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1 Oceanic subduction to continental collision in the NE Proto-
2 Tethys revealed by Early Paleozoic eclogites with high-T granulite
3 facies overprinting in the East Kunlun orogenic belt, northern
4 Tibet

5
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ABSTRACT

The East Kunlun orogenic belt (EKOB) in the northern Tibetan Plateau records a long-term accretionary and collisional history in the northeastern Proto-Tethys Ocean, important for reconstructing the paleogeography of Early Paleozoic East Asia. Here we present an integrated petrology, geochemistry, geochronology, and metamorphic P – T study of newly found eclogites in the middle Nuomuhong segment of the EKOB. The eclogites are composed mainly of garnet, omphacite and low sodium clinopyroxene, amphibole and plagioclase with minor orthopyroxene, biotite, quartz, accessory rutile, ilmenite, titanite and zircon. Detailed petrographic observations, conventional geothermobarometry and phase equilibrium modeling, point to the presence of five metamorphic mineral assemblages with corresponding P – T conditions related to: (1) prograde M_1 stage P – T estimates >14.0 kbar/ ~ 470 – 506 °C; (2) P_{max} M_2 eclogite facies stage P – T conditions of ~ 26 kbar/ ~ 570 °C; (3) early retrograde M_3 high- P granulite facies stage; (4) subsequent M_4 retrograde medium- P granulite facies at T_{max} of ~ 860 – 900 °C; and (5) later M_5 retrograde amphibolite facies stage P – T conditions of <6.2 kbar/ ~ 710 – 730 °C. These P – T estimates define a clockwise P – T path characterized by heating during the P_{max} formation of the eclogite facies, to the T_{max} exhumation stage for the granulite lithologies, the latter of which is identified for the first time in retrograde eclogites from the EKOB. Whole-rock geochemical composition indicate a mid-oceanic ridge basalt (MORB) affinity for the eclogites protoliths and a fragmented oceanic crust origin. SHRIMP zircon U–Pb isotopic analyses for the eclogite yielded two groups of weighted mean $^{206}\text{U}/^{238}\text{Pb}$ ages of 464 ± 8 Ma and 419 ± 4 Ma, interpreted as the ages of the eclogite protolith and the lower threshold for peak eclogite facies metamorphism, respectively. Our new data, together with regional eclogite facies metamorphism, suggest a ca. 520–460 Ma age for the subduction of

45 the eastern Kunlun oceanic crust, within the northern Proto-Tethys Ocean, to a depth of ~83 km, with
46 early subduction–accretionary orogenesis occurring at ca. 419 Ma. Overprinting by high-*T* granulite
47 facies, linked to the maturation of the collisional orogenesis, point to exhumation of the middle to
48 shallow oceanic crust at this time. Collectively, the preserved eclogite and high-temperature (*T*)
49 granulite mineral assemblage provide new constraints on the tectonic evolution and detailed
50 accretionary-to-collisional orogenesis of the Proto-Tethys Ocean. They suggest that the ca. 428–411
51 Ma subduction-collisional event marked the termination of the Proto-Tethys Ocean and the eventual
52 formation of a ~500-km-long, high to ultra-high pressure metamorphic belt in the EKOB.

53

54 **Keywords:** eclogite; subduction; continental collision; Proto-Tethys Ocean; East Kunlun; northern
55 Tibet

INTRODUCTION

Eclogite is a dense high pressure (HP) to ultra-high pressure (UHP) metamorphic rock comprised dominantly of omphacite and garnet, commonly associated with suture zones of accretionary and collisional orogenic belts (Bingen et al., 2001; Dobretsov, 1991; Hertgen et al., 2016; Klonowska et al., 2016; Meng et al., 2016; Sajeev et al., 2013; Schorn and Diener, 2017; Smith, 1984; Sobolev et al., 1986). Some eclogites may undergo high temperature (HT) and even ultra-high temperature (UHT) metamorphic overprinting during collisional orogenesis (Wang et al., 2022a; Wang et al., 2021). The reconstruction of the pressure–temperature–time (P – T – t) path for eclogite, reliant on proper estimates of pressure–temperature (P – T) evolution and determination of precise metamorphic ages, is thus important for deciphering the thermal history and large-scale tecto-orogenic processes along paleo-subduction-collision interfaces (Hertgen et al., 2016; Wang et al., 2017).

The Tethyan orogenic system, comprised of the Proto-Tethys, Paleo-Tethys to the Neo-Tethys, is the largest collisional orogen on Earth (Dong et al., 2018; Şengör, 1984; Zhao et al., 2018). Its reconstruction represents one of the most important and yet difficult to resolve puzzles in solid earth science research. In northern Tibet, northwest China, two early Paleozoic HP/UHP metamorphic belts exist (Fig. 1). The succession includes a HP metamorphic belt in the North Qilian orogenic belt and a UHP metamorphic belt in the northern Qaidam block, with interpreted formation in oceanic and continental subduction zone environments, respectively, during the evolution of the Proto-Tethyan orogenic belts (Han et al., 2015; Song et al., 2018a; Song et al., 2014; Song et al., 2012; Song et al., 2007; Yu et al., 2013a; Zhang et al., 2010a; Zhang et al., 2016; Zhang et al., 2015a; Zhang et al., 2008; Zhang et al., 2009; Zhang et al., 2015b). Recently, a several-kilometer-

78 wide HP/UHP metamorphic belt was recognized along the Central East Kunlun Fault in the East
79 Kunlun orogenic belt (EKOB, Fig. 1) (Chen et al., 2016; Meng et al., 2015a; Qi et al., 2014; Qi et
80 al., 2016a; Song et al., 2018b). This metamorphic belt was regarded as a subduction-collision suture
81 zone that records the tectonic evolution of the eastern Kunlun Ocean-a branch in the Proto-Tethys
82 Ocean (Bi et al., 2022; Song et al., 2018b). despite decades of igneous and metamorphic research,
83 the tectonic affinity of eclogite protoliths, the mechanism for subduction and exhumation, the
84 details of orogenesis in the EKOB and the evolution of the Proto-Tethys Ocean remain controversial
85 (Dong et al., 2018; Feng et al., 2023; Sun et al., 2022; Wang et al., 2022b; Yu et al., 2020a). Some
86 researchers suggested that the late Ordovician Tumuleke glaucophane schist and associated gabbro
87 ($^{40}\text{Ar}/^{39}\text{Ar}$ age: 445 ± 2 Ma) may signify the termination of oceanic subduction and the beginning of
88 continental collision in late Ordovician (Mo et al., 2007), whereas others proposed that the final
89 closure of the ocean basin occurred in mid-Silurian (Lu et al., 2010). New data suggest two
90 discontinuous and distinct orogenic cycles from the Proto-Tethys to the Paleo-Tethys in the EKOB
91 (Feng et al., 2023).

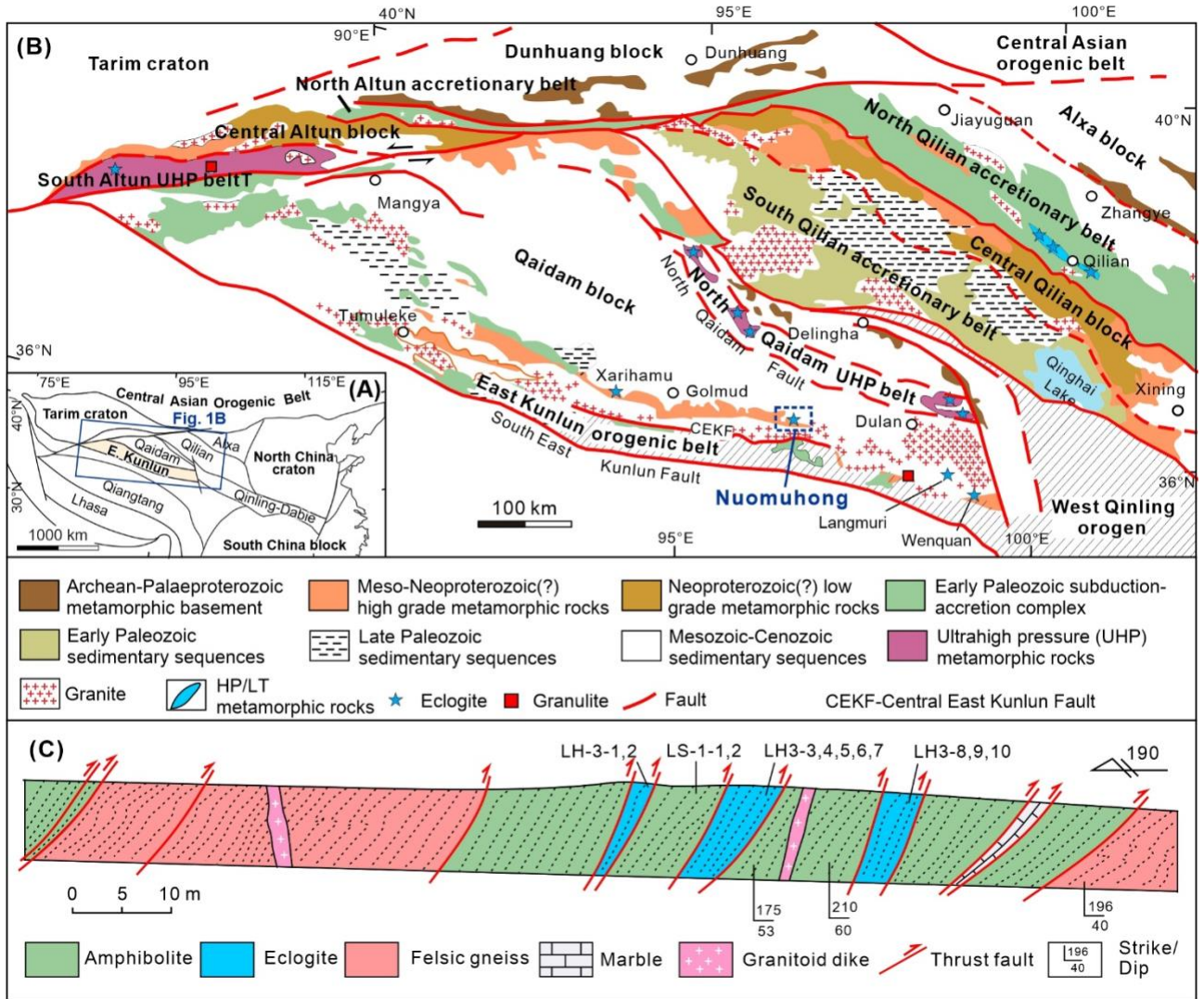


Figure 1. (A) Tectonic sketch map showing the major cratons and orogenic belts in northern China (Fu et al., 2022a). (B) Simplified geological map showing tectonic units in the northern Tibet Plateau (modified after (Meng et al., 2017; Zhang et al., 2015b; Zhang et al., 2017)). The locations of eclogites in the Nuomuhong area and other segments of the EQOB are marked (Meng et al., 2013b; Qi et al., 2014; Qi et al., 2016a; Song et al., 2018b). (C) An approximately N-S structural cross-section of the Nuomuhong area showing the main rock types and the location of samples.

In this contribution, we report a newly found eclogite that was overprinted by high-*T* granulite facies metamorphism in the Nuomuhong region in the middle segment of the EKOB (Figs. 1B and

1C). We present an integrated study combining petrology, whole-rock geochemistry, and SHRIMP zircon U–Pb ages from the eclogite to constrain its protolith and metamorphic P – T – t evolution, linked to two-stage ocean crust subduction and continental collision in the northeastern Proto-Tethys domain. The new metamorphic evidence together with regional geological data in the EKOB, highlight the early Paleozoic accretionary history and collisional orogenesis of the Proto-Tethyan EKOB.

GEOLOGICAL SETTING AND SAMPLING

The East Kunlun orogenic belt (EKOB) in the northern Tibet Plateau is bounded by the Qaidam block in the north, the Qiangtang-Songpan terrane in the south, and the West Kunlun orogenic belt separated by the Altyn Tagh strike-slip fault in the northwest (Li et al., 2018a; Meng et al., 2017; Song et al., 2018b; Wang et al., 2022b; Zhang et al., 2012; Zhang et al., 2015b) (Figs. 1A and 1B). The EKOB is subdivided into three tectonic belts. These include the North and South Kunlun belts, and the Muz Tagh-Anemaqen and Hoh Xil-Bayan Har Terranes by the North Kunlun Fault (NKLf), Middle Kunlun Fault (MKLF), South Kunlun Fault (SKLF), Muz Tagh-Anemaqen Fault (MAF), from north to south (Jiang et al., 1992; Luo et al., 1999; Meng et al., 2013b; Yang et al., 1986; Yu et al., 2020b).

The North Kunlun belt is composed of Precambrian metamorphic rocks, late Paleozoic volcanic-sedimentary rocks, and Paleozoic and Triassic granitoids. The Precambrian rocks are dominated by gneisses, migmatite and amphibolite of the Paleoproterozoic Jinshuikou Group (Jiang et al., 1992) and the greenschist facies carbonate and clastic rocks of the Mesoproterozoic Binggou Group (Meng et al., 2018). Zircon U–Pb ages of the gneiss and amphibolite from the Jinshuikou

124 Group suggest that high-grade metamorphism at ca. 1.8 Ga was followed by a two-phase tecto-
125 thermal event at ca. 1.0–0.9 Ga and ca. 400 Ma (Chen et al., 2008a; He et al., 2016; Meng et al.,
126 2013a; Song et al., 2018b; Zhou et al., 2020). Zircon ages of the schists from the Xiaomiao Group
127 point to the deposition of metasedimentary rocks during the Mesoproterozoic and subsequent
128 metamorphism at ca. 400 Ma (He et al., 2016; Wang et al., 2003a). These basement rocks were later
129 overlain by late Paleozoic volcanic-sedimentary rocks. Three phases of magmatism events, which
130 include the Neoproterozoic gneissic granites deposited at ca. 1006–870 Ma (Chen et al., 2015;
131 Meng et al., 2013b). The ca. 466–390 Ma Paleozoic diorites and granites and the ca. 250–200 Ma
132 Triassic granites, formed in this belt (Dong et al., 2018).

133 The South Kunlun belt (SKT) is mainly composed of Paleozoic–Triassic sedimentary and
134 volcanic rocks, with some Precambrian facies and Early Paleozoic and Permian–Triassic granites. It
135 stretches from the Wenquan area in the east, through the Wanbaogou area in the middle, to Chader
136 Tagh in the west. This succession witnessed the Caledonian to Indosinian events, including the
137 Wanbaogou island arc and the Qingshuiquan back arc basin activities. Although the Qingshuiquan
138 ophiolites and the volcanic rocks of the Wanbaogou Formation are the key indicators, their
139 formation age and genetic settings have been disputed (Chen et al., 2011; He et al., 2016; Liu et al.,
140 2016; Xu et al., 2016; Yu et al., 2020b).

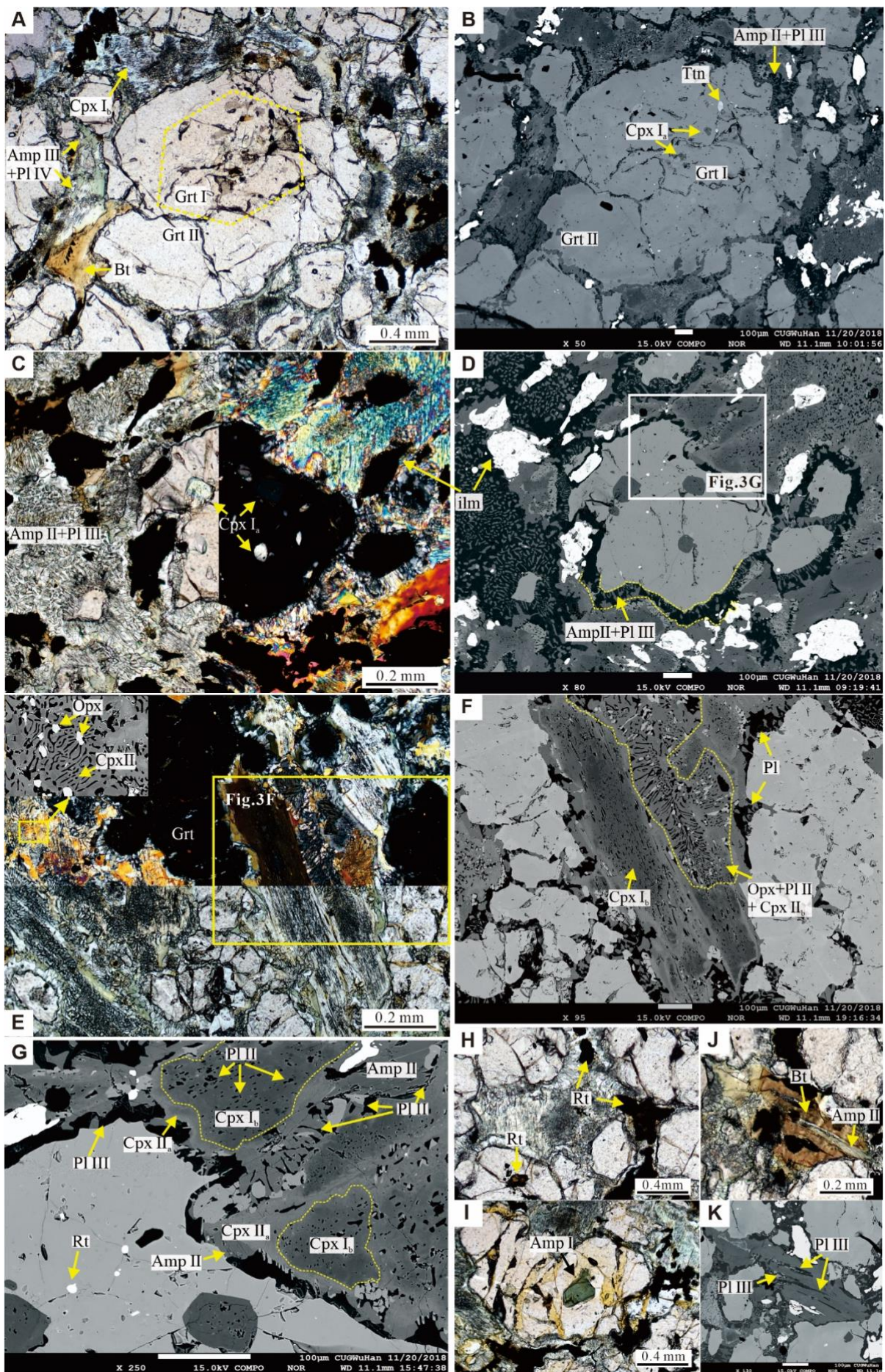
141 The Central East Kunlun arc-accretionary complex belt is represented by the 540–460 Ma Early
142 Paleozoic ophiolite, the 550–390 Ma arc volcanic and sedimentary rocks, widely regarded as a
143 subduction-collision suture zone (Dong et al., 2018; Li et al., 2018b; Meng et al., 2015b; Yang et al.,
144 2004; Zhou et al., 2020). Eclogite facies rocks are sporadically distributed in the Xiarihamu in the
145 west, and Kehete and Wenquan areas in the east, forming a >500 km HP–UHP metamorphic belt

146 (Meng et al., 2013b; Qi et al., 2014; Qi et al., 2016b). Recently, coesite-bearing UHP metamorphic
147 rocks were discovered in the Kehete area in the eastern segment (Fig. 1B)(Bi et al., 2018; Bi et al.,
148 2020).

149 Eclogites were newly found at the Nuomuhong valley approximately 150 km SE from Golmud
150 city in the central segment of the HP–UHP metamorphic belt in East Kunlun (Fig. 1B). Lithologies
151 at Nuomuhong are comprised mainly of granitic gneiss, eclogite, and amphibolite with minor
152 marble composition (Figs. 1C and 2). Eclogite occurs as lenses or blocks of 5–15 meters in diameter
153 enclosed in the host gneiss of the Paleoproterozoic Jinshuikou Group (Figs. 1C and 2A, C). The
154 eclogite has mainly been retrogressed (Fig. 2B, F) and at places, amphibolite can be found at the
155 outer edge of the eclogite block (Fig. 2B). The Amphibolite occurs as massive or foliated structures,
156 with some intercalated marble lenses/slices (Fig. 2D). In a ~500-meter-long cross-section from east
157 to west along the Nuomuhong valley, dozens of eclogite and/or retrograde eclogite were sampled
158 from three eclogite blocks (Figs. 1C and 2D). Three samples (LH3–2, LH3–4 and LH3–5) were
159 selected for detailed petrographic observations and mineral chemistry analyses. In addition, the
160 eclogite sample LH3–4 was performed for phase equilibrium modeling and SHRIMP U–Pb dating.
161 The host felsic gneiss shows a granoblastic texture and consists of mainly plagioclase, potassium
162 feldspar, quartz and biotite, with minor garnet (Fig. 2C–E). Twelve samples including 10 retrograde
163 eclogites and 2 garnet amphibolites were selected for whole-rock major and trace element analyses.
164 Mineral abbreviations are after Whitney and Evans (2010).



Figure 2. Field photographs of eclogite at Nuomuhong, in East Kunlun. (A) Eclogite block enclosed in the host felsic gneiss. (B) Eclogite retrograded to amphibolite at edges. The red dashed line marks the boundary between the retrograde eclogite and amphibolite. (C) The red dashed line showing the boundary between retrograde eclogite and the host felsic gneiss. (D) Marble intercalated in amphibolite that shows a foliated structure. (E) The host felsic gneiss consisted mainly of felsic minerals, biotite and garnet. (F) The retrograde eclogite consisted of mainly garnet, clinopyroxene, amphibole and quartz.



173 **Figure 3.** Photomicrographs of representative eclogites at Nuomuhong, EKOB. (A) A large garnet
 174 porphyroblast from the eclogite LH3–5 showing apparent zoning with abundant inclusions in the reddish
 175 core and minor in the light rim. Amphibole (Amp II), plagioclase, ilmenite and biotite (Bt) developed around
 176 the garnet. (B) Backscattered electron image (BSE) of the garnet porphyroblast in panel A showing
 177 inclusions of titanite (Ttn) and omphacite (Cpx I_a) in the core. (C–D) Corona of plagioclase (Pl III) +
 178 amphibole (Amp II) ± ilmenite (LH3–4) around a relict garnet porphyroblast with inclusions of omphacite
 179 (Cpx I_a). Symplectite of plagioclase (III) + amphibole develops in the matrix; (E–F) Symplectite of
 180 orthopyroxene (Opx)+ plagioclase (Pl II) around relict omphacite in matrix from the sample LH3–4. Corona
 181 of symplectite amp II + Pl develops around relict garnet and low-sodic clinopyroxene (Cpx II_a; light-colored
 182 in BSE) develops around relict omphacite porphyroblast (Cpx I_b; dark-colored in BSE). (G) Locally enlarged
 183 BSE image in panel D showing transition from relict omphacite porphyroblast (Cpx I_b; with no Opx) to
 184 clinopyroxene porphyroblast (Cpx II_b; with Opx), then to symplectite of Amp II + Pl II; (with Opx). Corona
 185 of plagioclase (Pl III) + amphibole (Amp II) rims garnet; (H) Rutile inclusions in garnet or in matrix from the
 186 sample LH3–2, showing partial replaced by ilmenite; (I) Amphibole (Amp I) included in garnet from sample
 187 LH3–2. (G–K) Plane-polarized photo with corresponding BSE image showing Biotite around amphibole
 188 (Amp II) from sample LH3–5.

190 **PETROLOGY**

191 **Petrography and Mineral Compositions**

192 Representative minerals were analyzed using a JEOL JXA–8230 electron probe micro-analyzer
 193 (EPMA) in China University of Geosciences (Wuhan). The detailed analytical method and results
 194 listed in Supplementary Text and [Table S1-S6](#), respectively. The Nuomuhong EKOB eclogites are

generally characterized by a massive structure with porphyroblastic/granoblastic texture. They comprise mainly 30–40 vol.% garnet, 25–30 % clinopyroxene, 15–20 % amphibole, 10–15 % plagioclase and 2–5 % biotite, with minor 2–5 % orthopyroxene and 1–3 % quartz, and accessory rutile/ilmenite, apatite, titanite and zircon (Fig. 3).

Garnet

Euhedral to subhedral 0.2–2.0 mm grain size crystals typically characterize the porphyroblastic garnet minerals in representative sample LH3-2, LH3-4 and LH3-5. The garnet crystals typically contain a greater amount of omphacite, rutile/ilmenite/titanite, epidote + plagioclase, amphibole and quartz inclusions in the reddish core, compared to the light-colored rim (Fig. 3A, B; Fig. 4C). These observations are consistent with an apparent core-rim structure revealed by back-scattered electronic (BSE) photos (Fig. 3A, B; Fig. 4B). The garnet minerals commonly show an embayed texture and tend to be replaced by amphibole, plagioclase and an ilmenite corona (Fig. 3A-D, G). In places, aggregated epidote minerals and albite develop as inclusions in the garnet (Fig. 4C).

A chemical profile for one large garnet porphyroblast in the eclogite sample LH3-4 shows clear compositional zonation for almandine, pyrope, grossular and spessartine (Fig. 4D, E). From core to rim, $X_{\text{Alm}} [= \text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg} + \text{Ca} + \text{Mn})]$ increases from 0.55 to 0.61, and then decreases to 0.52; $X_{\text{Grs}} [= \text{Ca}/(\text{Fe}^{2+} + \text{Mg} + \text{Ca} + \text{Mn})]$ decreases slightly from 0.32 to 0.28, before a sharp increase to 0.34 and then decreases again to 0.28; $X_{\text{Prp}} [= \text{Mg}/(\text{Fe}^{2+} + \text{Mg} + \text{Ca} + \text{Mn})]$ increases from 0.05 to 0.18; and $X_{\text{Sps}} [= \text{Mn}/(\text{Fe}^{2+} + \text{Mg} + \text{Ca} + \text{Mn})]$ decreases from 0.09 to <0.01. The X_{Sps} profile shows a classic bell-shaped zoning pattern, interpreted to represent growth zonation.

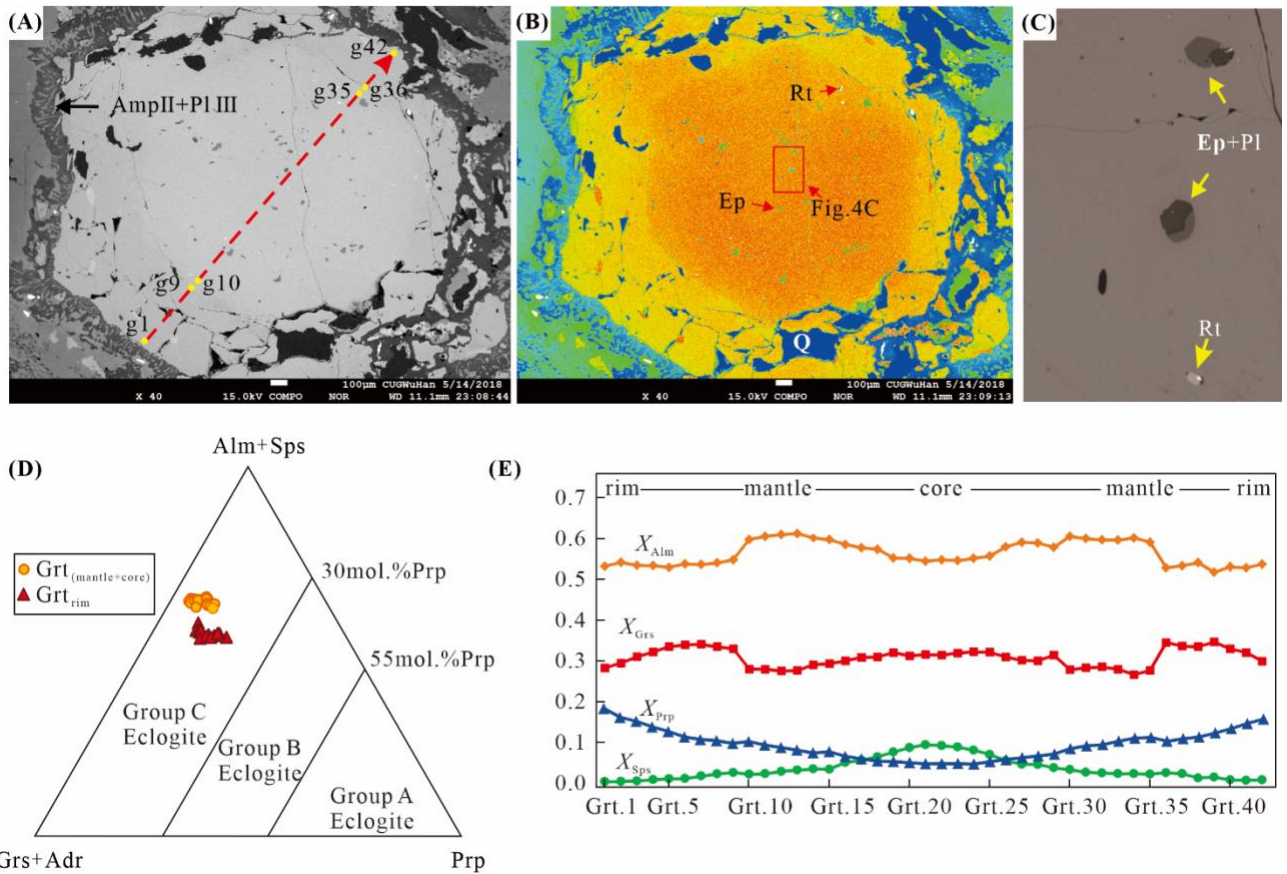


Figure 4. (A–B) BSE photographs of a large porphyroblastic garnet (LH3-4). The red dashed line represents cross section analysis by EPMA. (C) Enlarged photo in panel B with aggregated inclusions of Ep + Pl. (D) Diagram showing compositional variations of garnet. Both Grt_(mantle+core) (Grt I) and Grt_{rim} (Grt II) are suggested to belong to group C-type according to Coleman et al. (1965). (E) Zoning profile of X_{Alm} , X_{Sps} , X_{Prp} and X_{Grs} across garnet in the eclogite samples LH3-4 from Nuomuhong.

Clinopyroxene

Based on variations of occurrences and mineral compositions, clinopyroxene in sample LH3-4 show the following 4 archetypal subdivisions: (1) Cpx I, omphacite present as Cpx I_a, inclusions in garnet (Figs. 3C-D) or as Cpx I_b matrix rock-forming minerals (Figs. 3A and 3C–3E). Most of Cpx I_b phases are partially replaced by low-sodium clinopyroxene and plagioclase-containing symplectite. Cpx I_a generally has higher Jd content than Cpx I_b (Fig. 5A); (2) Cpx II occurs as Cpx

229 II_a together with plagioclase-constituting symplectite Cpx I_b rims, or as Cpx II_b together with
230 orthopyroxene and plagioclase replacing Cpx II_a. The Cpx II_a phases generally possess a higher Jd
231 composition with lower MgO and FeO contents than Cpx II_b (Table S2-S3, Fig. 5B). Both Cpx II_a
232 and Cpx II_b have lower SiO₂ and Jd component, but higher MgO and FeO concentration than Cpx I
233 (Table S2-S3, Fig. 5B). Away from Cpx I, Cpx II presents a lighter color in BSE images (Figs. 3E
234 and 3F), showing increasing Wo enrichment (Fig. 5B).

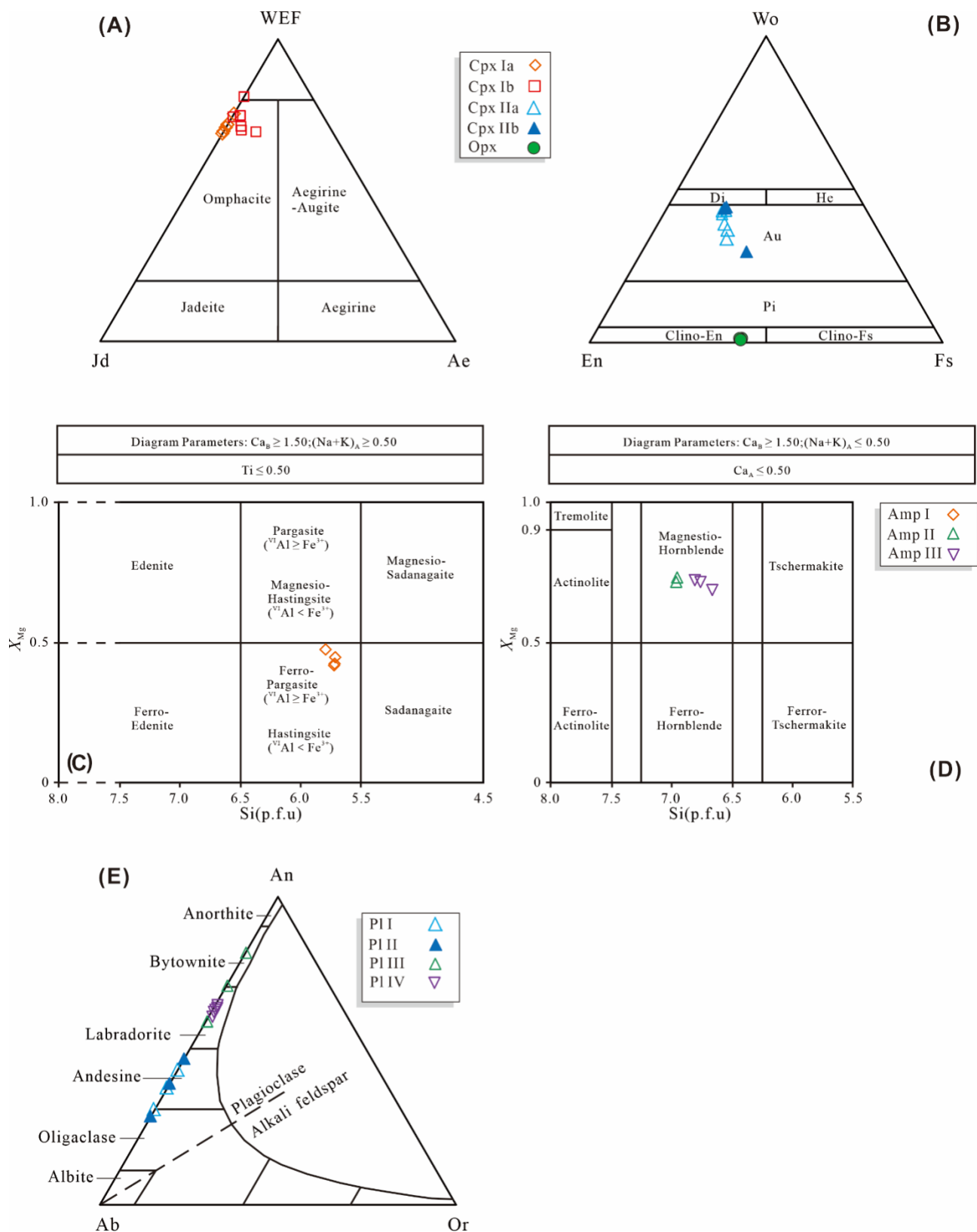


Figure 5. Mineral chemistry diagrams. (A–B) Ternary classification diagrams for clinopyroxene from the Nuomuhong eclogites, after Morimoto (1988); (A) Classification diagram for Quad–Jd–Ae; (B) Classification diagram for Wo–En–Fs. (C–D) Classification diagrams for amphiboles for the Nuomuhong

239 eclogite, after [Leake et al. \(2004\)](#) and [Song et al. \(2018b\)](#). (E) Ab–An–Or diagram showing the
 240 composition of plagioclase, after [Smith \(1974\)](#); $Ab = X_{Na} = Na / (Ca + K + Na)$; $An = X_{Ca} = Ca / (Ca + K + Na)$; Or
 241 $= X_K = K / (Ca + K + Na)$.

Stage Mineral	M ₁	M ₂	M ₃	M ₄	M ₅
Grt					
Omp					
Cpx					
Opx					
Amp					
Bt					
Pl					
Rt					
ilm					
Phn					

242
 243 **Figure 6.** Sequences of mineral assemblages for different metamorphic stages. Solid lines indicate minerals
 244 present in the samples, whereas the dashed line refers to inferred minerals.

245

246 *Amphibole*

247 Amphibole in sample LH3–4 occurs as inclusions ([Fig. 3I](#)) in garnet (Amp I), or together with
 248 plagioclase as corona ([Fig. 3C–3E](#)) around garnet (Amp II), or as rock-forming minerals in matrix
 249 (Amp III, [Figs. 3A and 3B](#)). Amp I exhibits a lower Si content of 5.71–5.72 (p.f.u.) with a higher
 250 ^{IV}Al composition of 2.22–2.29 (p.f.u.). Its Mg[#] [= (Mg/(Mg+Fe²⁺))] of 0.42–0.45 and (Na+K)_A ≤
 251 0.50 (p.f.u.), corresponds to ferro-pargasite ([Fig. 5C](#)) according to [Leake et al. \(1997\)](#). Compared to
 252 Amp I, a higher Si content of 6.95–6.96 (p.f.u.) and lower ^{IV}Al content of 1.04–1.05 (p.f.u.),
 253 characterizes Amp II. Both Amp II and Amp III have similar Mg[#] of 0.69–0.72 and (Na+K)_A ≤ 0.50
 254 (p.f.u.), indicative of a magnestio-hornblende composition ([Table S4, Fig. 5D](#)).

255

256 ***Plagioclase***

257 Plagioclase occurs either as inclusions in garnet (Fig. 4C), or together with matrix amphibole,
258 clinopyroxene and/or orthopyroxene (Fig. 3D, G). When included in garnet, plagioclase (LH3-2, Pl
259 I) co-exists with epidote, constituting composite inclusions and is albite (Fig. 4C). Matrix
260 plagioclase (LH3-4, Pl II) either forms symplectite after omphacite (Fig. 3E, F, G), or occurs
261 together with Amp II in the corona surrounding garnet (LH3-5, Pl III) (Fig. 3D, G). In places, large
262 LH3-2 Pl IV plagioclase shows texture equilibration with Amp III amphibole (Fig. 3A). On the
263 other hand, An₂₈₋₄₇Ab₅₃₋₇₂ Pl II plagioclase has an oligoclase-andesine affinity, whereas the An₆₁₋
264 ₆₄Ab₃₆₋₃₉ Pl III and An₆₀₋₈₂Ab₁₈₋₄₀ Pl IV forms, characterized by higher An values, are related to
265 labradorite (Fig. 5E, Table S5).

267 ***Orthopyroxene***

268 Fine-grained matrix Opx (LH3-2) develops mainly in association with Pl II and Cpx II_b-
269 containing symplectite after Cpx II_a (Fig. 3E-3G). In the Wo-En-Fs diagram, Opx is shown to
270 belong to hypersthene with X_{En} of 56.3-56.9 and X_{Fs} of 41.8-42.4 (Table S6, Fig. 5B).

272 ***Minor minerals***

273 The occurrence of minor fine-grained biotite in the matrix (LH3-4) and around garnet (Fig. 3A) or
274 amphibole (Fig. 3J), is interpreted to represent the formation of phengite during early
275 metamorphism (Fig. 6). Epidote and anorthosite exist as composite inclusions in garnet but absent
276 in the matrix (Fig. 4C). Rutile, partially replaced by ilmenite/titanite, is present both as inclusions in
277 garnet and in the matrix (Figs. 3H and 4C).

278

279 **Minerology and metamorphic stages**

280 Based on petrographic observations and mineral compositions, the following five mineral
281 assemblages can be inferred for the eclogite at Nuomuhong, east Kunlun: (1) M₁ prograde
282 metamorphic stage amphibole eclogite facies evidenced by Cpx I_a + Amp I + Rt + Ep + Qz
283 inclusions in garnet core and mantle/garnet core-mantle compositions; (2) Metamorphic M₂ peak
284 stage eclogite facies evidenced by Grt rim, matrix rock-forming Cpx I_b, Rt and quartz. Omphacite
285 inclusions in zircons from Group #2 (Fig. 7) are further inferred to belong to metamorphic peak
286 stage mineral assemblage; (3) Early retrograde metamorphic stage high-pressure granulite facies
287 (M₃), is substantiated by Cpx II_a with low Jd symplectite content and plagioclase (Pl II) rimming
288 Cpx I_b; (4) Subsequent retrograde metamorphic stage medium-pressure granulite facies (M₄)
289 represented by garnet surrounding Opx coronas and Opx + Pl II + Cpx II_b replacing Cpx II_a
290 symplectite; (5) Later retrograde metamorphic stage amphibolite facies (M₅) indicated by Amp II
291 and Pl II garnet-surrounding intergrowth and large-grained matrix Pl IV and Amp III. In addition,
292 Ilm replacing Rt and the occurrence of matrix Bt (replacing phengite), likely formed at this stage
293 (Fig. 6).

294

295 **METAMORPHIC *P–T* CONDITIONS**

296 In this study, to reconstruct the metamorphic *P–T* path for eclogite formation at Nuomuhong,
297 we selected representative eclogite LH3–4 samples for further study based on the progressive
298 growth zonation retained in porphyroblastic garnet and the relatively complete mineral sequences
299 recorded in these samples. We use both conventional geothermobarometry and phase equilibrium

modelling to constrain P – T conditions for different metamorphic stages.

Conventional Geothermobarometry

Conventional geothermobarometry, including the garnet–clinopyroxene (Grt–Cpx) thermometry (Ravna, 2000), the Al-in-hornblende barometry (Schmidt, 1992) combined with the amphibole–plagioclase (Amp–Pl) thermometry (Holland and Blundy, 1994), and the two-pyroxene thermometry (Wood, 1973) were used for P – T estimates for different stage mineral assemblages. P – T conditions for prograde stage (M_1) metamorphism calculated using the Grt–Cpx thermometry on garnet-core (Grt I) composition, and omphacite (Cpx I_a), indicate formation at metamorphic pressure >14 kbar and temperature of 470–506 °C. Grt–Cpx thermometry on garnet rim (Grt II) and matrix omphacite (Cpx I_b), suggest peak stage metamorphism (M_2) occurred at a temperature range of 525–585 °C at a pressure of 20 kbar according to previous studies on eclogite from the EKOB (Meng et al., 2015b; Qi et al., 2014; Qi et al., 2016b; Song et al., 2018b). Calculated retrograde stage (M_4) metamorphic temperature of 860–900 °C using the two-pyroxene thermometry and compositions of orthopyroxene (Opx) and low-sodic clinopyroxene (Cpx II_b), assumes a medium pressure of 6 kbar. The P – T conditions for late retrograde stage metamorphism (M_5) using Al-in-hornblende barometry, Amp–Pl thermometry and compositions of large matrix amphibole (Amp III) and plagioclase (Pl IV), point to formation at ~6 kbar and 710–730 °C (Fig. 6).

Phase Equilibrium Modelling

Phase diagrams were drawn using the updated March 2014 THERMOCALC software version 3.40, and the November 2016 updated version of the associated internally consistent

thermodynamic dataset ds62 (Holland and Powell, 2011). The NCKFMASHTO system Na₂O–CaO–K₂O–FeO–MgO–Al₂O₃–SiO₂–H₂O–TiO₂–O chemical composition was selected for analysis, with *a*–*x* relationships implemented as follows: amphibole and clinopyroxene (Green et al., 2016); garnet, phengitic muscovite and biotite (White et al., 2014); epidote (Holland and Powell, 2011). Rutile, lawsonite, quartz and H₂O were considered to be in the pure phase. Bulk rock XRF composition was used for modelling after correction of CaO, SiO₂, Al₂O₃ contents for the P₂O₃ and MnO contained in apatite and spessartine. Fe₂O₃ was determined by wet chemistry. The corrected bulk composition in mol% used in phase equilibrium modeling was SiO₂ (51.99), Al₂O₃ (8.51), CaO (11.82), MgO (11.21), FeO (12.26), K₂O (0.11), Na₂O (2.17), TiO₂ (0.92) and O (1.0). H₂O was assumed to be in excess, considering the abundance of various hydrous mineral inclusions (e.g., epidote and amphibole) in garnet.

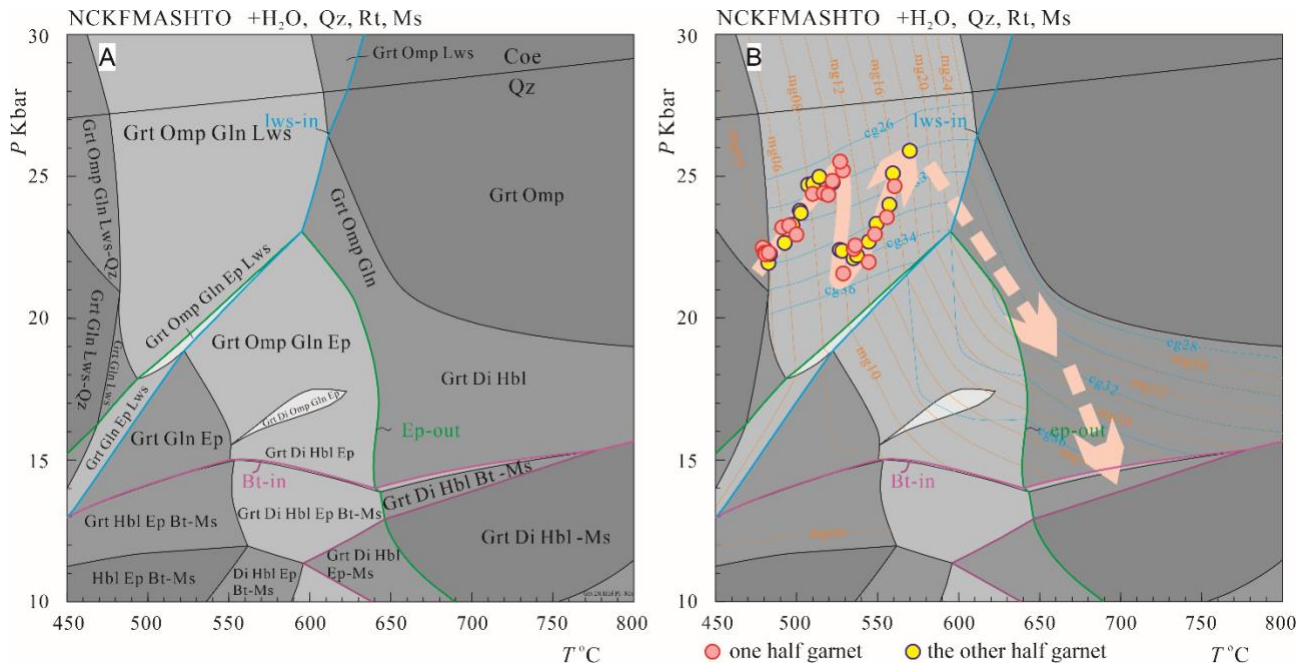


Figure 7. (A) *P*–*T* pseudosection for eclogite LH3–4 at Nuomuhong in the NCKFMASHTO system. Mineral abbreviations follow Thermocalc dataset (B). cg and mg represent calculated isopleths for grossular [Ca/(Ca+Mg+Fe+Mn)] and pyrope [Mg/(Ca+Mg+Fe+Mn)] endmembers in garnet, respectively. For instance,

337 mg06 denotes 0.06 pyrope and cg26 0.26 grossular. Mineral abbreviations are after [Whitney and Evans](#)
338 [\(2010\)](#).

339 The P – T pseudosection for the retrograde eclogite LH3–4 had a P – T range of 10–30 kbar and
340 450–800 °C ([Fig. 7](#)). Figure 8A places the phase assemblage fields of lawsonite at 12–30 kbar and
341 400–600 °C and epidote at 10–23 kbar and 400–635 °C. Lawsonite is replaced by epidote at P < 23
342 kbar and T of < 595 °C, and by garnet and omphacite at T > 595 °C and P > 17.5 kbar. In the phase
343 assemblage fields of $\text{Grt} + \text{Omp} (\text{Di}) + \text{Gln} (\text{Hbl}) \pm \text{Ep} + \text{Qz} + \text{Rt} + \text{Ms} + \text{H}_2\text{O}$, glaucophane
344 gradually changes to hornblende and omphacite to diopside at decreasing pressure. The replacement
345 of muscovite by biotite in the phase assemblage fields occurs at a P range of 14–15.5 kbar before
346 being replaced again by hornblende and clinopyroxene at T > 595 °C. Isopleths for 26–36 mol% Grs
347 and 5–26 mol% Prp in garnet have been calculated for the P – T range related to the Gln (Hbl)-
348 bearing and Ms-bearing phase assemblage fields ([Fig. 7B](#)). In the law-bearing phase assemblage
349 fields, isopleths for Grs in garnet have gentle to moderate positive slopes with Grs values
350 decreasing with pressure, whereas isopleths of Prp in garnet have almost vertical slopes with Prp
351 values increasing with temperature. In the law-absent phase assemblage fields, isopleths for Grs in
352 garnet have vertical to moderate negative slopes with Grs values tending to decrease with rising
353 temperature, whereas the garnet Prp isopleths have moderate negative slopes with Prp values
354 increasing simultaneously with temperature.

355 The observed M₂ peak stage mineral assemblage corresponds to the modelled field with the
356 phase assemblage of $\text{Grt} + \text{Omp} (\text{Di}) + \text{Gln} (\text{Hbl}) + \text{Qtz} + \text{Rt} + \text{Ms} + \text{H}_2\text{O}$ at 14.0–26.5 kbar and
357 595–800 °C. However, isopleths for the measured Grs and Prp content in garnet (27–35 mol% and
358 5–18 mol%, respectively) yield P – T conditions of 21.5–26 kbar and 480–570 °C in the phase

359 assemblage field of Grt + Omp + Gln + Lws + Qtz + Rt + Ms + H₂O (Fig. 7B). Both muscovite and
360 lawsonite were not detected in the thin section. The modelled muscovite content in this phase
361 assemblage field was <1.5 mode%. Its low contents may be the reason for non-detection by thin
362 section analysis; or may be pointing to complete retrograde transformation to biotite during the late
363 stage metamorphism as evidenced by the presence of matrix biotite (Fig. 3A, J). Lawsonite may
364 have been present in the peak mineral assemblage but was subsequently replaced by amphibole and
365 clinopyroxene with increasing exhumation T and or was replaced by epidote due to effective bulk
366 rock composition in confined equilibration volume (Wei et al., 2010). Aggregates of Ep + Ab
367 (potentially originating from paragonite) as inclusions in garnet may be pseudomorphs produced
368 after lawsonite (Fig. 4C). Both situations correlate with dehydration reactions and may be easily
369 triggered when T increases or P decreases. The inferred presence of lawsonite during prograde
370 metamorphism has previously been reported in many HP/UHP eclogite terrane based on composite
371 inclusions of Ep/Zo \pm Pg/Ab in garnet (Wei et al., 2010; Hamelin et al., 2018). For instance, in
372 western Dabie, epidote inclusions, coupled with paragonite, was interpreted to reflect the former
373 presence of lawsonite (Wei et al., 2010). In this study, because of intense retrogression during post-
374 eclogite facies stages, the eclogite at Nuomuhong has been strongly retrograded with most garnet
375 porphyroblast replaced by later stage mineral aggregates (e.g., amphibole, plagioclase and ilmenite).
376 However, the well-preserved garnet growth zoning for a carefully selected garnet porphyroblast
377 indicates the prograde information could have been potentially preserved in this refractory mineral.
378 Using phase equilibrium modeling and compositional isopleth geothermobarometry, we interpret
379 the P – T regime of 21.5–26 kbar and 480–570 °C for lawsonite stability to represent possible
380 prograde stage P – T conditions.

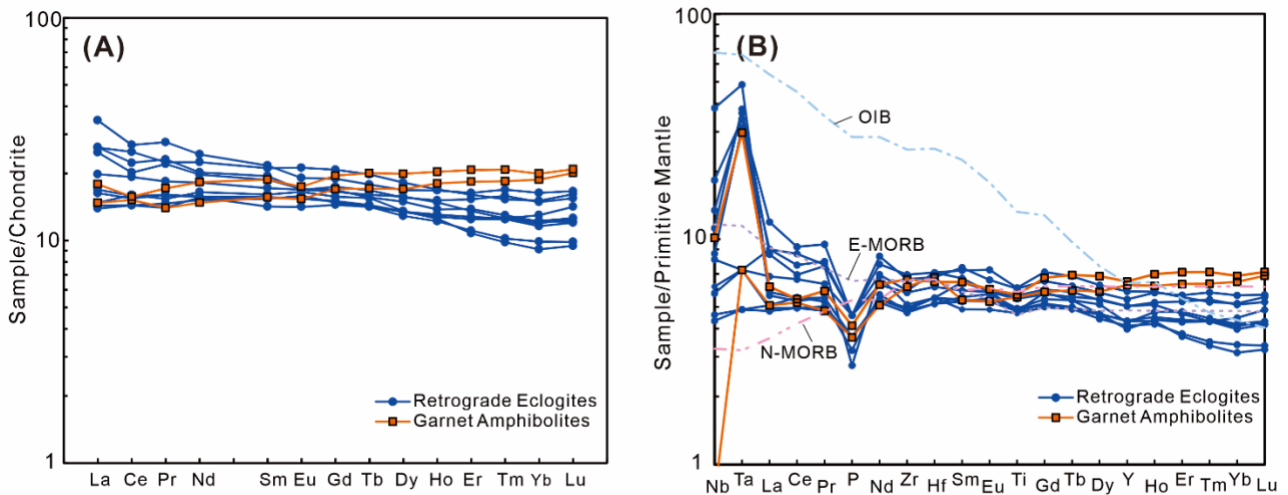
Therefore, the inferred peak mineral assemblage of Grt + Omp + Amp + Qz + Rt at the M₂ stage to correspond to the modelled phase assemblage field of Grt + Omp + Gln + Lws + Qz + Rt + Ms + H₂O at *P* of 21.5–26 kbar and *T* of 480–570 °C. Glaucophane may have been gradually replaced by Na-poor amphibole during decompression. Amphibole inclusion in garnet with higher Na content than that in the matrix, may be assumed as support for this conclusion. Besides, variations of endmembers across the garnet could be indicative of two-stage garnet porphyroblast growth with various *P–T* evolutions, first controlled by increasing pressure and temperature, followed by a second rise in pressure and temperature and then by an eventual decrease in pressure (Fig. 7B). During initial exhumation, lawsonite decomposed and the *P–T* path crossed the modelled phase assemblage of Grt + Omp (Di) + Gln (Hbl) + Qz + Rt + Ms + H₂O with *P–T* conditions of 14.0–26.5 kbar and 595–800 °C. Further exhumation led to the transition of muscovite to biotite and omphacite to diopside and plagioclase, which may correspond to the modelled phase assemblage field of Grt + Di + Hbl + Qz + Rt + Bt + H₂O with *P–T* conditions of 13.0–15.5 kbar and 645–775 °C. However, with a change in the effective bulk rock composition due to the presence of garnet, this *P–T* regime remains uncertain. *P–T* conditions for the formation of orthopyroxene have not been constrained for the change of effective bulk rock composition.

397

398 **WHOLE-ROCK GEOCHEMISTRY**

The analytical procedure for whole rock geochemistry determination is listed in the Supplementary Text, and the results in Supplementary Table S7. The data show that the retrograde eclogites at Nuomuhong are basaltic in composition. They possess low SiO₂ (48.33–51.07 wt.%), high Al₂O₃ (13.39–15.37 %) and CaO contents (10.39–12.75 %), and moderate TiO₂ (1.02–1.32 %)

403 and Cr (154–290 ppm) compositions. On the AFM [(Na₂O+K₂O) –FeO^T–MgO] diagram, all data
 404 fall in the tholeiite series field (Fig. 11E). The retrograded eclogites are relatively low in total rare
 405 earth elements abundance (ΣREEs =36.31–59.19 ppm). On the chondrite-normalized REE diagram
 406 (Fig. 8A), they exhibit nearly flat to enriched REE patterns, without significant Eu anomalies
 407 (δEu =0.91–1.05) and are slightly enriched LREE, with La_N/Yb_N ratios of 1.17–2.21. By contrast,
 408 the garnet amphibolites exhibit slight LREEs depletion (La_N/Sm_N=0.79–0.90). Primitive mantle-
 409 normalized trace element analysis (Fig. 8B), suggests the retrograde eclogites are strongly enriched
 410 in Nb and Ta but depleted in Zr and Ti. On the other hand, the garnet amphibolites are enriched with
 411 Zr, with Nb–Ta showing significant positive anomalies relative to La.



412
 413 **Figure 8.** (A) Chondrite-normalized REE distribution patterns. (B) Plots for primitive mantle-normalized
 414 retrograde eclogites and garnet amphibolites. The chondrite and primitive mantle values are from (Sun and
 415 McDonough, 1989).

416

417 ZIRCON U-Pb DATING

418 Zircon grains from the LH3–4 eclogite display a euhedral to subhedral morphology, with a
 419 tendency to be rounded, being 70–130 μm in length. The majority of the zircons are homogeneous

or show weak or sector zonation in cathodoluminescence (CL) images (Figs. 9A, B), a typical characteristic of a metamorphic origin (Corfu et al., 2003; Wang et al., 2013b; Wu and Zhen, 2004). Some grains have core-rim structures (Fig. 9A), broad zonation and contrast bright cores taken to indicate residual cores that survived metamorphic alteration.

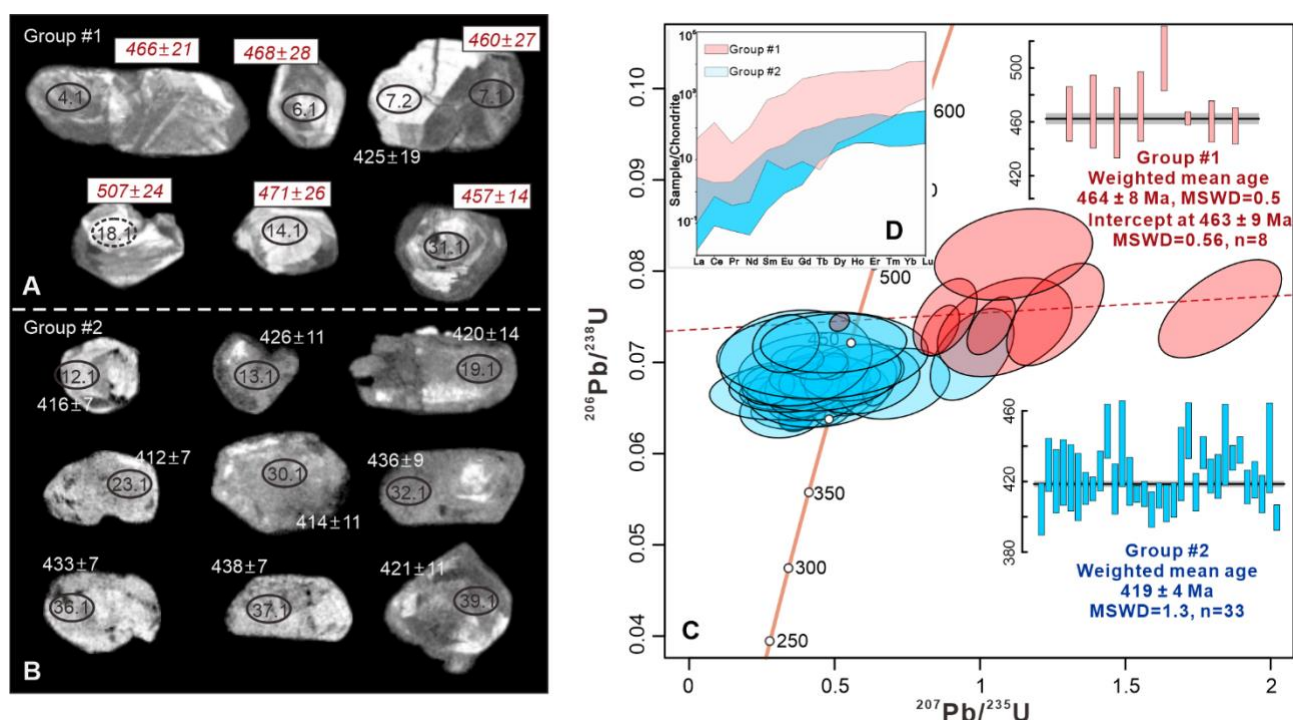


Figure 9. (A–B) Zircon CL images, (C) SHRIMP U–Pb age concordia diagram and weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages, and (D) Chondrite-normalized REE distribution patterns for the Nuomuhong retrograde eclogite LH3–4.

A total of 45 analyses were obtained by SHRIMP dating (Table S8). The Th and U contents of most samples are low, with Th/U ratios <0.1 . A majority of the analyses contain near flat heavy REE (HREE) patterns in the chondrite normalized diagram (Fig. 9D). A few of the zircons reveal Th/U ratios >0.1 , interpreted as an attribute of the dissolution of Th-enriched minerals such as epidote, under HT conditions (Hermann, 2002; Yu et al., 2013b). The weighted mean of $^{206}\text{Pb}/^{238}\text{U}$ ages represented two groups, with Group #1 consisting of 8 analyses yielding an intercept age of

463±9 Ma with an MSWD of 0.56 and an identical weighted mean age of 464±8 Ma with an MSWD of 0.5 (Fig. 9C). Group #2, comprised of 33 analyses, yielded a weighted mean age of 419±4 Ma with an MSWD of 1.3 (Fig. 9C). The laser Raman spectroscopy of the inclusions in the second group zircons indicate a omphacite and garnet composition, suggesting that the Group #2 zircons represent a lower age limit for when peak eclogite facies metamorphism occurred (Figs. 10A–10C).

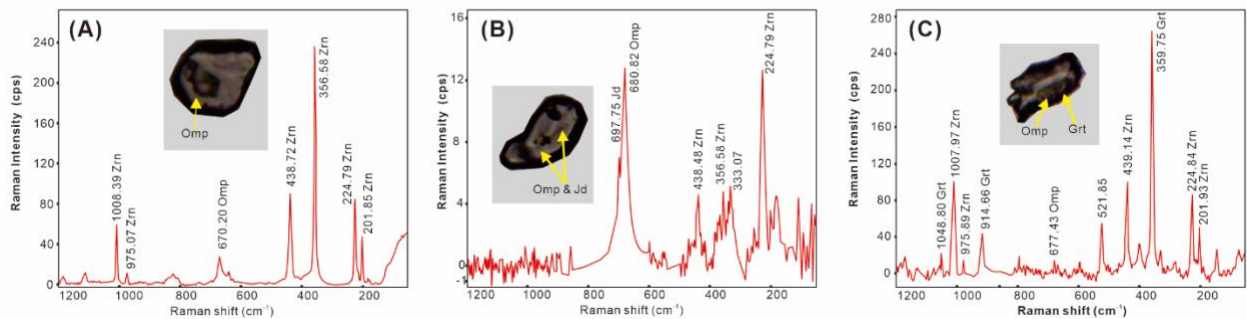


Figure 10. Raman spectra of (A) omphacite (Omp) inclusions, (B) omphacite/jadeite inclusions, and (C) garnet (Grt) and omphacite inclusions in Group #2 zircon (Zrn) grains from the Nuomuhong retrograde eclogite, middle East Kunlun orogen.

DISCUSSION

Constraints on the Timing of Metamorphism

Two distinct metamorphic age groups of 464±9 Ma (MSWD=0.5) and 419±4 Ma (MSWD=1.3) were obtained from the Nuomuhong eclogites (Figs. 9). The first-group zircons possess core–rim structures with broad zoning and core contrast brightness suggestive of potential residual metamorphic zircons. Though most of the zircons from these two groups yielded low Th/U ratios, the first group shows a progressive increase in HREE patterns from Dy to Lu (Fig. 9D). We

interpret the first group of zircon age to approximate the age of eclogite protoliths, which is similar to the 520–460 Ma age inferred for regional ophiolite formation in this setting (Qi et al., 2016c) and the 471–454 Ma magmatic events of Proto-Tethys oceanic crust subduction (Fu et al., 2022b).

In contrast, the second-group zircons have typical morphological and textural characteristics of metamorphic zircons (Wu and Zheng, 2004), with similarly extremely low Th/U ratios (Table S8). During metamorphic recrystallization, Th is more likely to be expelled from the zircon lattice than U, accounting for the relatively low Th/U ratios observed. Laser Raman spectroscopy analyses of the inclusions in the second-group zircons reveals the presence of typical eclogite facies minerals like omphacite and garnet, indicating a younger age for the Group #2 zircons compared to peak-pressure metamorphism. The nearly flat HREE patterns further suggests these zircons grew in relatively high-pressure conditions in the presence of garnet (Fig. 9D). Therefore, we interpret the younger 419 ± 4 Ma age as the lower age limit for peak eclogite facies metamorphism. This age is consistent with previously reported (near) peak ages of 428–411 Ma for eclogites in other localities in the EKOB (Bi et al., 2020; Guo et al., 2020; Jia et al., 2014; Meng et al., 2013b; Pan and Zhang, 2020; Qi et al., 2014; Qi et al., 2016b; Song et al., 2018b; Tang et al., 2022; Wang et al., 2012; Wang, 2020). In summary, our SHRIMP zircon U-Pb data suggest that the protoliths of the Nuomuhong eclogites could have been formed at ~464 Ma, after which they experienced eclogite facies metamorphism prior to 419 ± 4 Ma, coincident with protolith and metamorphic ages from regional EKOB eclogites.

Tectonic Affinity of Protoliths of the Eclogites

Although eclogites may undergo complex prograde and retrograde metamorphic processes, the

474 study of eclogites in many orogenic belts indicate that the activity of external fluids did not cause
475 obvious element migration, especially for the HFSE and REE (Wang et al., 2013a). In this study,
476 the low loss on ignition of <0.38 and the relatively coherent patterns in the normalized REE and
477 trace element diagrams (Figs. 8A and 8B), suggest limited modification of most elements in the
478 Nuomuhong eclogites. Here we use the fluid-immobile elements to fingerprint the tectonic
479 protoliths of the Nuomuhong eclogites.

480 The Nuomuhong eclogites have low SiO_2 in the range of 48.57–51.07 wt.%, and moderate
481 1.04–1.32 wt.% TiO_2 , 6.43–8.77 wt.% MgO and 154–290 ppm Cr contents, similar to tholeiitic
482 basalts. In the normalized REE and trace element diagrams, most of the eclogite samples have near-
483 flat and slightly enriched LREE, a characteristic reminiscent of N-MORB and E-MORB (Figs. 8A
484 and 8B). The low Zr/Y ratios preclude an intra-plate origin, as supported by the Zr vs. Zr–Y cross
485 plot (Fig. 11A). Tectonic discrimination utilizing exemplary HFSEs and REEs such as Nb, Ta, La,
486 Ce, Yb and Y, allude to a majority of the samples converging on E-MORB and N-MORB within the
487 MORB–OIB array (Figs. 11B–D), an indication of their derivation from MORB-type oceanic crust.
488 These observations demonstrate that the protoliths of the Nuomuhong eclogites are essentially
489 subducted MORB-like oceanic crust basalt or gabbro, similar to oceanic crust-derived eclogites in
490 the eastern segment of the EKOB locality (Song et al., 2018b).

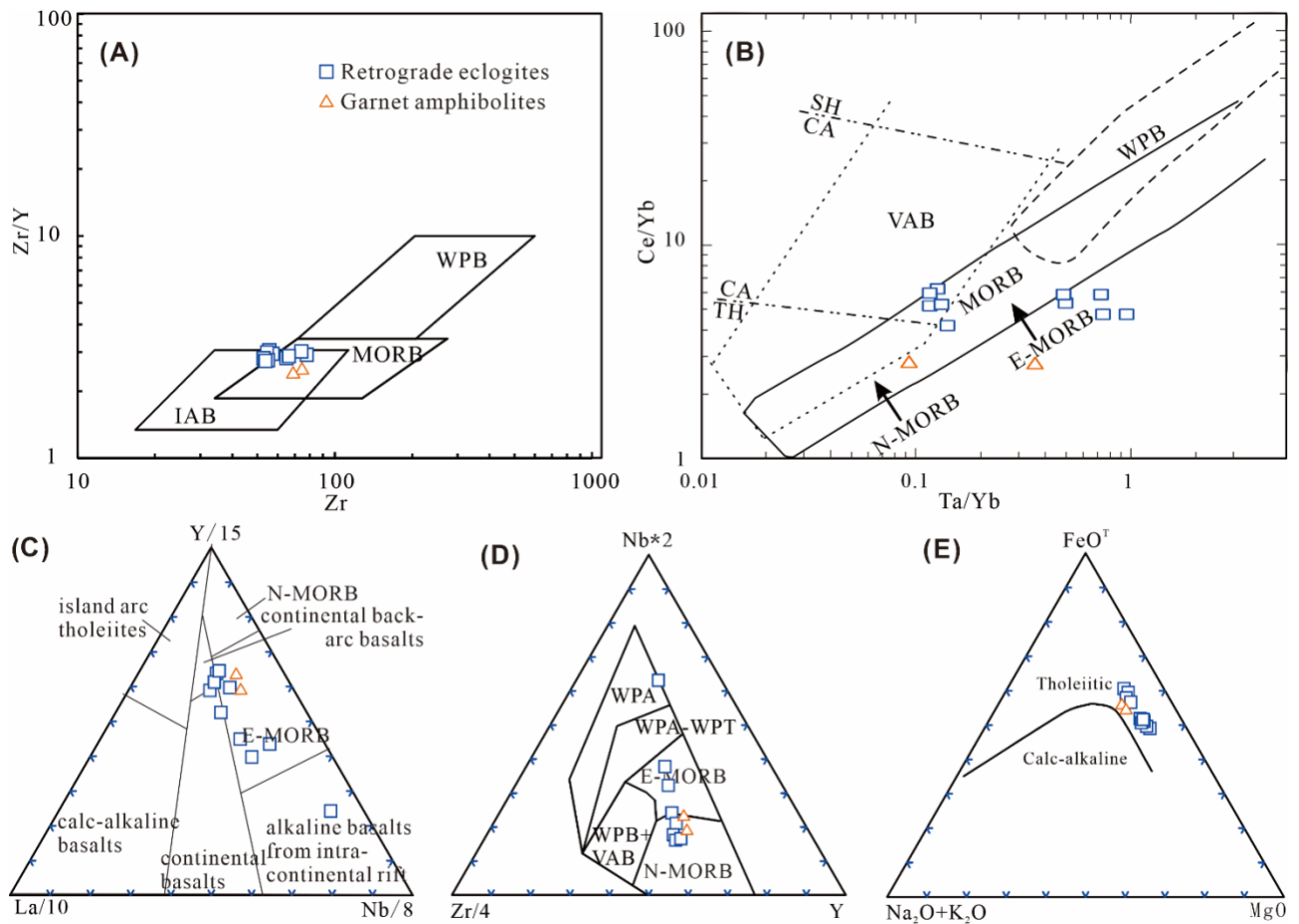
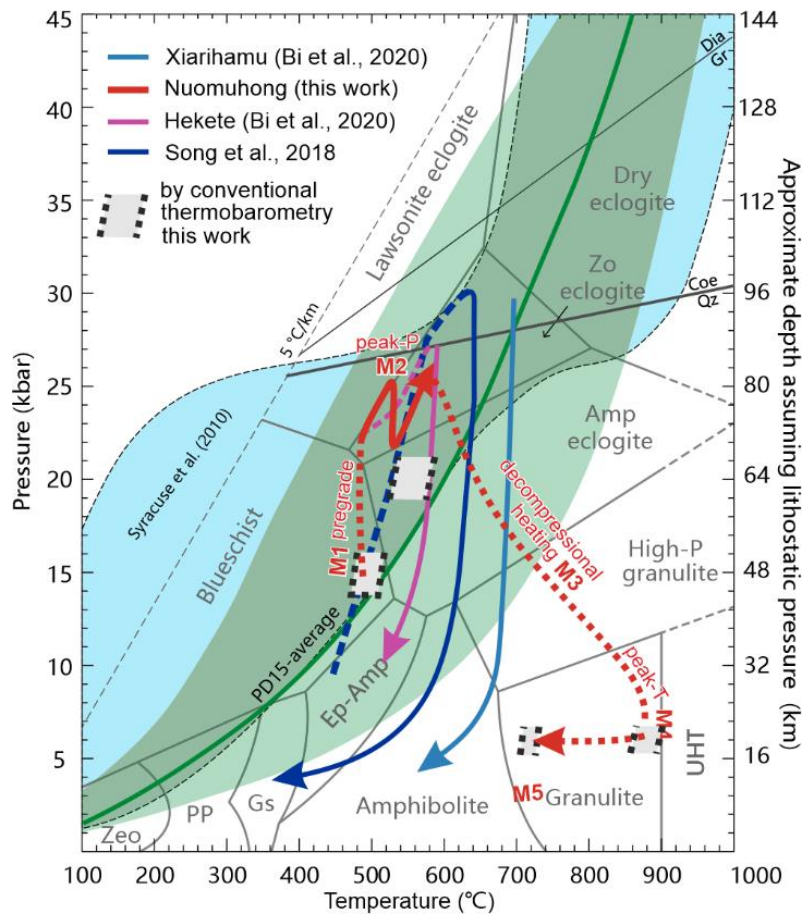


Figure 11. Tectonic discrimination diagrams (A–D) for the retrograde eclogite. (A) Zr–Zr/Y diagram (Pearce and Norry, 1979); (B) Ce/Yb–Ta/Yb diagram (Pearce, 1982); (C) Y–La–Nb diagram (Cabanis and Lecolle, 1989); (D) Nb–Zr–Y diagram (Meschede, 1986); (E) AFM diagram (Irvine and Baragar, 1971). W corresponds to CA–calc-alkaline, MORB–mid-ocean ridge basalt, SH–shoshonitic, TH–tholeiitic, VAB–volcanic arc basalt, WPB–within plate basalt.

Metamorphic records for the oceanic subduction and continental collision in the northern Proto-Tethys

Based on petrographic observations, conventional geothermobarometry and phase equilibrium modelling, five metamorphic stages and associated P – T conditions were determined for the Nuomuhong eclogites, namely: (1) the prograde M_1 stage with P – T conditions of >14.0 kbar/~470–

503 506°C; (2) the peak-*P* M₂ eclogite facies stage at ~26 kbar *P* and ~570°C *T*; (3) the early M₃
504 retrograde high-*P* granulite facies stage; (4) the subsequent (M₄ retrograde medium-*P* granulite
505 facies stage with peak *T* at ~860–900°C at 6 kbar; and (5) the later M₅ retrograde amphibolite facies
506 stage at <6.2 kbar *P* and ~710–730°C *T*. These *P*–*T* estimates define a clockwise *P*–*T* path
507 characterized by heating decompression from the *P*_{max} stage of eclogite facies formation to the
508 *T*_{max} stage for the granulite facies, followed by a final decompressional cooling stage to
509 amphibolite facies (Fig. 12).



510
511 **Figure 12.** The *P*–*T* path for the Nuomuhong eclogite in this study, compared with eclogite in the eastern
512 segment of the East Kunlun orogen from Song et al. (2018b). Boundaries for various metamorphic facies,
513 High-*P* granulite, UHT metamorphic facies according to Schreyer (1988), Syracuse et al. (2010), and
514 Maruyama et al. (1996). Abbreviations and phase equilibria are after Liou et al. (2004).

515

516 As already mentioned, the protoliths of the eclogite lithologies are interpreted to be subducted
517 MORB-type oceanic crust, a fossil of the East Kunlun branch of the Proto-Tethys Ocean. The
518 metamorphic change from M₁ prograde to M₂ peak-*P* eclogite facies at pressures of up to ~26 kbar,
519 indicates that the oceanic crust was subducted down to ~83 km (Fig. 13A). This conclusion
520 considers a lithostatic pressure of 1 kbar \approx 3.2 km, where the eclogites underwent subduction zone
521 *HP* metamorphism. The estimated *P*–*T* conditions for the peak-*P* stage Nuomuhong eclogites,
522 corresponding to an apparent thermal gradient of ~220 °C/GPa, is a typical feature of generalized
523 <375 °C/GPa low *T/P* geothermal subduction zones (Xia et al., 2022a). Locally, subduction of the
524 oceanic crust under UHP condition resulted in the production of the coesite pseudomorphs recorded
525 in the eastern EKOB rocks (Bi et al., 2018; Song et al., 2018b). Phase equilibrium modelling
526 suggests that both the core and garnet rim minerals suggest a two phase increase in pressure and
527 temperature conditions that ended with a reversed drop in pressure (Fig. 13C). The decompression
528 process likely records a failed exhumation attempt that was followed by further burial, as
529 demonstrated by the second segment of prograde evolution. In subduction channels, HP/UHP rock-
530 bearing mélanges formed and evolved with different fates, including 1) successful exhumation to a
531 shallow level accretionary complex, or 2) failed exhumation and subduction into the mantle.
532 Multiple cycles of *P* increase during a single orogenic event, interpreted to represent burial-partial
533 exhumation cycles, have been reported in eclogite from the Alps (Rubatto et al., 2011), western
534 Dabie (Xia et al., 2022b) and the western Tianshan (Li et al., 2016) HP/UHP orogens. These cycles
535 could have arisen because of convective flow in the subduction channel (Zheng et al., 2012).
536 Therefore, M₁ and M₂ metamorphism of the Nuomuhong eclogites preserve thermal state history of

537 a Proto-Tethyan subduction zone and a complicated account of a Proto-Tethyan ocean crust
538 subduction event during accretionary orogenesis.

539 The peak-*P* stage was followed by M₃ retrograde high-*P* granulite facies metamorphism and M₄
540 medium-*P* granulite facies, characterized by the symplectite Cpx II + Pl II rimming Cpx I_b, and the
541 symplectite Opx + Pl II rimming Cpx II. The calculated peak temperatures of ~860–900°C at ~6
542 kbar indicate that eclogite was exhumed to the middle crust level, undergoing decompressional
543 heating in the process. The high *T* metamorphic overprint on eclogite has not been recognized in
544 other localities in the EKOB, implying that the Nuomuhong eclogite may have stayed in the middle
545 crust for a sustained amount of time before final exhumation to the Earth surface. Such a situation
546 was recently recognized in southern Tibet (Wang et al., 2021), where high-*T* overprinting of
547 eclogite facies is regarded as metamorphic evidence of initial to mature stage continental collision.
548 During the maturation of continental collision, the structural, magmatic, and metamorphic response
549 changes significantly in the orogen. Firstly, the orogenic belt significantly thickens due to tectonic
550 compression and continuous subduction of the down going continental lithosphere. Secondly, the
551 subducting oceanic slab breaks off, leading to the buoyant exhumation of the deeply subducted
552 continental crust to the middle-shallow level. In some circumstances, the change of geometry of
553 orogenic wedges, experienced in mainly foreland basin sequences, accretionary and arc complexes,
554 hampers the exhumation of HP/UHP rocks, resulting to persistence in the middle crust. In addition,
555 slab break-off and crustal thinning promoted by upwelling of the asthenosphere, results in the
556 eventual underplating of a large volume of mafic magma in the lower crust, leading to intense
557 partial melting of crustal rocks and the generation of collision-related felsic magmatism. The
558 underplating during collision-related magmatism acts as a potential heat source for the high-*T*

559 metamorphism that overprints previously exhumed HP/UHP metamorphic rocks (Fig. 13B).

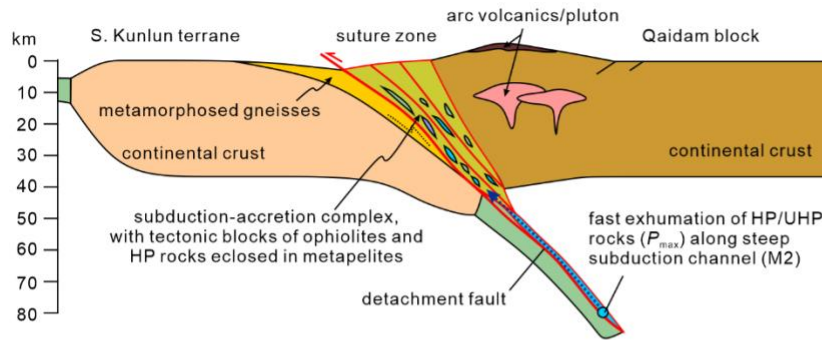
560 Therefore, the Nuomuhong eclogites preserve a long-term record for early subduction-accretionary
561 to later collisional orogenesis.

562

563 **Implications for the evolution of the East Kunlun branch of the Proto-Tethys Ocean**

564 In the Qilian–Qaidam–Kunlun area along the northern margin of the Tibetan Plateau, several
565 Early Paleozoic sutures separating microcontinental blocks and/or arc terranes were distributed
566 between the northern Gondwana and combined Tarim–North China cratons, terminating in the
567 ultimate closure of the Proto-Tethys Ocean (Fu et al., 2022a; Li et al., 2018c; Song et al., 2018a;
568 Zhao et al., 2018). The remnants of the Proto-Tethys Ocean preserved in northern Tibet can be
569 divided into the Qilian Ocean and North Qilian backarc in the north, the South Qilian Ocean in the
570 middle, and the East Kunlun Ocean in the south, separated by the Central Qilan and Qaidam blocks
571 (Fig. 13D), respectively (Song et al., 2018a). The detailed evolutionary history from continental
572 rifting during the break of Rodinia, oceanic subduction-accretion, terrane accretion/collision and
573 final continental collision, remains debated (Fu et al., 2019; Fu et al., 2018; Song et al., 2018b;
574 Song et al., 2014; Wu et al., 2021; Wu et al., 2020; Wu et al., 2019; Xiao et al., 2009; Zuza et al.,
575 2017). The EKOB contains complex geological units related to continental rifting, oceanic
576 subduction and continental collision, providing an excellent window for evidencing the evolution of
577 the Proto-Tethys Ocean and associated orogenesis (Song et al., 2018b).

A) Initial collision with fast exhumation of HP/UHP rocks (ca. 430 Ma)



B) Mature collision with granulite facies overprinting (ca. 420 Ma)

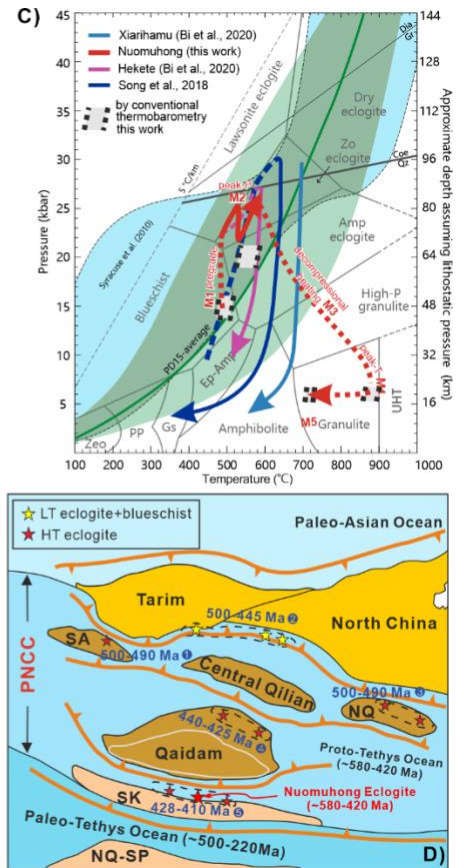
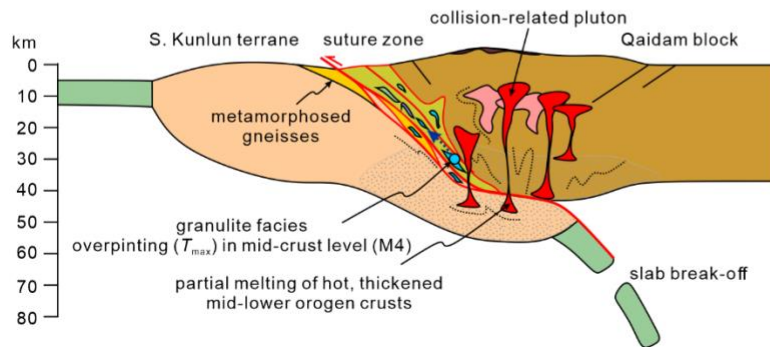


Figure 13. Tectonic model for the Eastern Kunlun orogen and the Proto-Tethys Ocean.

The continental rifting, supported by meta-gabbro in the south Jinshui Kou Group in East Kunlun, yielded 796 ± 41 Ma formation age (Ren et al., 2011). These data suggest that the East Kunlun began breaking up no later than 796 ± 41 Ma, the Qingshuiquan ophiolite at 522 ± 4 Ma and 518 ± 3 Ma, the Tatuo ophiolite at 522 ± 3 Ma, and the Buqingshan Delisitai MOR-ophiolite at 516 ± 6 Ma (Liu et al., 2011b). The Early Paleozoic 535 ± 10 Ma MOR-gabbro in the Maji Mountain area (Li, 2008), contains ample evidence for the formation of the East Kunlun oceanic crust (Lu et al., 2002; Yang et al., 1996). Subsequently, during the start of the late-Cambrian, the Kunlun Ocean began to subduct northward, with a series of magmatic and metamorphic events associated with this subduction event. The 507 ± 8 Ma Qingshuiquan granulite in the central East Kunlun Suture zone and the 480 ± 3 Ma Yaziquan island-arc diorite in the Qimantag Mountains (Cui et al., 2011; Li et al.,

2006), are an expression of these magmatic and metamorphic activities in the center and North Kunlun areas. Moreover, the time of formation of the 515 ± 4 Ma quartz diorite in the Kekesha area in Dulan, signifies the start of ocean basin subduction (Zhang et al., 2010b). During this time, the East Kunlun area stretched into several extensional oceanic or back-arc basins, as the oceanic crust was in a state of continuous expansion (Qi et al., 2016a).

From the late Ordovician to the early Silurian, the uninterrupted extension and distribution of back-arc basins in the Central East Kunlun zone continued with persistent and abundant magmatic activity (Chen et al., 2016). This conclusion is exemplified by the distribution of 448 ± 4 Ma basaltic-dacitic lavas near Central East Kunlun, including the deposition of the Bairiqiete intermediate acidic rock suite that formed island-arc granodiorites marked by the 441 ± 6 Ma and the 438 ± 3 Ma island-arc rhyolite porphyry, the 440 ± 6 Ma Yikehalaer granodiorites of typical adakite geochemical characteristics (Li et al., 2014; Liu et al., 2011a), the 447 ± 9 Ma metamorphosed diorite in the southern Xiangride area and the 450 ± 4 Ma rhyolite in the Nachita Group (Zhang et al., 2010c). The diagenesis of arc magma occurred in response to oceanic crust subduction, while the 445 ± 5 Ma SHRIMP ages for the Dagele ophiolite gabbro probably denote the ultimate subduction of the Proto-Tethys oceanic crust (Du et al., 2017).

After middle-late Silurian, final closure of the Kunlun branch of the Proto-Tethys Ocean, resulted into continental subduction and collisional orogeny. The high angle thrust nappe deformation in the East Kunlun Fault zone records a 426–408 Ma age for this event (Wang et al., 2003b), and marks the disappearance of the island arc environment alongside contemporaneous early Paleozoic collisional orogenic activity. There are a great deal of medium-late Silurian to early Devonian collisional granites (Li et al., 2013; Liu et al., 2012). These granites are typified by the

613 425±7 Ma Helegangnaren A-type alkali feldspar granite, the 407±3 Ma Yuejinshan granodiorite, the
614 423±5 Ma syn-collisional granite from the Changshishan mélange belt, distributed between the
615 north Kunlun and the southern margin of the Qaidam block. Collectively, these lithologies are
616 identical with this tectonic environment, while the presence of the 428–411 Ma Nuomuhong
617 eclogite and others in the East Kunlun record the ensuing continental subduction and collisional
618 orogeny.

619 We propose that when the Kunlun Ocean crust subducted towards the north and under the
620 southern margin of the Qaidam Block during the Early Paleozoic before 440 Ma, the continental
621 basaltic protolith of the East Kunlun eclogites formed in a continental margin setting, were
622 impacted by oceanic crust subduction. The high-amphibolite to granulite facies metamorphism
623 owing to tecto-thermal events of oceanic crust subduction, is associated with the prograde minerals
624 assemblage of the Nuomuhong eclogites and the 460 Ma Jinshuikou Group gneissic lithologies
625 (Zhang et al., 2003). After the early Silurian continental subduction and collisional orogeny closure
626 of the Proto-Tethys Ocean, the protolith of the Jinshuikou Group basement mafic rocks were buried
627 down to >100 km depth in the subduction channel. Evidence of HP-UHP metamorphism, in
628 addition to the eclogite facies, is supported by the intercalation of the country rocks with eclogites
629 (Bi et al., 2020).

630 When the East Kunlun orogenic belt began its post-collisional extension in the middle-late
631 Silurian, the eclogites were exhumed onto the shallow crust. The slight 430–411 Ma timing gap for
632 the accumulation of these eclogites in East Kunlun (Meng et al., 2013b; Qi et al., 2014; Qi et al.,
633 2016a; Song et al., 2018b), is probably attributed to uneven timing and speed of exhumation in
634 different parts of the enormous orogenic belt, accompanied by internal asymmetric subduction

635 suturing (Bi et al., 2022), evidenced by eclogites in the eastern and western Kunlun outcrops.
636 Eventually the molasse sedimentary assemblage of the Devonian Maoniushan group signified the
637 end of the early Paleozoic Proto-Tethys Ocean tectonic cycle in East Kunlun and the beginning of
638 the new cycle of ocean-continental evolution associated with the North Paleo-Tethys Ocean (Chen
639 et al., 2008b; Li et al., 2013).

640 The discovery of the Nuomuhong eclogite constrained the timing of transition from continental
641 subduction to collision in the early Devonian and formed a super HP-UHP metamorphic belt with
642 other eclogite outcrops in the EKOB block. This assemblage represents an excellent example of an
643 early Paleozoic continental convergence boundary between the Qaidam Block and the East Kunlun
644 Massif, which is of great significance for furthering the understanding, formation, and evolution of
645 the Proto-Tethys system.

646

647 CONCLUSION

648 (1) Retrograde eclogites with garnet and omphacite formed during partial tectonic
649 decompression, characterizes the Nuomuhong area in the eastern part of the East Kunlun orogenic
650 belt. The retrograde eclogites underwent prograde, eclogite, HP granulite, granulite, and
651 amphibolite facies metamorphisms, along a P – T clockwise pathway: (1) the M1 prograde stage with
652 P – T conditions of >14.0 kbar/ ~ 470 – 506°C ; (2) the peak- P eclogite facies stage (M2, ~ 26
653 kbar/ $\sim 570^{\circ}\text{C}$); (3) the early retrograde high- P granulite facies stage (M3); (4) the subsequent
654 retrograde high- T granulite facies stage (M4) with peak T at ~ 860 – 900°C at a pressure of 6 kbar;
655 and (5) the later retrograde amphibolite facies stage (M5, < 6.2 kbar/ ~ 710 – 730°C). The
656 orthopyroxene associated with eclogite in EKOB revealed that the Nuomuhong eclogites

experienced granulite metamorphism different from the other eclogites in EKOB.

(2) The protolith of the Nuomuhong eclogite with slight LREE enrichment has MOR basalt-like geochemical signatures. Zircon U–Pb analyses and Raman spectrometer show the peak metamorphism or early exhumation formed at 419 ± 4 Ma (MSWD=1.3). The zircon cores ages yielding 464 ± 4 Ma (MSWD=0.5) recorded the protolith ages of Nuomuhong eclogite rather than the Middle Ordovician tectonic-thermal events associating with the metamorphic ages of Jinshuikou Group.

(3) The oceanic crust of East Kunlun Ocean, the southern part of Proto-Tethys Ocean, formed before the middle Cambrian and began to subduct northward after initial late-Cambrian. From the late Ordovician to the early Silurian, the back-arc basins distributing along the Central East Kunlun continued extending with abundant magmatic activities. After middle-late Silurian, the Kunlun Ocean, a branch of Proto-Tethys Ocean, had closed finally and transformed into the continental subduction and collisional orogeny. The presence of Nuomuhong eclogite and other eclogites ($428\text{--}411$ Ma) in East Kunlun also recorded the continental subduction and collisional orogeny. Finally, the later Devonian molasse sedimentary assemblage represented the end of the Proto-Tethys evolution and the beginning of Paleo-Tethys evolution in East Kunlun. The discovery of Nuomuhong eclogite formed a HP-UHP metamorphism belt with other eclogite dew points in East Kunlun.

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682

683 **REFERENCES**

- 684 Bi, H., Song, S., Dong, J., Yang, L., Qi, S., and Allen, M. B., 2018, First discovery of coesite in eclogite from East Kunlun,
685 northwest China: Science Bulletin, v. 63, no. 23, p. 1536-1538.
- 686 Bi, H., Whitney, D., Song, S., and Zhou, X., 2022, HP–UHP eclogites in the East Kunlun Orogen, China: P–T evidence for
687 asymmetric suturing of the Proto-Tethys Ocean: Gondwana Research, v. 104, p. 199-214.
- 688 Bi, H. Z., Song, S. G., Yang, L. M., Allen, M. B., Qi, S. S., and Su, L., 2020, UHP metamorphism recorded by coesite-
689 bearing metapelite in the East Kunlun Orogen (NW China): Geological Magazine, v. 157, no. 2, p. 160-172.
- 690 Bingen, B., Davis, W. J., and Austrheim, H., 2001, Zircon U-Pb geochronology in the Bergen arc eclogites and their
691 Proterozoic protoliths, and implications for the pre-Scandian evolution of the Caledonides in western Norway:
692 Geological Society of America Bulletin, v. 113, no. 5, p. 640-649.
- 693 Cabanis, B., and Lecolle, M., 1989, Le diagramme La/10Y/15Nb/8: un outil pour la discrimination des sries volcaniques
694 et la mise en vidence des procsses de mlanges et/ou de contamination crus-tale: CR Acad. Sci., Sr, v. 2, p. 2023-
695 2029.
- 696 Chen, J. J., Fu, L. B., Wei, J. H., Tian, N., Xiong, L., Zhao, Y. J., and Qi, Y. Q., 2016, Geochemical characteristics of Late
697 Ordovician granodiorite in Gouli Area, Eastern Kunlun Orogenic Belt, Qinghai Province: Implications on the
698 Evolution of Proto-Tetys Ocean.: Earth Science, v. 41, no. 11, p. 1863-1882.
- 699 Chen, N., Sun, M., Wang, Q., Zhang, K., Wan, Y., and Chen, H., 2008a, U-Pb dating of zircon from the Central Zone of
700 the East Kunlun Orogen and its implications for tectonic evolution: Science in China Series D: Earth Sciences, v.
701 51, no. 7, p. 929-938.
- 702 Chen, N. S., Sun, M., Wang, Q. Y., Zhang, K. X., Wan, Y. S., and Chen, H. H., 2008b, Zircon U-Pb dating and tectonic
703 evolution implications in the central belt of East Kunlun Orogenic Belt SCIENCE CHINA Earth Sciences, v. 38, no.
704 6, p. 657-666.

705 Chen, X., Xu, R. K., Zheng, Y. Y., Wang, Y. K., Wang, H. J., Bai, J., Du, W. Y., and Lu, R., 2015, The determination of peak
706 temperature of eclogites in the west of Tieshiguan area, North Qaidam UHP of Qinghai Province, and its
707 geological significance: *Geological Bulletin of China*, v. 34, no. 12, p. 2292-2301.

708 Chen, Y. X., Pei, X. Z., Li, R. B., Liu, Z. Q., Li, Z. C., Zhang, X. F., Chen, G. C., Liu, Z. G., Ding, S., and Guo, J., 2011, Zircon U-
709 Pb Age of Xiaomiao Formation of Proterozoic in the Eastern Section of the East Kunlun Orogenic Belt:
710 *GEOSCIENCE*, v. 25, no. 3, p. 510-521.

711 Coleman, R. G., Lee, D. E., Beatty, L. B., and Brannock, W. W., 1965, Eclogites and Eclogites: Their Differences and
712 Similarities: *Geological Society of America Bulletin*, v. 76, no. 5, p. 483.

713 Corfu, F., Hanchar, J. M., Hoskin, P. W. O., and Kinny, P., 2003, Atlas of Zircon Textures: Reviews in Mineralogy and
714 Geochemistry, v. 53, no. 1, p. 469–500.

715 Cui, M. H., Meng, F. C., and Wu, X. K., 2011, Early Ordovician island arc of Yaziquan, west of Qimantag Mountain, East
716 Kunlun: evidences from geochemistry, Sm-Nd isotope and geochronology of intermediate-basic rocks: *Acta*
717 *Petrologica Sinica* v. 27, no. 11, p. 3365-3379.

718 Dobretsov, N. L., 1991, Blueschists and eclogites: a possible plate tectonic mechanism for their emplacement from the
719 upper mantle: *Tectonophysics*, v. 186, no. 3-4, p. 253–268.

720 Dong, Y. P., He, D. F., Sun, S. S., Liu, X. M., Zhou, X. H., Zhang, F. F., Yang, Z., Cheng, B., Zhao, G. C., and Li, J. H., 2018,
721 Subduction and accretionary tectonics of the East Kunlun orogen, western segment of the Central China
722 Orogenic System: *Earth-Science Reviews*, v. 186, p. 231-261.

723 Du, W., Jiang, C., Xia, M., Xia, Z., Zhou, W., Ling, J., Wang, B., and Yu, S., 2017, A newly discovered Early Paleozoic
724 ophiolite in Dagele, Eastern Kunlun, China, and its geological significance: *Geological Journal*, v. 52, p. 425-435.

725 Feng, D., Wang, C., Song, S., Xiong, L., Zhang, G., Allen, M. B., Dong, J., Wen, T., and Su, L., 2023, Tracing tectonic
726 processes from Proto- to Paleo-Tethys in the East Kunlun Orogen by detrital zircons: *Gondwana Research*, v.

727 115, p. 1-16.

728 Fu, C. L., Yan, Z., Guo, X. Q., Niu, M. L., Cao, B., Wu, Q., Li, X., and Wang, Z. Q., 2019, Assembly and dispersal history of
729 continental blocks within the Altun-Qilian-North Qaidam mountain belt, NW China: International Geology
730 Review, v. 61, no. 4, p. 424-447.

731 Fu, D., Huang, B., Johnson, T. E., Wilde, S. A., Jourdan, F., Polat, A., Windley, B. F., Hu, Z., and Kusky, T., 2022a, Boninitic
732 blueschists record subduction initiation and subsequent accretion of an arc–forearc in the northeast Proto-
733 Tethys Ocean: Geology, v. 50, no. 1, p. 10-15.

734 Fu, D., Kusky, T., Wilde, S. A., Polat, A., Huang, B., and Zhou, Z., 2018, Early Paleozoic collision-related magmatism in the
735 eastern North Qilian orogen, northern Tibet: A linkage between accretionary and collisional orogenesis: GSA
736 Bulletin, v. 131, no. 5-6, p. 1031-1056.

737 Fu, L., Bagas, L., Wei, J., Chen, Y., Chen, J., Zhao, X., Zhao, Z., Li, A., and Zhang, W., 2022b, Growth of early Paleozoic
738 continental crust linked to the Proto-Tethys subduction and continental collision in the East Kunlun Orogen,
739 northern Tibetan Plateau: GSA Bulletin.

740 Green, E. C. R., White, R. W., Diener, J. F. A., Powell, R., Holland, T. J. B., and Palin, R. M., 2016, Activity-composition
741 relations for the calculation of partial melting equilibria in metabasic rocks: Journal of Metamorphic Geology,
742 v. 34, no. 9, p. 845-869.

743 Guo, F., Wang, P., Wang, Z., and Feng, N., 2020, Geochemical and geochronology characteristics of retrograde eclogite
744 in Xiarihamu area, East Kunlun Mountains, and its geological implications: Sedimentary Geology and Tethyan
745 Geology, v. 40, no. 4, p. 45-55.

746 Han, L., Zhang, L., and Zhang, G., 2015, Ultra-deep subduction of Yematan eclogite in the North Qaidam UHP belt, NW
747 China: Evidence from phengite exsolution in omphacite: American Mineralogist, v. 100, no. 8-9, p. 1848-1855.

748 He, D. F., Dong, Y. P., Liu, X. M., Yang, Z., Sun, S. S., Cheng, B., and Li, W., 2016, Tectono-thermal events in East Kunlun,

749 Northern Tibetan Plateau: Evidence from zircon U–Pb geochronology: *Gondwana Research*, v. 30, p. 179-190.

750 Hermann, J., 2002, Allanite: Thorium and light rare earth element carrier in subducted crust: *Chemical Geology*, v. 192,

751 no. 3, p. 289-306.

752 Hertgen, S., Yamato, P., Morales, L., and Angiboust, S., Brittle/Ductile deformation at depth during continental crust

753 eclogitization (Mont-Emilius klippe, Western Internal Alps), *in* Proceedings EGU General Assembly

754 Conference2016, Volume 18.

755 Holland, T., and Blundy, J., 1994, Non-ideal interactions in calcic amphiboles and their bearing on amphibole-

756 plagioclase thermometry: *Contributions to Mineralogy and Petrology*, v. 116, no. 4, p. 433-447.

757 Holland, T. J. B., and Powell, R., 2011, An improved and extended internally consistent thermodynamic dataset for

758 phases of petrological interest, involving a new equation of state for solids: *Journal of metamorphic Geology*, v.

759 29, no. 3, p. 333-383.

760 Irvine, T. N., and Baragar, W. R. A., 1971, A Guide to the Chemical Classification of the Common Volcanic Rocks:

761 *Canadian Journal of Earth Sciences*, v. 8, no. 5, p. 523-548.

762 Jia, L. H., Meng, F. C., and Feng, H. B., 2014, Fluid activity during eclogite-facies peak metamorphism: Evidence from a

763 quartz vein in eclogite in the East Kunlun, NW China: *Acta Petrologica Sinica*, v. 30, no. 8, p. 2339-2350.

764 Jiang, C. F., Yang, J. S., Feng, B. G., Zhu, Z. Z., Zhao, M., Chai, Y. C., Shi, X. D., Wang, H. D., and Hu, J. Q., 1992, Opening-

765 Closing Tectonics of Kunlun Mountains, Beijing, Geological Publishing House Geol. Memo. Series 5.

766 Klonowska, I., Janák, M., Majka, J., Froitzheim, N., and Kościńska, K., 2016, Eclogite and garnet pyroxenite from Stor

767 Jougdan, Seve Nappe Complex, Sweden: implications for UHP metamorphism of allochthons in the

768 Scandinavian Caledonides: *Journal of Metamorphic Geology*, v. 34, no. 2, p. 103-119.

769 Leake, B. E., Woolley, A. R., Arps, C. E., Birch, W. D., Gilbert, M. C., Grice, J. D., Hawthorne, F. C., Kato, A., Kisch, H. J.,

770 and Krivovichev, V. G., 1997, Nomenclature of amphiboles; report of the Subcommittee on Amphiboles of the

771 International Mineralogical Association Commission on new minerals and mineral names: Mineralogical
 772 magazine, v. 61, no. 405, p. 295-310.

773 Leake, B. E., Woolley, A. R., Birch, W. D., Burke, E. A., Ferraris, G., Grice, J. D., Hawthorne, F. C., Kisch, H. J., Krivovichev,
 774 V. G., and Schumacher, J. C., 2004, Nomenclature of amphiboles: additions and revisions to the International
 775 Mineralogical Association's amphibole nomenclature: Mineralogical Magazine, v. 68, no. 1, p. 209-215.

776 Li, B. S., Yan, M. D., Zhang, W. L., Fang, X. M., Yang, Y. P., Zhang, D. W., Chen, Y., and Guan, C., 2018a, Paleomagnetic
 777 Rotation Constraints on the Deformation of the Northern Qaidam Marginal Thrust Belt and Implications for
 778 Strike-Slip Faulting Along the Altyn Tagh Fault: Journal of Geophysical Research: Solid Earth, v. 123, no. 9, p.
 779 7207-7224.

780 Li, H. K., Lu, S. N., Xiang, Z. Q., Zhou, H. Y., Guo, H., Song, B., Zheng, J. K., and Gu, Y., 2006, SHRIMP U-Pb zircon age of
 781 the granulite from the Qingshuiquan area, Central Eastern Kunlun Suture Zone: Earth Science Frontiers, v. 13,
 782 no. 6, p. 311-321.

783 Li, J., Gao, J., and Wang, X., 2016, A subduction channel model for exhumation of oceanic-type high-pressure to
 784 ultrahigh-pressure eclogite-facies metamorphic rocks in SW Tianshan, China: Science China Earth Sciences, v.
 785 59, no. 12, p. 2339-2354.

786 Li, R. B., Pei, X. Z., Li, Z. C., Chen, G. C., Liu, C. J., Chen, Y. X., Liu, Z. Q., and Pei, L., 2014, Age, Geochemical
 787 Characteristics and Tectonic Significance of Yikehalaer Granodiorite in Buqingshan Tectonic Mélange Belt,
 788 Southern Margin of East Kunlun: Acta Geoscientia Sinica, v. 4, p. 434-444.

789 Li, R. B., Pei, X. Z., Li, Z. C., Pei, L., Chen, G. C., Wei, B., Chen, Y. X., Liu, C. J., and Wang, M., 2018b, Cambrian (~ 510 Ma)
 790 ophiolites of the East Kunlun orogen, China: A case study from the Acite ophiolitic tectonic mélange:
 791 International Geology Review, v. 60, no. 16, p. 2063-2083.

792 Li, R. B., Pei, X. Z., Li, Z. C., Sun, Y., Pei, L., Chen, G. C., Chen, Y. X., Liu, C. J., and Wei, F. H., 2013, Regional Tectonic

793 Transformation in East Kunlun Orogenic Belt in Early Paleozoic: Constraints from the Geochronology and
 794 Geochemistry of Helegangnaren Alkali-feldspar Granite: ACTA GEOLOGICA SINICA English Edition, v. 87, no. 2,
 795 p. 333-345.

796 Li, S. Z., Zhao, S. J., Liu, X., Cao, H. H., Yu, S., Li, X. Y., Somerville, I., Yu, S. Y., and Suo, Y. H., 2018c, Closure of the Proto-
 797 Tethys Ocean and Early Paleozoic amalgamation of microcontinental blocks in East Asia: Earth-Science
 798 Reviews, v. 186, p. 37-75.

799 Li, W. Y., 2008, Chronology and Geochemistry of ophiolite and Island arc magmatic rocks in West Qingling-East Kunlun
 800 Orogenic Belt, Constraint for Tethys evolution [doctor: University of Science and Technology of China, 1-154 p.

801 Liou, J. G., Tsujimori, T., Zhang, R. Y., Katayama, I., and Maruyama, S., 2004, Global UHP Metamorphism and
 802 Continental Subduction/Collision: The Himalayan Model: International Geology Review, v. 46, no. 1, p. 1-27.

803 Liu, B., Ma, C. Q., Zhang, J. Y., Xiong, F. H., Huang, J., and Jiang, H. A., 2012, Petrogenesis of Early Devonian intrusive
 804 rocks in the east part of Eastern Kunlun Orogen and implication for Early Palaeozoic orogenic processes: Acta
 805 Petrologica Sinica, no. 6, p. 1785-1807.

806 Liu, Q., Meng, F., Li, S., Feng, H., Jia, L., and Tian, G., 2016, Geochronology of zircon from the paragneiss of Kuhai Group
 807 in southern East Kunlun terrane: ACTA PETROLOGICA ET MINERALOGICA, v. 35, no. 3, p. 15.

808 Liu, Z. Q., Pei, X. Z., Li, R. B., Li, Z. C., Chen, G. C., Chen, Y. X., Gao, J. M., Liu, C. J., Wei, F. H., Wang, X. L., and Zhang, G.,
 809 2011a, Early Paleozoic intermediate-acid magmatic activity in Bairiqiete area along the Buqingshan tectonic
 810 melange belt on the southern margin of East Kunlun: Constraints from zircon U-Pb dating and geochemistry:
 811 Geology in China, v. 38, no. 5, p. 1150-1167.

812 Liu, Z. Q., Pei, X. Z., Li, R. B., Li, Z. C., Zhang, X. F., Liu, Z. G., Chen, Y. X., Chen, G. C., Ding, S. P., and Guo, J. F., 2011b, LA-
 813 ICP-MS Zircon U-Pb Geochronology of the Two Suites of Ophiolites at the Buqingshan Area of the A'nyemaqen
 814 Orogenic Belt in the Southern Margin of East Kunlun and its Tectonic Implication: ACTA GEOLOGICA SINICA, v.

815 85, no. 2, p. 185-194.

816 Lu, L., Wu, H. Z., Hu, D. G., BAROSH, P. J., Hao, S., and C.J., Z., 2010, Zircon U-Pb age for rhyolite of the Maoniushan
817 Formation and its tectonic significance in the East Kunlun Mountains: *Acta Petrologica Sinica*, v. 26, no. 4, p.
818 1150-1158.

819 Lu, S. N., Yu, H. F., Jin, W., Li, H. K., and Zheng, J. K., 2002, Microcontinents on the eastern margin of Tarim
820 paleocontinent: *Acta Petrologica et Mineralogica*, v. 21, no. 4, p. 317-326.

821 Luo, Z. H., Deng, J. F., Cao, Y. Q., Guo, Z. F., and Mo, X. X., 1999, On Late Paleozoic-Early Mesozoic volcanism and
822 regional tectonic evolution of eastern Kunlun, Qinghai Province: *Geoscience*, v. 13, no. 1, p. 51-56.

823 Maruyama, S., Liou, J., and Terabayashi, M. J. I. g. r., 1996, Blueschists and eclogites of the world and their exhumation,
824 v. 38, no. 6, p. 485-594.

825 Meng, F., Cui, M., Wu, X., Wu, J., and Wang, J., 2013a, Magmatic and metamorphic events recorded in granitic gneisses
826 from the Qimantag, East Kunlun Mountains, Northwest China: *Acta Petrologica Sinica*, v. 29, no. 6, p. 2107-
827 2122.

828 Meng, F. C., Cui, M. H., Jia, L. H., Ren, Y. F., and Feng, H. B., 2015a, Paleozoic continental collision of the East Kunlun
829 orogen: Evidence from protoliths of the eclogites: *Acta Petrologica Sinica*, v. 31, no. 12, p. 3581-3594.

830 Meng, F. C., Cui, M. H., Wu, X. K., and Ren, Y. F., 2015b, Heishan mafic-ultramafic rocks in the Qimantag area of Eastern
831 Kunlun, NW China: Remnants of an early Paleozoic incipient island arc: *Gondwana Research*, v. 27, no. 2, p.
832 745-759.

833 Meng, F. C., Jia, L. H., Ren, Y. F., Liu, Q., and Duan, X. P., 2017, Magmatic and metamorphic events recorded in the
834 gneisses of the Wenquan region, East Kunlun Mountains, Northwest China: Evidence from the zircon U-Pb
835 geochronology: *Acta Petrologica Sinica*, v. 33, no. 12, p. 3691-3709.

836 Meng, F. C., Tian, G., Duan, X. P., Fan, Y., and Ren, Y., 2018, Evidence from Garnet for Genesis of Garnet-Cordierite-

837 Granite in the Jinshuikou Area, Eastern Segment of the East Kunlun Mountains: Bulletin of Mineralogy,
838 Petrology Geochemistry v. 37, no. 2, p. 192-204.

839 Meng, F. C., Yang, H. J., Makeyev, A. B., Ren, Y. F., Kulikova, K. V., and Bryanchaninova, N. I., 2016, Jadeitite in the Syum-
840 Keu ultramafic complex from Polar Urals, Russia: insights into fluid activity in subduction zones: European
841 Journal of Mineralogy, v. 28, no. 6, p. 1079-1097.

842 Meng, F. C., Zhang, J. X., and Cui, M. H., 2013b, Discovery of Early Paleozoic eclogite from the East Kunlun, Western
843 China and its tectonic significance: Gondwana Research, v. 23, no. 2, p. 825-836.

844 Meschede, M., 1986, A method of discriminating between different types of mid-ocean ridge basalts and continental
845 tholeiites with the Nb • 1bZr • 1bY diagram: Chemical geology, v. 56, no. 3-4, p. 207-218.

846 Mo, X. X., Luo, Z. H., Deng, J. F., Yu, X. H., Liu, C. D., Chen, H. W., and Liu, H. Y., 2007, Granitoids and Crustal Growth in
847 the East Kunlun Orogenic Belt: Geological Journal of China Universities, v. 13, no. 3, p. 403-414.

848 Morimoto, N., 1988, Nomenclature of pyroxenes: Mineralogy & Petrology, v. 39, no. 1, p. 55-76.

849 Pan, T., and Zhang, Y., 2020, Geochemical Characteristics and Metallogenic Response of the Eclogite from Xiarihamu
850 Magmatic Ni-Cu Sulfide Deposit in Eastern Kunlun Orogenic Belt: Geotectonica et Metallogenia, v. 44, no. 3, p.
851 447-464.

852 Pearce, J. A., 1982, Trace element characteristics of lavas from destructive plate boundaries, *in* Thorpe, R. S., ed.,
853 Andesites: Orogenic Andesites and Related Rocks: Chichester, England, John Wiley & Sons, p. 528-548.

854 Pearce, J. A., and Norry, M. J., 1979, Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks:
855 Contributions to Mineralogy & Petrology, v. 69, no. 1, p. 33-47.

856 Qi, S. S., Song, S. G., Shi, L. C., Cai, H. J., and Hu, J. C., 2014, Discovery and its geological significance of Early Paleozoic
857 eclogite in Xiarihamu-Suhaitu area, western part of the East Kunlun: Acta Petrologica Sinica, v. 30, no. 11, p.
858 3345-3356.

859 Qi, X. P., Fan, X. G., Yang, J., Cui, J. T., Wang, B. Y., and Fan, Y. Z., 2016a, The discovery of Early Paleozoic eclogite in the
860 upper reaches of Langmuri in eastern East Kunlun Mountains and its significance: Geological Bulletin of China,
861 v. 35, no. 11, p. 1771-1783.

862 Qi, X. P., Fan, X. G., Yang, J., Cui, J. T., Wang, B. Y., and Fan, Y. Z., 2016b, The discovery of Early Paleozoic eclogite in the
863 upper reaches of Langmuri in eastern East Kunlun Mountains and its significance: Geological Bulletin of China,
864 v. 35, no. 11, p. 1771-1783.

865 Qi, X. P., Yang, J., Fan, X. G., Cui, J. T., Cai, Z. F., Zeng, X. W., Wei, W., Qu, X. X., and Zhai, Y. M., 2016c, Age, geochemical
866 characteristics and tectonic significance of Changshishan ophiolite in central East Kunlun tectonic mélange
867 belt along the east section of East Kunlun Mountains: Geology in China, v. 43, no. 3, p. 797--816.

868 Ravna, K., 2000, The garnet–clinopyroxene Fe²⁺–Mg geothermometer: an updated calibration: Journal of
869 Metamorphic Geology, v. 18, no. 2, p. 211-219.

870 Ren, J. H., Zhang, K., Liu, Y. Q., Zhou, D. W., and Feng, Q., 2011, Geochemical characteristics and zircon dating of blasto-
871 gabro from the South Jinshui Kou area, Eastern Kunlun: JOURNAL OF NORTHWEST UNIVERSITY(NATURAL
872 SCIENCE EDITION), v. 41, no. 1, p. 100-106.

873 Rubatto, D., Regis, D., Hermann, J., Boston, K., Engi, M., Beltrando, M., and McAlpine, S. R. B., 2011, Yo-yo subduction
874 recorded by accessory minerals in the Italian Western Alps: Nature Geoscience, v. 4, no. 5, p. 338-342.

875 Sajeev, K., Windley, B. F., Hegner, E., and Komiya, T., 2013, High-temperature, high-pressure granulites (retrogressed
876 eclogites) in the central region of the Lewisian, NW Scotland: Crustal-scale subduction in the Neoproterozoic:
877 Gondwana Research, v. 23, no. 2, p. 526-538.

878 Schmidt, M. W., 1992, Amphibole composition in tonalite as a function of pressure: an experimental calibration of the
879 Al-in-hornblende barometer: Contributions to Mineralogy & Petrology, v. 110, no. 2, p. 304-310.

880 Schorn, S., and Diener, J. F. A., 2017, Details of the gabbro-to-eclogite transition determined from microtextures and

881 calculated chemical potential relationships: *Journal of Metamorphic Geology*, v. 35, no. 1, p. 55-75.

882 Schreyer, W., 1988, Experimental studies on metamorphism of crustal rocks under mantle pressures: *Mineralogical*

883 *Magazine*, v. 52, no. 364, p. 1-26.

884 Şengör, A. M. C., 1984, The Cimmeride Orogenic System and the Tectonics of Eurasia, *The Cimmeride Orogenic System*

885 and the Tectonics of Eurasia, Volume 195, Geological Society of America, p. 0.

886 Smith, D. C., 1984, Coesite in clinopyroxene in the Caledonides and its implications for geodynamics: *Nature*, v. 310, no.

887 5979, p. 641-644.

888 Smith, J. V., 1974, *Chemical and textural properties*, Berlin Heidelberg New York, Springer, Feldspar minerals.

889 Sobolev, N. V., Dobretsov, N. L., Bakirov, A. B., and Shatsky, V. S., 1986, Eclogites from various types of metamorphic

890 complexes in the USSR and the problems of their origin: *Geological Society of America Memoirs*, p. 349-364.

891 Song, S., Niu, Y., Zhang, G., and Zhang, L., 2018a, Two epochs of eclogite metamorphism link 'cold' oceanic subduction

892 and 'hot' continental subduction, the North Qaidam UHP belt, NW China: *Geological Society of London*, v. 474,

893 p. 1-15.

894 Song, S. G., Bi, H. Z., Qi, S. S., Yang, L. M., Allen, M. B., Niu, Y. L., Su, L., and Li, W. F., 2018b, HP–UHP Metamorphic Belt

895 in the East Kunlun Orogen: Final Closure of the Proto-Tethys Ocean and Formation of the Pan-North-China

896 Continent: *Journal of Petrology*, v. 59, no. 11, p. 2043-2060.

897 Song, S. G., Niu, Y. L., Su, L., Zhang, C., and Zhang, L. F., 2014, Continental orogenesis from ocean subduction, continent

898 collision/subduction, to orogen collapse, and orogen recycling: The example of the North Qaidam UHPM belt,

899 NW China: *Earth-Science Reviews*, v. 129, p. 59-84.

900 Song, S. G., Su, L., Li, X. H., Niu, Y. L., and Zhang, L. f., 2012, Grenville-age orogenesis in the Qaidam-Qilian block: the

901 link between South China and Tarim: *Precambrian Research*, v. 220, p. 9-22.

902 Song, S. G., Zhang, I. F., Wei, C. J., Liou, J. G., and Sun, G. M., 2007, Eclogite and carpholite - bearing metasedimentary

903 rocks in the North Qilian suture zone, NW China: implications for Early Palaeozoic cold oceanic subduction
 904 and water transport into mantle *Journal of Metamorphic Geology*, v. 25, no. 5, p. 547-563.

905 Sun, J., Dong, Y., Ma, L., Chen, S., and Jiang, W., 2022, Devonian to Triassic tectonic evolution and basin transition in the
 906 East Kunlun–Qaidam area, northern Tibetan Plateau: Constraints from stratigraphy and detrital zircon U–Pb
 907 geochronology: *GSA Bulletin*, v. 134, no. 7-8, p. 1967-1993.

908 Sun, S. S., and McDonough, W. F., 1989, Chemical and isotopic systematic of Oceanic basalt: Implications for the
 909 mantle composition and processes, Geological Society, London, Special Publications, 313-345 p.:

910 Syracuse, E. M., van Keken, P. E., and Abers, G. A., 2010, The global range of subduction zone thermal models: *Physics*
 911 *of the Earth and Planetary Interiors*, v. 183, no. 1, p. 73-90.

912 Tang, H., Zhang, H. F., Zhang, M. J., Zou, H., and Zhang, J., 2022, Neoproterozoic and early Paleozoic metamorphism
 913 recorded in gneisses from the East Kunlun Orogenic belt: *Precambrian Research*, v. 375.

914 Wang, B. Z., Luo, Z. H., Pan, T., Song, T. Z., Xiao, P. X., and Zhang, Z. Q., 2012, Petrotectonic assemblages and LA-ICP-MS
 915 zircon U-Pb age of Early Paleozoic volcanic rocks in Qimantag area, Tibetan Plateau: *Geological Bulletin of*
 916 *China*, v. 31, no. 6, p. 860-874.

917 Wang, G., Chen, N., Zhu, Y., and Zhang, K., 2003a, Late Caledonian Ductile Thrusting Deformation in the Central East
 918 Kunlun Belt, Qinghai, China and Its Significance: Evidence from Geochronology: *Acta Geologica Sinica - English*
 919 *Edition*, v. 77, no. 3, p. 311-319.

920 Wang, G., Chen, N., Zhu, Y., and Zhang, K., 2003b, Late Caledonian Ductile Thrusting Deformation in the Central East
 921 Kunlun Belt, Qinghai, China and Its Significance: Evidence from Geochronology: *Acta Geologica Sinica*, v. 77,
 922 no. 3, p. 311-319.

923 Wang, H., Wu, Y., Gao, S., Liu, X., Liu, Q., Qin, Z., Xie, S., Zhou, L., and Yang, S., 2013a, Continental origin of eclogites in
 924 the North Qinling terrane and its tectonic implications: *Precambrian Research*, v. 230, no. Complete, p. 13-30.

925 Wang, H., Xiao, W., Windley, B. F., Zhang, Q. W. L., Tan, Z., Wu, C., and Shi, M., 2022a, Diverse P-T-t Paths Reveal High-
 926 Grade Metamorphosed Forearc Complexes in NW China, v. 127, no. 6, p. e2022JB024309.

927 Wang, H. R., Zhao, H. G., Qiao, J. X., and Gao, S. H., 2013b, Theory and application of zircon U-Pb isotope dating
 928 technique: *Geology and Resources*, v. 22, no. 3, p. 229-232.

929 Wang, H. Y. C., Chen, H.-X., Zhang, Q. W. L., Shi, M.-Y., Yan, Q.-R., Hou, Q.-L., Zhang, Q., Kusky, T., and Wu, C.-M., 2017,
 930 Tectonic mélange records the Silurian–Devonian subduction-metamorphic process of the southern Dunhuang
 931 terrane, southernmost Central Asian Orogenic Belt: *Geology*, v. 45, no. 5, p. 427-430.

932 Wang, J. M., Lanari, P., Wu, F. Y., Zhang, J. J., Khanal, G. P., and Yang, L., 2021, First evidence of eclogites overprinted by
 933 ultrahigh temperature metamorphism in Everest East, Himalaya: Implications for collisional tectonics on early
 934 Earth: *Earth and Planetary Science Letters*, v. 558.

935 Wang, Q., 2020, Geochemical Characteristics and Geological Significance of Eclogite in Airikehansen Area, Dulan
 936 County, Qinghai Province: *Northwestern Geology*, v. 53, no. 1, p. 1-12.

937 Wang, Q., Zhao, J., Zhang, C., Yu, S., Ye, X., and Liu, X., 2022b, Paleozoic post-collisional magmatism and high-
 938 temperature granulite-facies metamorphism coupling with lithospheric delamination of the East Kunlun
 939 Orogenic Belt, NW China: *Geoscience Frontiers*, v. 13, no. 1, p. 101271.

940 White, R. W., Powell, R., Holland, T. J. B., Johnson, T. E., and Green, E. C. R., 2014, New mineral activity-composition
 941 relations for thermodynamic calculations in metapelitic systems: *Journal of Metamorphic Geology*, v. 32, no. 3,
 942 p. 261-286.

943 Whitney, D. L., and Evans, B. W., 2010, Abbreviations for names of rock-forming minerals: *American Mineralogist*, v. 95,
 944 no. 1, p. 185-187.

945 Wood, B. J., 1973, Garnet-orthopyroxene and orthopyroxene-clinopyroxene relationship in simple and complex
 946 systems: *Contributions to Mineralogy&Petrology*, v. 42, no. 2, p. 109-124.

947 Wu, C., Li, J., Zuza, A. V., Haproff, P. J., Chen, X., and Ding, L., 2021, Proterozoic– Phanerozoic tectonic evolution of the
948 Qilian Shan and Eastern Kunlun Range, northern Tibet: GSA Bulletin.

949 Wu, C., Liu, C., Fan, S., Zuza, A. V., Ding, L., Liu, W., Ye, B., Yang, S., and Zhou, Z., 2020, Structural analysis and tectonic
950 evolution of the western domain of the Eastern Kunlun Range, northwest Tibet: GSA Bulletin, v. 132, no. 5-6,
951 p. 1291-1315.

952 Wu, C., Zuza, A. V., Chen, X., Ding, L., Levy, D. A., Liu, C., Liu, W., Jiang, T., and Stockli, D. F., 2019, Tectonics of the
953 Eastern Kunlun Range: Cenozoic reactivation of a Paleozoic – early Mesozoic orogen: Tectonics, v. 38, no. 5, p.
954 1609-1650.

955 Wu, Y., and Zheng, Y., 2004, Genesis of zircon and its constraints on interpretation of U-Pb age: Chinese Science
956 Bulletin, v. 49, no. 15, p. 1554-1569.

957 Wu, Y. B., and Zhen, Y. F., 2004, Study on mineralogy of zircon formation and its constraints on U-Pb age interpretation:
958 Chinese Science Bulletin, v. 49, no. 16, p. 1589-1604.

959 Xia, B., Cui, Y., Shang, Y. F., and Shi, J. T., 2022a, Petrology of Eclogite at Huwan, Western Dabie and Implications for
960 Phase Equilibrium Modeling on LT-HP/UHP Eclogite: Journal of Earth Science. doi.org/10.1007/s12583-022-
961 1719-9.

962 Xia, B., Shang, Y. F., Lu, X. B., and Wu, Y. B., 2022b, UHP eclogite from western Dabie records evidence of polycyclic
963 burial during continental subduction: American Mineralogist. doi.org/10.2138/am-2022-8446

964 Xiao, W. J., Windley, B. F., Yong, Y., Yan, Z., Yuan, C., Liu, C. Z., and Li, J. L., 2009, Early Paleozoic to Devonian multiple-
965 accretionary model for the Qilian Shan, NW China: Journal of Asian Earth Sciences, v. 35, no. 3-4, p. 323-333.

966 Xu, X., Song, S., and Su, L., 2016, Formation age and tectonic significance of the Wanbaogou basalts in the middle East
967 Kunlun orogenic belt: ACTA PETROLOGICA ET MINERALOGICA, v. 35, no. 6, p. 16.

968 Yang, J. S., Jiang, C. F., Feng, B. G., Zhu, Z. Z., Zhao, M., Shi, X. D., and Hu, J. Q., 1986, An outline on the tectonics of the

969 Kunlun region: Bulletin of the Institute of Geology Chinese Academy of Geological Sciences, v. 2, p. 010.

970 Yang, J. S., Robinson, P. T., Jiang, C. F., and Xu, Z. Q., 1996, Ophiolites of the Kunlun Mountains, China and their tectonic
971 implication: Tectonophysics, v. 258, no. 1-4, p. 215-231.

972 Yang, J. S., Wang, X. B., Shi, R. D., Xu, Z. Q., and Wu, C. L., 2004, The Dur'ngoi ophiolite in East Kunlun, northern
973 Qinghai-Tibet Plateau: a fragment of paleoTethyan oceanic crust: Zhongguo Dizhi(Geology in China), v. 31, no.
974 3, p. 225-239.

975 Yu, J., Zheng, Y., Xu, R., Hou, W., and Cai, P., 2020a, Zircon U-Pb Chronology, Geochemistry of Jiangjunmu Ore-Bearing
976 Pluton, Eastern Part of East Kunlun and Their Geological Significance: Earth Science, v. 45, no. 4, p. 1151-1167.

977 Yu, M., Dick, J. M., Feng, C., Li, B., and Wang, H., 2020b, The tectonic evolution of the East Kunlun Orogen, northern
978 Tibetan Plateau: A critical review with an integrated geodynamic model: Journal of Asian Earth Sciences, v.
979 191, p. 104168.

980 Yu, S., Zhang, J., Li, H., Hou, K., Mattinson, C. G., and Gong, J., 2013a, Geochemistry, zircon U-Pb geochronology and Lu-
981 Hf isotopic composition of eclogites and their host gneisses in the Dulan area, North Qaidam UHP terrane:
982 New evidence for deep continental subduction: Gondwana Research, v. 23, no. 3, p. 901-919.

983 Yu, S., Zhang, J. X., Gong, J. H., and Li, Y. S., 2013b, Research on HP granulite-facies metamorphism and anatexis: A case
984 study of Dulan area in the North Qaidam Mountains: Acta Petrologica Sinica, v. 29, no. 6, p. 2061-2072.

985 Zhang, G. B., Ellis, D. J., Christy, A. G., Zhang, L. F., and Song, S. G., 2010a, Zr-in-rutile thermometry in HP/UHP eclogites
986 from Western China: Contributions to Mineralogy&Petrology, v. 160, no. 3, p. 427-439.

987 Zhang, G. B., Ireland, T., Zhang, L. F., Gao, Z., and Song, S. G., 2016, Zircon geochemistry of two contrasting types of
988 eclogite: Implications for the tectonic evolution of the North Qaidam UHPM belt, northern Tibet: Gondwana
989 Research, v. 35, p. 27-39.

990 Zhang, G. B., Niu, Y. L., Song, S. G., Zhang, L. F., Tian, Z. L., Christy, A., and Han, L., 2015a, Trace element behavior and P-

991 T-t evolution for partial melting of exhumed eclogite in the North Qaidam UHPM belt (NW China):
 992 implications for adakite genesis: *Lithos*, v. 226, p. 65–80.

993 Zhang, G. B., Zhang, L. F., and Song, S. G., 2012, An overview of the tectonic evolution of North Qaidam UHPM belt:
 994 From oceanic subduction to continental collision: *Geological Journal of China Universities*, v. 18, no. 1, p. 28-
 995 40.

996 Zhang, J. X., Mattinson, C. G., Meng, F. C., Wan, Y., and Tung, K., 2008, Polyphase tectonothermal history recorded in
 997 granulitized gneisses from the north Qaidam HP/UHP metamorphic terrane, western China: Evidence from
 998 zircon U-Pb geochronology: *Geological Society of America Bulletin*, v. 120, no. 5-6, p. 732-749.

999 Zhang, J. X., Meng, F. C., Li, J. P., and Mattinson, C. G., 2009, Coesite in eclogite from the North Qaidam Mountains and
 1000 its implications: *Chinese Science Bulletin*, no. 6, p. 1105-1110.

1001 Zhang, J. X., Meng, F. C., Wan, Y. S., Yang, J. S., and Dong, G. A., 2003, Early Paleozoic tectono-thermal event of the
 1002 Jinshuikou Group on the southern margin of Qaidam: Zircon U-Pb SHRIMP age evidence: *GEOLOGICAL*
 1003 *BULLETIN OF CHINA*, v. 22, no. 6, p. 397-404.

1004 Zhang, J. X., Yu, S. Y., Li, Y. S., Yu, X. X., Lin, Y. H., and Mao, X. H., 2015b, Subduction, accretion and closure of Proto-
 1005 Tethyan Ocean: Early Paleozoic accretion/collision orogeny in the Altun-Qilian-North Qaidam orogenic system:
 1006 *Acta Petrologica Sinica*, v. 31, no. 12, p. 3531-3554.

1007 Zhang, J. X., Yu, S. Y., and Mattinson, C. G., 2017, Early Paleozoic polyphase metamorphism in northern Tibet, China:
 1008 *Gondwana Research*, v. 41, p. 267-289.

1009 Zhang, Y. F., Pei, X. Z., Ding, S. P., Li, R. B., Feng, J. Y., Sun, Y., Li, C., and Chen, Y. X., 2010b, LA-ICP-MS zircon U-Pb age of
 1010 quartz diorite at the Kekesha area of Dulan County, eastern section of the East Kunlun orogenic belt, China
 1011 and its significance: *Geological Bulletin of China*, v. 29 no. 1, p. 79-85.

1012 Zhang, Y. L., Zhang, X. J., Hu, D. G., Shi, Y. R., and Lu, L., 2010c, SHRIMP zircon U-Pb ages of rhyolite from the Naij Tal

1013 group in the East Kunlun orogenic belt: Journal of Geomechanics, v. 16, no. 1, p. 21-27.

1014 Zhao, G. C., Wang, Y. J., Huang, B. C., Dong, Y. P., Li, S. Z., Zhang, G. W., and Yu, S., 2018, Geological reconstructions of

1015 the East Asian blocks: From the breakup of Rodinia to the assembly of Pangea: Earth-Science Reviews, v. 186,

1016 p. 262-286.

1017 Zheng, Y.-F., Zhang, L., McClelland, W. C., and Cuthbert, S., 2012, Processes in continental collision zones: Preface:

1018 Lithos, v. 136-139, p. 1-9.

1019 Zhou, W., Xiaocheng, z., and Xinbiao, L., 2020, Petrology, Geochemistry and Chronology of the Baishahe Formation in

1020 Numohong Area of Eastern Kunlun Orogenic Belt: Journal of Earth Science, v. 45, no. 12, p. 4370-4388.

1021 Zuza, A. V., Wu, C., Reith, R. C., Yin, A., Li, J., Zhang, J., Zhang, Y., Wu, L., and Liu, W., 2017, Tectonic evolution of the

1022 Qilian Shan: An early Paleozoic orogen reactivated in the Cenozoic: GSA Bulletin, v. 130, no. 5-6, p. 881-925.

1023

1024 **Figure and Table captions**

1025 **Figure captions:**

1026 **Figure 1.** (A) The location of the northern part of Qinghai-Tibet Plateau. (B) Geological sketch map
1027 of the East Kunlun Orogenic belt (modified after [Meng et al., 2017](#); [Zhang et al., 2015b](#);
1028 [Zhang et al., 2017](#)) and the location of the eclogites in the Nuomuhong area and other
1029 segments ([Meng et al., 2013b](#); [Qi et al., 2014](#); [Qi et al., 2016a](#); [Song et al., 2018b](#)). (C) The
1030 approximately N-S structural cross-section of the Nuomuhong area showing main rock types
1031 and the location of samples.

1032
1033 **Figure 2.** Field photographs of eclogite at Nuomuhong, in East Kunlun. (A) Eclogite block
1034 enclosed in the host felsic gneiss. (B) Eclogite retrograded to amphibolite at edges. The red
1035 dashed line marks the boundary between the retrograde eclogite and amphibolite. (C) The red
1036 dashed line showing boundary between retrograde eclogite and the host felsic gneiss. (D)
1037 Marble intercalated in amphibolite that showing banded structure. (E) The host felsic gneiss
1038 consisted mainly of felsic minerals, biotite and garnet. (F) The retrograde eclogite consisted of
1039 mainly garnet, clinopyroxene, amphibole and quartz.

1040
1041 **Figure 3.** Photomicrographs of representative eclogite at Nuomuhong, EKOB. Mineral
1042 abbreviations are after [Whitney and Evans \(2010\)](#). (A) A large garnet porphyroblast from the
1043 eclogite LH 3–5 showing apparent zoning with abundant inclusions in the reddish core and
1044 minor in the light rim. Amphibole (Amp II), plagioclase, ilmenite and biotite (Bt) develop
1045 around the garnet. (B) Backscattered electron image (BSE) of the garnet porphyroblast in Fig.

3A showing inclusions of titanite (Ttn) and omphacite (Cpx I_a) in the core. (C–D) Corona of plagioclase (Pl III) + amphibole (Amp II) ± ilmenite (LH3–4) around a relict garnet porphyroblast with inclusions of omphacite (Cpx I_a). Symplectite of plagioclase (III) + amphibole develops in the matrix; (E–F) Symplectite of orthopyroxene (Opx)+ plagioclase (Pl II) around relict omphacite in matrix from the sample LH3–4. Corona of symplectite amp II + Pl develops around relict garnet and low-sodic clinopyroxene (Cpx II_a; light-colored in BSE) develops around relict omphacite porphyroblast (Cpx I_b; dark-colored in BSE). (G) Locally enlarged BSE image in Fig. 3D showing transition from relict omphacite porphyroblast (Cpx I_b; with no Opx) to clinopyroxene porphyroblast (Cpx II_b; with Opx), then to symplectite of Amp II + Pl II; (with Opx). Corona of plagioclase (Pl III) + amphibole (Amp II) rims garnet; (H) Rutile as inclusions in garnet or in matrix from the sample LH 3–2. It has been partial replaced by ilmenite; (I) Amphibole (Amp I) included in garnet from sample LH 3–2. (G–K) Plane-polarized photo with corresponding BSE image showing Biotite around amphibole (Amp II) from sample LH 3–5.

Figure 4. Backscattered electron image of the garnet porphyroblast (LH 3–4) with EPMA composition section (A, B) and the locally enlarged photo of inclusions (3) with the mineral assemblage of Ep + Pl (Ab). (D) Diagram showing the compositional variation of garnet porphyroblast, the Grt_(mantle+core) (Grt I) and Grt_{rim} (Grt II) are both group C-type after [Coleman et al. \(1965\)](#). (E) Zoning profile of $X_{alm} [=Fe^{2+}/(Fe^{2+} + Mn + Mg + Ca)]$, X_{sps} , X_{prp} and X_{grs} defined accordingly across garnet in the eclogite samples LH 3–4 from the Nuomuhong area].

1068 **Figure 5.** Mineral chemistry diagrams. (A–B) Ternary classification diagrams for pyroxenes of the
1069 Nuomuhong eclogites, after [Morimoto \(1988\)](#): (A) The classification diagram for Quad-Jd-Ae.
1070 (B) The classification diagram for Wo-En-Fs. (C–D) The classification diagrams for
1071 amphiboles of Nuomuhong eclogite, after Leake et al. (2004) and [Song et al. \(2018b\)](#). (E) Ab–
1072 An–Or diagram showing the composition of plagioclase, after [Smith \(1974\)](#); $Ab = X_{Na} = Na / (Ca$
1073 $+ K + Na)$; $An = X_{Ca} = Ca / (Ca + K + Na)$; $Or = X_K = K / (Ca + K + Na)$.

1074
1075 **Figure 6.** Mineral assemblages for different metamorphic stages. Solid lines indicate minerals
1076 present in the samples, whereas the dashed line refers to inferred minerals.

1077
1078 **Figure 7.** Raman spectra of (A) omphacite (Omp) inclusions, (B) omphacite/jadeite inclusions, and
1079 (C) garnet (Grt) and omphacite inclusions in zircon (Zrn) grains from the Nuomuhong
1080 retrograde eclogite, middle East Kunlun orogen.

1081
1082 **Figure 8.** Chondrite-normalized REE distribution patterns (A) and primitive mantle-normalized
1083 spidergram of the retrograde eclogites and garnet amphibolites (B). The chondrite and
1084 primitive mantle values are from [Sun and McDonough, 1989](#).

1085
1086 **Figure 9.** (A–B) Zircon CL images, (C) SHRIMP U–Pb age concordia diagram and weighted mean
1087 $^{206}\text{Pb}/^{238}\text{U}$ ages and (D) Chondrite-normalized REE distribution patterns for the Nuomuhong
1088 retrograde eclogite LH3–4.

1089

1090 **Figure 10.** (A) P – T pseudosection for Nuomuhong eclogite sample LH 3–4 (MnNCKFMASHTO
1091 system); (B) Grossular $[\text{Ca}/(\text{Ca}+\text{Mg}+\text{Fe}+\text{Mn}) * 100]$ and pyrope $[\text{Mg}/(\text{Ca}+\text{Mg}+\text{Fe}+\text{Mn}) * 100]$
1092 isopleths.

1093

1094 **Figure 11.** Tectonic discrimination diagrams (A–D) for the retrograde eclogite (A) Zr–Zr/Y diagram
1095 (Pearce and Norry, 1979); (B) Ce/Yb–Ta/Yb diagram (Pearce, 1982); (C) Y–La–Nb diagram
1096 (Cabanis and Lecolle, 1989); (D) Nb–Zr–Y diagram (Meschede, 1986); (E) AFM diagram
1097 (Irvine and Baragar, 1971). WPB–Within Plate Basalts; IAB–Island Arc Basalts; MORB–Mid-
1098 Ocean Ridge Basalts.

1099

1100 **Figure 12.** The P – T path for the Nuomuhong eclogite in this study, in comparison with eclogite in the
1101 eastern segment of the East Kunlun orogen from Song et al. (2018b). Boundaries for various
1102 metamorphic facies, High- P granulite, UHT follow Schreyer (1988), Syracuse et al. (2010) and
1103 Maruyama et al. (1996), metamorphic facies, their abbreviations, and phase equilibria are after Liou et
1104 al. (2004).

1105

1106 **Figure 13.** Tectonic model for the Eastern Kunlun orogen, and Proto-Tethys Ocean.

1107

1108	Table captions:
1109	Table S1. Representative electron microprobe analyses of garnet in eclogite samples.
1110	Table S2. Representative analyses of clinopyroxene (omphacite)in eclogite samples.
1111	Table S3. Representative microprobe analyses of low-sodic clinopyroxene in eclogite samples.
1112	Table S4. Representative microprobe analyses of amphibole in eclogite samples.
1113	Table S5. Representative microprobe analyses of plagioclase in eclogite samples.
1114	Table S6. Representative microprobe analyses of other minerals (orthopyroxene and epidote) in
1115	eclogite samples
1116	Table S7. Whole rock major (wt%) and trace element (ppm) analyses of eclogites in Nuomuhong
1117	area, EKOB.
1118	Table S8. SHRIMP Zircon U-Pb isotopic data from the eclogite in Nuomuhong area, EKOB.
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