + Ca + Mn)] from ~0.05



Fig. 4. Photomicrographs of minerals and textures of metapelite. (a) Chloritoid–glaucophane schist with assemblage Cld + Gln + Phn + Chl (QS35, plane polarized light); (b) Garnet–chloritoid–glaucophane–phengite schist (BJ17, plane polarized light); (c) Mg-carpholite–chloritoid schist with assemblage of Grt + Car + Cld + Phn + Qtz + Rt, of which chloritoid and carpholite are altered (2Q34, cross-polarized light). (d) Back-scattered image showing euhedral carpholite crystals in matrix and in chloritoid porphyroblast (2Q35); (e) garnet–omphacite–glaucophane schist with assemblage Grt + Omp + Gln + Ep + Phn + Rt + Qtz (2Q33, plane-polarized light); (f) Cross-polarized photo showing the texture of garnet–omphacite–glaucophane schist.

Table 2. Representative analyses of minerals from mafic eclogites in the North Qilian suture zone

Sample		Q01				2Q04							2Q27							2Q19		
Mineral	Grt	Omp	Phn	Grt	Omp	Phn	Lws	Cz	Grt	Grt	Omp	Phn	Lws	Cz	Cz	Pg	Gln	Grt	Omp	Phn	Gln	Cz
SiO ₂	37.74	55.93	51.56	38.78	56.47	51.87	39.78	39.56	38.06	37.85	55.04	52.44	38.61	40.13	38.49	47.93	57.85	38.46	55.33	50.08	57.47	38.01
TiO ₂	0.03	0.06	0.27	0.03	0.02	0.16	0.00	0.02	0.00	0.08	0.04	0.18	0.06	0.04	0.56	0.02	0.00	0.07	0.04	0.21	0.00	0.12
Al_2O_3	21.30	8.45	25.69	22.10	11.42	27.46	31.72	31.14	22.05	21.45	9.66	23.96	31.48	28.76	29.78	39.30	11.44	22.33	12.08	27.76	11.58	27.78
Cr_2O_3	0.01	0.04	0.04	0.09	0.00	0.16	0.01	0.09	0.00	0.01	0.05	0.27	0.03	0.08	0.10	0.08	0.05	0.00	0.12	0.02	0.15	0.03
FeO	27.87	6.65	2.91	24.57	3.33	1.39	0.45	1.73	30.14	20.57	5.97	3.15	0.52	5.04	3.47	0.28	6.11	27.65	6.30	2.16	5.94	7.53
MnO	0.39	0.00	0.00	0.52	0.01	0.06	0.05	0.05	0.36	8.74	0.00	0.00	0.04	0.17	0.00	0.06	0.06	0.55	0.02	0.01	0.05	0.11
MgO	3.66	8.68	3.81	5.19	8.15	3.80	0.03	0.02	4.19	1.55	8.17	4.40	0.02	0.30	0.13	0.06	13.02	4.89	6.43	3.45	13.33	0.18
CaO	8.84	13.15	0.00	9.11	12.68	0.00	16.52	24.04	6.17	10.03	12.64	0.00	17.62	24.06	23.72	0.47	1.32	7.69	9.81	0.00	1.35	23.16
Na ₂ O	0.02	6.53	0.32	0.05	7.56	0.75	0.02	0.02	0.02	0.07	7.33	0.20	0.01	0.16	0.18	5.24	7.02	0.04	9.18	0.76	6.94	0.00
K ₂ O	0.01	0.00	11.01	0.00	0.00	10.04	0.02	0.00	0.00	0.01	0.02	10.49	0.00	0.01	0.00	0.06	0.02	0.01	0.01	9.97	0.03	0.00
Total	99.88	99.50	95.61	100.45	99.65	95.72	88.60	96.67	100.99	100.36	98.92	95.10	88.39	98.75	96.43	93.50	96.89	101.68	99.32	94.48	96.85	96.92
0	12	6	11	12	6	11	8	12.5	12	12	6	11	8	12.5	12.5	11	23	12	6	11	23	12.5
Si	2.98	2.01	3.45	3.00	2.00	3.42	2.03	3.05	2.99	3.00	1.98	3.49	2.03	3.06	2.99	3.08	7.84	2.97	1.96	3.37	7.77	2.97
Al ^{IV}	0.02	0.00	0.55	0.00	0.00	0.58	0.00	0.00	0.01	0.00	0.02	0.51	0.00	0.00	0.01	0.00	0.16	0.03	0.04	0.63	0.23	0.03
Al ^{VI}	1.97	0.36	1.47	2.01	0.47	1.56	1.96	2.82	1.99	2.00	0.38	1.37	1.95	2.58	2.72	2.97	1.67	2.00	0.47	1.57	1.62	2.53
Ti	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.01	0.00	0.01
Cr	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.02	0.00
Fe ³⁺	0.00	0.07	0.00	0.00	0.04	0.00	0.00	0.11	0.00	0.00	0.10	0.00	0.00	0.32	0.23	0.00	0.26	0.00	0.00	0.00	0.38	0.49
Fe ²⁺	1.84	0.13	0.16	1.59	0.06	0.08	0.02	0.00	1.72	1.36	0.08	0.18	0.02	0.00	0.00	0.02	0.43	1.78	0.19	0.12	0.30	0.00
Mn	0.03	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.02	0.59	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.04	0.00	0.00	0.01	0.01
Mg	0.43	0.47	0.38	0.60	0.43	0.37	0.00	0.00	0.52	0.18	0.44	0.44	0.00	0.03	0.02	0.01	2.63	0.56	0.34	0.35	2.69	0.02
Ca	0.75	0.51	0.00	0.75	0.48	0.00	0.96	1.98	0.75	0.85	0.49	0.00	0.99	1.96	1.98	0.03	0.19	0.64	0.37	0.00	0.20	1.94
Na	0.00	0.46	0.04	0.01	0.52	0.10	0.00	0.00	0.00	0.01	0.51	0.03	0.00	0.02	0.03	0.65	1.84	0.01	0.63	0.10	1.82	0.00
Κ	0.00	0.00	0.94	0.00	0.00	0.85	0.00	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.01	0.00
Cations	8.02	4.00	7.01	8.00	4.00	6.97	4.99	7.98	8.00	8.00	4.00	6.92	5.00	8.00	8.01	6.76	15.04	8.02	4.00	7.00	15.02	7.99

Table 3. Representative analyses of minerals from chloritoid-bearing schists in the North Qilian suture zone

Sample		QS	535				XZ07					2Q34					2Q	35			BJ17					
Mineral	Cld	Gln	Ep	Phn	Cld	Cz	Gln	Pg	Grt	Grt	Phn	Cld	Car	Car	Grt	Car	Car-i	Phn	Cld	Gln	Gln	Cld	Phn	Grt	Ep	Chl
SiO ₂	24.59	56.57	37.67	50.14	25.07	38.52	58.36	48.11	37.85	37.54	53.13	25.39	38.44	38.52	38.59	39.22	40.96	52.35	25.70	59.36	57.37	25.33	49.50	37.68	37.48	26.42
TiO ₂	0.00	0.03	0.00	0.20	0.00	0.11	0.03	0.08	0.04	0.07	0.13	0.04	0.06	0.00	0.01	0.00	0.00	0.21	0.00	0.04	0.01	0.00	0.18	0.08	0.06	0.00
Al_2O_3	39.13	8.41	23.95	27.75	41.49	27.62	11.65	39.08	21.75	20.99	25.61	40.95	31.66	30.62	21.36	32.05	30.39	26.56	40.64	8.48	10.27	40.71	26.93	21.21	23.70	21.85
Cr ₂ O ₃	0.09	0.05	0.16	0.03	0.11	0.08	0.04	0.20	0.08	0.20	0.37	0.81	0.68	0.59	0.11	0.40	0.58	0.82	0.19	0.25	0.09	0.06	0.11	0.02	0.08	0.30
FeO	22.57	13.14	11.69	4.00	19.00	6.26	7.10	0.44	27.69	27.99	2.66	15.54	6.70	5.03	26.62	4.37	8.74	3.11	16.54	10.04	7.86	18.50	2.68	29.19	10.77	19.26
MnO	0.50	0.13	0.24	0.03	0.00	0.27	0.05	0.07	0.00	2.93	0.05	0.08	0.05	0.05	4.70	0.00	0.00	0.02	0.00	0.03	0.00	0.04	0.00	1.28	0.08	0.03
MgO	5.07	10.61	0.10	2.85	6.14	0.01	12.32	0.26	3.39	3.52	3.88	8.56	11.25	11.02	3.30	11.62	9.51	3.43	8.02	11.46	12.73	7.39	3.11	4.12	0.17	20.45
CaO	0.01	0.45	22.41	0.04	0.01	24.07	1.28	0.17	8.57	6.08	0.02	0.00	0.21	0.22	5.45	0.15	0.22	0.00	0.00	0.45	1.11	0.00	0.00	6.33	22.73	0.03
Na ₂ O	0.06	7.59	0.04	0.59	0.00	0.00	6.85	6.37	0.01	0.08	0.39	0.02	0.07	0.16	0.05	0.04	0.08	0.65	0.03	7.27	6.65	0.00	0.80	0.04	0.02	0.07
K_2O	0.01	0.02	0.02	10.05	0.00	0.00	0.01	1.04	0.00	0.00	9.35	0.01	0.10	1.28	0.00	0.09	0.34	8.60	0.02	0.02	0.01	0.00	10.00	0.01	0.00	0.00
Total	92.03	97.01	97.57	95.69	91.82	96.94	97.69	95.82	99.38	99.4	95.59	91.40	89.25	87.55	100.19	87.98	90.88	95.75	91.14	97.40	96.10	92.03	93.31	99.96	95.09	88.41
Oxygen	6	23	12.5	11	6	12.5	23	11	12	12	11	6	8	8	12	8	8	11	6	23	23	6	11	12	12.5	14
Si	1.01	7.93	3.00	3.35	1.01	3.03	7.89	3.05	2.99	2.99	3.50	1.01	1.96	2.00	3.04	2.00	2.07	3.44	1.03	8.06	7.91	1.01	3.38	2.98	3.02	2.66
Ti	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00
Al	1.89	1.39	2.25	2.18	1.97	2.56	1.86	2.92	2.03	1.97	1.99	1.93	1.91	1.88	1.99	1.93	1.81	2.06	1.92	1.36	1.67	1.92	2.17	1.98	2.25	2.60
Cr	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.02	0.03	0.03	0.02	0.01	0.02	0.02	0.04	0.01	0.03	0.01	0.00	0.01	0.00	0.01	0.02
Fe ³⁺	0.10	0.34	0.77	0.06	0.00	0.25	0.09	0.00	0.00	0.03	0.03	0.02	0.10	0.10	0.00	0.06	0.10	0.11	0.01	0.62	0.17	0.05	0.00	0.07	0.69	0.07
Fe ²⁺	0.67	1.20	0.01	0.16	0.64	0.16	0.72	0.02	1.83	1.84	0.12	0.50	0.19	0.12	1.76	0.13	0.27	0.06	0.55	0.52	0.74	0.57	0.15	1.86	0.03	1.56
Mn	0.02	0.02	0.02	0.00	0.00	0.02	0.01	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.01	0.00
Mg	0.31	2.22	0.01	0.28	0.37	0.00	2.48	0.03	0.40	0.42	0.38	0.51	0.86	0.86	0.39	0.88	0.72	0.34	0.48	2.32	2.62	0.44	0.32	0.49	0.02	3.07
Ca	0.00	0.07	1.91	0.00	0.00	2.03	0.19	0.01	0.73	0.52	0.00	0.00	0.01	0.01	0.46	0.01	0.01	0.00	0.00	0.07	0.16	0.00	0.00	0.54	1.96	0.00
Na	0.01	2.06	0.01	0.08	0.00	0.00	1.80	0.78	0.00	0.01	0.05	0.00	0.0	0.02	0.01	0.00	0.01	0.08	0.00	1.91	1.78	0.00	0.11	0.01	0.00	0.01
K	0.00	0.00	0.00	0.86	0.00	0.00	0.00	0.08	0.00	0.00	0.79	0.00	0.01	0.09	0.00	0.01	0.02	0.72	0.00	0.00	0.00	0.00	0.87	0.00	0.00	0.00
Sum	4.00	15.35	7.99	6.99	4.00	8.06	15.06	6.92	7.99	8.00	6.89	4.00	5.07	5.10	7.96	5.03	5.03	6.85	4.00	15.10	15.11	4.00	7.01	8.00	8.00	10.00

Car-i represents carpholite inclusion in chloritoid.

to ~0.18 respectively. Grossular content (X_{grs} [=Ca/ (Mg + Fe + Ca + Mn)]) decreases from the core to the rim (~0.31 to ~0.25).

All plots in Fig. 6a are analyses of rims of eclogitic garnet where omphacite inclusions occur, and show compositional variation of garnet rims in different grains and samples. In contrast to type II eclogite, garnet of type I eclogite is characterized by lower pyrope contents ($X_{\rm prp} \sim 0.05-0.12$) and higher grossular contents ($X_{\rm grs} \sim 0.28$ to ~0.35).

Garnet in metapelites is chemically more complex because of the broad compositional variation of different protoliths. Most garnet in meta-pelites has lower grossular contents than garnet in eclogites (Fig. 6b). In

Sample			2q28					2Q	2Q33						
Mineral	Phn	Grt	Omp	Ep	Gln(C)	Gln(R)	Grt	Phn	Omp	Gln	Ep	Grt	Omp	Phn	Gln
SiO ₂	54.22	38.43	55.70	37.88	56.81	57.11	38.44	52.25	55.64	58.71	37.98	39.02	56.28	52.76	59.50
TiO ₂	0.22	0.00	0.01	0.13	0.00	0.05	0.00	0.24	0.03	0.04	0.10	0.00	0.00	0.22	0.03
Al_2O_3	25.27	22.11	10.36	27.55	11.16	10.86	22.13	26.48	9.54	10.51	25.36	22.06	11.57	27.58	11.52
Cr_2O_3	0.27	0.03	0.06	0.11	0.01	0.06	0.00	0.29	0.11	0.10	0.52	0.02	0.12	0.23	0.11
FeO	2.71	26.37	7.59	7.44	11.39	7.67	30.49	1.45	9.07	7.59	8.65	26.69	7.20	2.11	6.54
MnO	0.00	0.56	0.00	0.04	0.03	0.00	0.35	0.00	0.07	0.00	0.12	0.16	0.01	0.00	0.01
MgO	4.26	6.40	6.51	0.20	9.23	12.73	4.20	3.95	6.47	12.54	0.07	6.00	5.82	3.42	12.33
CaO	0.01	6.83	9.98	22.70	0.48	1.06	6.05	0.04	10.60	0.51	23.15	6.87	9.25	0.04	0.46
Na ₂ O	0.42	0.04	9.06	0.02	7.45	7.20	0.04	0.57	8.44	7.33	0.05	0.05	9.39	0.64	7.17
K ₂ O	9.58	0.00	0.01	0.01	0.01	0.03	0.00	9.97	0.00	0.02	0.00	0.01	0.00	8.28	0.04
Total	96.99	100.80	99.37	96.08	96.57	96.77	101.73	95.22	100.00	97.35	96.00	100.88	99.64	95.28	97.75
0	11	12	6	12.5	23	23	12	11	6	23	12.5	12	6	11	12.5
Si	3.50	2.97	1.98	2.98	7.92	7.78	2.98	3.46	1.99	7.93	3.02	3.00	2.00	3.46	7.97
Al ^{IV}	0.50	0.03	0.02	0.02	0.08	0.22	0.02	0.54	0.01	0.07	0.00	0.00	0.00	0.54	0.03
Al ^{VI}	1.42	1.98	0.42	2.54	1.75	1.53	2.01	1.53	0.39	1.60	2.37	2.00	0.48	1.59	1.79
Ti	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00
Cr	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.02	0.00	0.01	0.03	0.00	0.00	0.01	0.01
Fe ³⁺	0.00	0.00	0.19	0.49	0.17	0.45	0.00	0.00	0.18	0.38	0.57	0.00	0.16	0.00	0.22
Fe ²⁺	0.15	1.70	0.04	0.00	1.16	0.42	1.98	0.08	0.09	0.48	0.00	1.72	0.05	0.12	0.51
Mn	0.00	0.04	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00
Mg	0.41	0.74	0.35	0.02	1.92	2.59	0.49	0.39	0.34	2.53	0.01	0.69	0.31	0.33	2.46
Ca	0.00	0.57	0.38	1.91	0.07	0.16	0.50	0.01	0.41	0.07	1.97	0.57	0.35	0.00	0.07
Na	0.05	0.00	0.63	0.00	2.01	1.90	0.00	0.07	0.58	1.92	0.01	0.01	0.65	0.08	1.86
K	0.79	0.00	0.00	0.00	0.00	0.01	0.00	0.84	0.00	0.00	0.00	0.00	0.00	0.69	0.01
Cations	6.84	8.02	4.00	7.99	15.09	15.06	8.00	6.94	4.00	15.00	7.99	8.00	4.00	6.84	14.94

Table 4. Representative analyses of minerals from omphacite-bearing meta-pelite from the North Qilian suture zone

C = core and R = rim.



Fig. 5. Compositional profile of a lawsonite-bearing eclogitic garnet grain in Fig. 3f.

the Car–Cld schist (2Q34 & 2Q35), garnet is also characterized by chemical zoning with cores enriched in spessartine relative to almandine and pyrope, which changes from core compositions $X_{\rm sps} \sim 0.066-0.072$, $X_{\rm alm} \sim 0.60-0.63$, $X_{\rm prp} \sim 0.133-0.139$ and $X_{\rm grs} \sim 0.154-$ 0.167 to rim with $X_{\rm sps} \sim 0.016-0.025$, $X_{\rm alm} \sim 0.59-0.62$, $X_{\rm prp} \sim 0.19-0.23$ and $X_{\rm grs} \sim 0.163-0.165$. Garnet in Grt–Cld–Pg–Gln schist, however, shows a large chemical variation in grossular contents in different grains (Fig. 6b).

Garnet in Grt-Omp-Gln-Phn schists (sample 2Q28, 2Q32 & 2Q33) from the Baijingsi cross-section (Fig. 1c) has smaller grain size (0.3–0.8 mm) and is characterized by extremely low spessartine contents

 $(X_{\rm sps} \sim 0.004$ –0.012). Compositional zoning of some large grains is revealed by antithetic changes of almandine relative to pyrope and grossular contents from core to rim with $X_{\rm alm}$ decrease from 0.68 to 0.56, $X_{\rm prp}$ increase from 0.16 to 0.24 and $X_{\rm grs}$ from 0.17 to 0.19 (Fig. 6b).

Sodic clinopyroxene

Sodic clinopyroxene from two eclogite types has an omphacitic composition without clear compositional zoning. As shown in Fig. 7a, omphacite in type I phengite–eclogite varies in a relatively narrow range of $X_{\rm Jd} \sim 0.33$ –0.47, $X_{\rm Ae} \sim 0.11$ –0.17 and $X_{\rm Au} \sim 0.46$ –0.55. Omphacite in type II epidote–eclogite, on the other hand, shows wider compositional variations, with the jadeite component ($X_{\rm Jd}$) ranging from 0.28 to 0.54, and aegirine component ($X_{\rm Ae}$) from 0 to 0.25.

Sodic clinopyroxene from pelitic Grt–Omp–Gln– Phn schist ranges in jadeite content from 0.36 to 0.52 and aegirine from 0.11 to 0.31, and contain higher aegirine-component than mafic eclogite (Fig. 7b).

Lawsonite

A few small lawsonite inclusions occur in eclogitic garnet (Table 2) together with lawsonite pseudomorphs of Cz + Pg (Fig. 3e,f) from both type I (Q04) and type II eclogites (2Q27). Lawsonite analyses contain low FeO (0.45-0.52 wt%), MnO (0.04-0.05 wt%) and MgO (0.02-0.03 wt%).



Fig. 6. Diagrams showing compositional variation of garnet from eclogite (a) and from meta-pelite (b). The arrow shows change in composition from core to rim.

Fig. 7. Jadeite (NaAlSi₂O₆)-aegirine (NaFe³⁺ Si₂O₆)-augite (Ca(FeMg)Si₂O₆) ternary diagram showing sodic clinopyroxene compositions in eclogite (a) and metapelite (b) from the North Qilian HP belt.

White mica

Most white mica from the two types of eclogite is phengite and ranges in Si content from 3.41 to 3.47 cations per formula unit (p.f.u.) on the basis of 11 oxygen for those in type I eclogites and ~3.37– 3.43 p.f.u. in type II eclogite (Fig. 8a). A general positive trend can be established for silica and Fe + Mg but an antithetic trend for silica and X_{Na} [=Na/ (K + Na)]. Some white mica in lawsonite-pseudomorph inclusions in garnet is paragonite composition and rare paragonite coexists with phengite in the matrix of the two types of eclogite.

Compositions of phengite from various meta-pelites are shown in Fig. 8b. In garnet-free Cld–Gln schist (QS35), phengite contains relatively lower silica contents (\sim 3.36–3.39 p.f.u.) and higher X_{Na} (\sim 0.08–0.11) than other metapelites. Phengite in Grt–Cld–Gln–Phn schist shows silica contents from 3.38 to 3.41 cations, and, in Car–Cld schist, from 3.44 to 3.51 cations. Phengite from Grt–Omp–Gln–Phn schist has the highest silica content from 3.46 to 3.53. Paragonite in Grt–Cld–Gln–Pg schist has 3.05–3.11 Si cations per formula unit.

Sodic amphibole

Sodic amphibole with Si > 7.7 and Na/(Na + Ca) > 0.90 is a ubiquitous phase and is almost pure glaucophane in all studied rocks. Most glaucophane, either from mafic eclogites or from metapelites, invariably possesses clear compositional zoning with increased Mg/(Mg + Fe²⁺) and Fe³⁺/(Fe³⁺ + Al) ratios towards the rim. Glaucophane in type I eclogite has a lower Mg/(Mg + Fe²⁺) ratio than that in type II eclogite. Composition of glaucophane in metapelites



Fig. 8. Phengite compositions for eclogite (a) and meta-pelite (b) from the North Qilian HP belt shown in terms of Si and (Mg + Fe) per formula unit (p.f.u.). The ideal celadonite-muscovite substitution line is also shown.



Fig. 9. Diagram showing compositional variation of glaucophane from eclogite and meta-pelite. The dashed lines join compositions of core and rim.

varies considerably in different protoliths and samples as shown in Fig. 9.

Mg-carpholite

Carpholite of two carpholite–chloritoid schist samples (2Q34 & 2Q35) was analysed (Table 3) and their structural formula (Fe,Mn,Mg)Al₂Si₂O₆(OH,F)₄ was calculated on the basis of eight oxygen. The Fe³⁺ (Fe³⁺ = 2 – Al) and Fe²⁺ contents were calculated after Goffé & Oberhänsli (1992). Mg-carpholite is characterized by high MgO, low FeO and extremely low MnO contents with X_{Mg} [=Mg/(Mg + Fe²⁺ + Mn)] ranging from 0.73 to 0.87, X_{Fe} from 0.13 to 0.27, and X_{Mn} from 0.000 to 0.002 (Fig. 10a). Carpholite

inclusions in chloritoid have higher $X_{Fe}\,(up \ to \ 0.27)$ than large crystals in matrix.

Chloritoid

Chloritoid of various chloritoid-bearing schists differs in FeO and MgO contents. The Mg/(Mg + Fe) ratio of Cld ranges between 0.17–0.29, 0.46–0.55 and 0.36– 0.40 in Grt-free Cld–Gln schist, Car-bearing schist and Grt–Gln–Cld schist respectively (Fig. 10b).

Epidote group minerals

Ferric iron in epidote group minerals was recalculated assuming two-site ordering with a total of six silica, aluminium and ferric cations per 12.5 oxygen. Epidote group minerals include clinozoisite in eclogite, and epidote in eclogite and meta-pelites. Clinozoisite inclusions in eclogitic garnet contain less Fe³⁺ (Cz [= $(Al - 2)/(Al - 2 + Fe^{3+})$] ~ 0.88–0.76) than in the matrix of eclogite (Cz ~ 0.40–0.68) and in the meta-pelite (Cz ~ 0.24–0.41).

PRESSURE-TEMPERATURE ESTIMATES

Two geothermobarometric methods are employed for P-T estimates of rocks from the North Qilian HP belt: (1) Grt–Omp–Phn(-Ky) geothermobarometry of Ravna & Terry (2004); and (2) the THERMOCALC program (v. 3.23; Holland & Powell, 1998).

P–*T* estimates for eclogite

Petrographic observations indicate that eclogite at the peak metamorphic stage contains the typical low-temperature assemblage Grt + Omp + Lws + Phn + Rt,



Fig. 10. Diagrams showing compositions of Mg-carpholite (a) and chloritoid from meta-pelites (b).

as lawsonite is preserved together with omphacite as inclusions in garnet, whereas glaucophane and epidote are obviously late-stage minerals that replace omphacite in most studied samples. P-T estimates are based on the combination of the garnet–clinopyroxene Fe^{2+} –Mg exchange thermometer of Ravna (2000) and the geothermobarometric formulation derived from the reaction:

3 celadonite + 2 grossular + 1 pyrope

= 6 diopside + 3 muscovite

(Ravna & Terry, 2004). The rim composition of garnet was used for P-T calculation and Fe³⁺ in omphacite was assumed Fe³⁺ = (Na - Al - Cr).

The results are listed in Table 5 and Fig. 11. The calculations give a temperature range of 460–510 °C and a pressure range of 2.20–2.60 GPa, which lie mainly in the lawsonite–eclogite field. In strongly foliated eclogite samples (2Q19, 2Q22 & 2Q24), on the other hand, omphacite and phengite are orientated along foliation with clinozoisite and glaucophane, and the calculated temperatures range between 475 and 500 °C and pressures range between 1.75 and 1.95 GPa, which are significantly lower than those of weakly deformed eclogite.

Because epidote and glaucophane are retrograde phases and overprint Grt + Omp(+Lws) in eclogite samples (Fig. 3), using the THERMOCALC program, rather complex results were obtained (Table 5).

P-T estimate for Grt-Omp-Phn-Gln schist.

Using Grt-Omp-Phn geothermobarometry of Ravna & Terry (2004), *P*-*T* calculations for the Grt-Omp-Phn-Gln schist yield 445-495 °C and 2.15-2.25 GPa

Table 5. P-T results of eclogite and meta-pelite from the North Qilian suture zone.

Sample	Rock type	T(R - 2000)	$Fe^{3+} = Na - Al - Cr$ P (Grt-Phe-Cpx) (GPa)	THERMOCALC average T (°C)	THERMOCALC average P (GPa)	$\sigma_{ m fit}$	
Eclogite							
Q01	Type I eclogite	498	2.45	555 (SD 40)	2.23 (SD 0.29)	0.67	
Q04	Type I eclogite	482	2.34	453 (SD 31)	2.53 (SD 0.15)	0.79	
Q67	Type I eclogite	459	2.45	472 (SD 88)	2.40 (SD 0.28)	0.76	
Q68	Type I eclogite	492	2.51	452 (SD 80)	1.71 (SD 0.28)	1.03	
QS45	Type I eclogite	464	2.20	nr	nr		
2Q19	Type II foliatedeclogite	476	1.73	578 (SD 48)	2.16 (SD 0.28)	1.66	
2Q22	Type II foliatedeclogite	478	1.94	nr	nr		
2Q24	Type II foliatedeclogite	497	1.95	575 (SD 65)	2.36 (SD 0.37)	2.35	
2Q25	Type II eclogite	477	2.30	nr	nr		
2Q27	Type II eclogite	508	2.59	588 (SD 48)	2.57 (SD 0.37)	2.05	
Metapelite							
2Q28	Grt-Omp-Phn-Glnschist	445	2.25	542 (SD 51)	2.57 (SD 0.47)	2.26	
2Q32	Grt-Omp-Phn-Glnschist	469	2.15	494 (SD 48)	2.40 (SD 0.34)	1.83	
2Q33	Grt-Omp-Phn-Glnschist	496	2.15	532 (SD 54)	2.13 (SD 0.36)	1.38	
2Q34	Grt-Car-Cld-Phn-Glnschist			532 (SD 12)	2.46 (SD 0.10)	1.19	
2Q35	Grt-Car-Cld-Phn-Glnschist			524 (SD 18)	2.49 (SD 0.21)	1.74	
BJ17	Grt-Cld-Phn-Glnschist			530 (SD 20)	2.14 (SD 0.32)	2.06	
XZ06	Grt-Cld-Pg-Gln-Epschist			512 (SD 13)	1.51 (SD 0.14)	1.08	
XZ07	Grt-Cld-Pg-Gln-Epschist			525 (SD 13)	1.81 (SD 0.14)	1.16	

nr = no result.



Fig. 11. P-T-t path for mafic eclogite (a) and metapelites (b) from the North Qilian suture zone. The petrogenetic grid is after Oh & Liou (1998). The il and i2 invariant points and univariant reactions are after Wei & Powell (2004). Divariant lines of Car = Cld + Qtz + v are after Agard *et al.* (2005) and calculated by **THERMOCALC** 3.23 (Holland & Powell, 1998).

(Table 5), which are consistent with the P-T estimates of eclogites. However, THERMOCALC average P-T program (v. 3.23; Powell *et al.*, 1998) gives 495–540 °C and 2.15–2.60 GPa (Table 5).

P-T estimates for chloritoid-bearing schist

Mineral equilibria were calculated using the THERMO-CALC program (v. 3.23; Holland & Powell, 1998). Endmember activities used in the P-T calculations are obtained using the AX program (Holland, http:// www.esc.cam.ac.uk/astaff/holland/thermocalc.html) assuming temperature at 500 °C and pressure at 2.0 GPa with the activities of quartz/coesite and lawsonite assumed to be unity, and fluid assumed to be pure water and in excess.

The Gln + Cld assemblage is ubiquitous in the four chloritoid-bearing schist types described above and has been considered to be an indicator for low-T blueschist facies recrystallization of metapelites (e.g. Guiraud *et al.*, 1990; El-Shazly & Liou, 1991; Okay & Kelley, 1994; Wei & Powell, 2004, 2006; Ko *et al.*, 2005). This association can be constrained through the reaction:

$$8 \text{ Pg} + 5 \text{ Clin} + 6 \text{ Qtz} = 13 \text{ Cld} + 4 \text{ Gln} + 11\text{H}_2\text{O}$$

Grt-Cld-Gln-Pg schist (XZ07)

El-Shazly & Liou (1991) calculated the stability field of coexisting Mg-chloritoid + glaucophane in the NMASH system to be constrained at > 2.4 GPa and < 530 °C. On the other hand, the Fe end-member glaucophane + chloritoid assemblage appears at pressures as low as 0.6 GPa and temperatures of 525 °C and the MgO-content of chloritoid and glaucophane is positively correlated with pressure.

Based on independent end-member reactions, the average P-T estimate for mineral assemblage Grt-Cld-Pg-Gln schist (XZ07) gives results of 528 ± 44 °C and 19.2 ± 2.4 kbar ($\sigma_{\rm fit} = 2.38$), which are coincident with P-T conditions for the Grt + Gln + Cld + Pg assemblage from other HP belts in, e.g. Oman (El-Shazly & Liou, 1991), Himalaya (Guillot *et al.*, 1997), Turkey (Okay, 2002) and Sanbagawa of Japan (Ko *et al.*, 2005).

Car-Cld schist

The Car–Cld schist (2Q34 & 2Q35) consists of Grt + Mg-Car + Cld + Gln + Phn + Rt. Microstructures shown in Fig. 4c,d indicate that garnet, phengite, carpholite and chloritoid occur as a likely equilibrium parageneses. Glaucophane is also an equilibrium phase as occurring in the matrix or within porphyroblastic garnet. According to Wei & Powell (2004, Fig. 3), the assemblage Car + Cld + Gln in the model system NKFMASH is related to a univariant reaction Car + Cld + Gln = Chl + Pa at \sim 1.95 GPa, whereas Grt + Car is related to a univariant reaction Car + Grt = Cld + Chl, which has a flat slope at ~ 2.5 GPa and < 520 °C, indicating that the Car + Grt paragenesis is stable at a pressure above 2.5 GPa. The MnO content in the bulk rock composition will affect the stability field of garnetbearing assemblages moving them to lower pressure and temperature (Mahar et al., 1997; Wei & Powell, 2004). Temperature can be constrained by univariant reactions Car + Cld = Ky + Chl (P < 2.0 GPa) and Car = Ky + Cld + Tlc (P > 2.0 GPa) (Fig. 11). Using THERMOCALC's average P-T programme (Powell et al., 1998), a temperature and pressure of 532 °C (SD 12) and 2.46 GPa (SD 0.10) were obtained with $\sigma_{\rm fit} =$ 1.19 for sample 2Q34 and 524 °C (SD 18) and 2.49 GPa (SD 0.21) with $\sigma_{\text{fit}} = 1.74$ for sample 2Q35.

DISCUSSION

Metamorphic history and *P*–*T*–*t* path

Based on parageneses and compositions of minerals, four major stages of metamorphism were recognized for the high P/T rocks from the North Qilian suture zone: (1) stage I pre-eclogite facies prograde metamorphism; (2) stage II peak eclogite facies metamorphism; (3) retrograde blueschist facies metamorphism and (4) greenschist facies metamorphism (Fig. 11a).

Stage I prograde metamorphism occurred during oceanic subduction and is revealed by epidote + albite inclusions in garnet cores and compositions of garnet cores characterized by higher spessartine, lower pyrope and almandine contents.

Stage II peak eclogite facies metamorphism is characterized by the lawsonite-bearing assemblage in basaltic eclogite, and omphacite- and carpholitechloritoid-bearing assemblages in pelitic schists. The *P*-*T* peak estimates of eclogite (460–510 °C, 2.20– 2.60 GPa) and carpholite-bearing schists (525–530 °C, 2.45–2.50 GPa) lie well in the lawsonite-eclogite (Lws-EC) stability field (Okamoto & Maruyama, 1999). U– Pb SHRIMP dating of zircon from two eclogite samples (QS45 & 2Q27) gave a mean age of 464 \pm 6 Ma (Song *et al.*, 2004, 2006), and ⁴⁰Ar/³⁹Ar isotopic dating for phengite from the Grt–Omp–Phn–Gln schist in the Baijingsi section yielded a plateau age of 462 \pm 1.3Ma (Zhang *et al.*, 1997).

Stage III is a retrograde blueschist facies metamorphism when some eclogites were retrogressed into foliated glaucophane-clinozoisite blueschists; most lawsonite reacted out to clinozoisite. Average P-Tcalculation for two mafic blueschist with assemblage of Grt + Gln + Ep + Ab + Phn + Pg + Qtz by THERMOCALC 3.23 gives results of 1.10-1.20 GPa and 480–495 °C. Ar/Ar dating for phengite from blueschists yielded well-defined plateau ages of 448 \pm 11 Ma (Liou *et al.*, 1989) and 442–454 Ma (Liu *et al.*, 2006).

Stage IV greenschist facies retrogression is ubiquitous in all types of HP/LT rocks, in which the earlier formed mineral assemblages are overprinted by chlorite and fibrous actinolitic amphibole to various degrees. Some 40 Ar/ 39 Ar ages of phengitic mica and glaucophane range from 420 to 400 Ma (Wu *et al.*, 1993; Zhang *et al.*, 1997) and most probably recorded the last exhumation of the North Qilian HP/LT belt during strong orogenic uplift, indicated by the Early Devonian molasses.

Early Palaeozoic cold oceanic subduction

The oldest UHP metamorphism at c. 620 Ma in the Pan-African zone implies that the Earth's continental crust was rigid enough and was subducted to mantle depths of greater than 100 km (e.g. Jahn et al., 2001). However, cold oceanic subduction with diagnostic lawsonite and carpholite has mostly been recorded in Tethyan belts with ages <80 Ma and no earlier than 500 Ma in Earth's orogenic belts (Agard et al., 2005). Besides the North Qilian suture zone, only two HP belts with similar ages of 475-450 Ma have been identified, i.e. Fe-Mg carpholite-bearing blueschist and lawsonite-bearing eclogite in Motalafijella, Svalbard Caledonides (Hirajima et al., 1988; Agard et al., 2005) and lawsonite-bearing eclogite in Port Macquarie, New England fold belt. Australia (Och et al., 2003). To our knowledge, meta-pelite with the Car-Grt-Gln-Cld-Phn assemblage has not been described in any HP belt before.

Isotopic geochronology of HP rocks corroborates that the North Qilian is one of the three oldest occurrences of cold oceanic subduction on Earth. From lawsonite–pumpellyite–aragonite blueschist (250–300 °C, 0.60–0.80 GPa, Wu *et al.*, 1993) to lawsonite eclogite and carpholite–chloritoid schist (460–530 °C, 2.20–2.60 GPa), we can deduce a progressive subduction path along a thermal gradient of 6–7 °C km⁻¹ as cold as Cenozoic to present-day oceanic subduction zones. Based on metamorphic ages from eclogite (*c.* 464 Ma, Song *et al.*, 2006) to blueschist facies metamorphism (454–446 Ma, Liou *et al.*, 1989; Zhang *et al.*, 1997; Liu *et al.*, 2006), exhumation rates for North Qilian HP rocks were estimated in the order of 0.24–0.50 cm year⁻¹.

Protoliths of North Qilian HP rocks include blocks of subducting oceanic slab with overlying pelagic and semi-pelagic sediments and terrigenous trench greywacke and marble. Greywacke is the major component and occupies more than half of the HP belt, whereas the oceanic blocks are minor. Mineral assemblages of these rocks indicate that they have been subducted to various depths and subjected to various degrees of eclogite- to blueschist facies metamorphism.

The North Qilian suture zone and the North Qaidam UHP belt in the south, which are juxtaposed \sim 250 km apart in distance, represent two end-member subduction complexes on Earth: 'cold' oceanic-type subduction and 'warm' continental subduction. Eclogites from both belts share similar metamorphic ages (464 v. 500-457 Ma. Song et al., 2006; Zhang et al., 2006) and protoliths of MORB and OIB affinities (Song et al., 2003b, 2006). UHP metamorphic ages of the North Qaidam UHP belt are well constrained c. 423 Ma by U-Pb SHRIMP dating of zircon from garnet peridotites (Song et al., 2005) and coesitebearing metapelites (Song et al., 2006). These data enable us to conclude that these two parallel belts may represent an evolutionary sequence from oceanic subduction to continental collision, and continental underthrusting, to final exhumation.

Implications for dehydration in the subduction channel

It is generally believed that island-arc basaltic magmas are sourced at depths of ~75–150 km in the mantle wedge (e.g. Gill, 1981), resulting from dehydration of subducting slab consisting of serpentinized mantle (Niu, 2004, 2005), altered basaltic crust and H₂O-enriched sediments through eclogitization and hydration of minerals, such as serpentine and chlorite (e.g. Iwamori, 1998; Hacker *et al.*, 2003; Arcay *et al.*, 2005). The amounts of dewatering, hence the genesis of arc magmatism are largely controlled by thermal gradient (cold v. warm) of the subduction zone (Peacock & Wang, 1999).

In recent years, several 'cold' subduction zones, for the formation of lawsonite- and/or Mg–Fe-carpholitebearing HP rocks, have been identified along ancient oceanic-type subduction zones (for details, see summaries of Agard *et al.*, 2005; Tsujimori *et al.*, 2006; Whitney & Davis, 2006). Their occurrences suggest that considerable amounts of H₂O can be stored to mantle depths along cold subduction zones (e.g. Maruyama & Liou, 2005; Niu, 2005).

Lawsonite-bearing eclogite and Mg-carpholitebearing metapelite of the Early Palaeozoic North Qilian HP belt represent a cold subducted oceanic slab that was exhumed from mantle depths (>75 km).

Lawsonite, which can accommodate ~12 wt% of water, is the major H₂O-carrier phase in HP metamorphic rocks. Experiments on basaltic compositions indicate that lawsonite is stable at pressures as high as 9 GPa and lawsonite eclogite is expected at the temperature-depth conditions in many subduction zones (Poli & Schmidt, 1995). As pointed by Zack *et al.* (2004); Whitney & Davis (2006) and Tsujimori *et al.* (2006), the rarity of lawsonite eclogite at the Earth's surface is a function of an uncommon exhumation history and is not a reflection of unusual P-T conditions during subduction.

The scarcity of Mg–Fe carpholite in eclogite would be explained by its narrow stability field and bulk rock composition (Agard et al., 2005). Carpholite in metapelites is even more difficult to preserve during exhumation unless a fast and 'cold' condition is sustained, because carpholite is only stable in a narrow P-T field (e.g. Wei & Powell, 2004) and metapelites are more readily deformed and thermally reequilibrated than eclogite. Microstructural observation in thin sections suggests that Car-Grt-Gln-Cld-Phn(-Rt-Otz) assemblage is an equilibrium paragenesis (see Fig. 4c,d). The equilibration between carpholite and chloritoid suggests that the P-T path is along or across the reaction $Car = Cld + Qtz + H_2O$. This unusual assemblage requires a more restricted stability field of high-pressure (≥2.4 GPa) and low-temperature (<530 °C) conditions (Wei & Powell, 2004). The Mgcarpholite in the North Qilian eclogite facies metapelite in the North Qilian suture zone suggests an Mg-rich but Ca-poor bulk-rock composition and reveals an example that sediments had subducted to depths greater than 75 km at a low thermal gradient of 6-7 °C km⁻¹ in oceanic subduction zones, which brought a large amount of water into the mantle in the Early Palaeozoic.

As shown in Fig. 11, either temperature increase or pressure decrease would dehydrate lawsonite and carpholite, respectively, to epidote and chloritoid. In a continuous cold subduction zone, increasing temperature does not seem to be the case, because the downgoing slab would generally retain a steady thermal gradient during subduction (e.g. Davies & Stevenson, 1992; Ponko & Peacock, 1995). A subduction path along a thermal gradient of 6-7 °C km⁻¹ (see above) is cold enough to protect lawsonite and carpholite from dehydration. This implies that most of H₂O could be retained in the protoliths of the downgoing slab until the breakdown of lawsonite at depths greater than 250 km (Schmidt & Poli, 1998). Isothermal exhumation paths (Fig. 11) always result in HP rocks crossing the Lws/Czo and Car/Cld transitions. Therefore, dehydration from lawsonite eclogite to epidoteeclogite is expected to occur during the exhumation rather than during the cold oceanic subduction. This implies that a lower amount of H₂O returns from the cold oceanic subduction zone, migrates upward to the sub-arc mantle wedge, and leads to relatively weaker island-arc volcanism than the warm oceanic subduction zone.

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