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Continental origin of the Gubaoquan eclogite and implications for evolution of the Beishan Orogen, Central Asian Orogenic Belt, NW China

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Continental origin of the Gubaoquan eclogite and implications for evolution of the Beishan Orogen, Central Asian Orogenic Belt, NW China

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Abstract

The Gubaoquan eclogite occurs in the Paleozoic Beishan Orogen of NW China. Previously it has been interpreted as a fragment of subducted oceanic crust that was emplaced as a mélange within continental rocks. Contrary to this, we demonstrate that the Gubaoquan eclogite protolith was a Neoproterozoic basic dyke/sill which intruded into Proterozoic continental rocks. The SHRIMP U-Pb zircon dating of the metamorphic rims of the Gubaoquan eclogite yields an age 466 ± 27 Ma. Subdued heavy rare earth element abundances and lack of negative Eu anomalies of the metamorphic zircon domains confirm that this age represents eclogite facies metamorphism. The host augen orthogneiss has a U-Pb zircon age of 920 ± 14 Ma, representing the timing of crystallization of the granitic protolith. A leucogranitic vein which intrudes the eclogite has a U-Pb zircon age of 424 ± 8.6 Ma. This granitic vein marks the end of high-grade metamorphism in this area.

The overcomplication of tectonic history of the Beishan Orogen is partially caused by inconsistent classifications and nomenclature of the same rock units and arbitrary subdivisions of Precambrian blocks as individual microcontinents. In an attempt to resolve this, we propose a simpler model that involves the partial subduction of the northern passive margin of the Dunhuang Block beneath the active continental margin developing on the Mazongshan-Hanshan Block to the north. Ocean closure and continental collision during the Late Ordovician resulted

in continental thickening and eclogite facies metamorphism recorded by the mafic dykes/sills (now the Gubaoquan eclogite). In the light of the new data, the tectonothermal evolution of the Beishan Orogen is reviewed and integrated with the evolution of the Central Asian Orogenic Belt.

1. Introduction

The Central Asian Orogenic Belt (CAOB), also known as the Altaids, encapsulates a long history of accretionary tectonics that lasted from the late Neoproterozoic until the Early Mesozoic (Sengor et al., 1993; Buckman and Aitchison, 2004; Xiao et al., 2004; Windley et al., 2007; Xiao et al., 2010). Numerous ophiolites, arcs and microcontinents accreted onto the margins of Tarim, North China and Siberian cratons constructing the Central Asian Orogenic Belt, which represents significant amount of continental growth throughout the Paleozoic (Coleman, 1989; Sengor et al., 1993; Xiao et al., 2010; Mao et al., 2012b). During the process, multiple episodes of subduction and arc-continent collisions led to numerous high pressure (HP) and ultra-high pressure (UHP) metamorphic episodes, forming HP granulites and eclogites among the collage of colliding terranes (Beane and Connelly, 2000; Jun and Klemd, 2000; Ota et al., 2007; Zhang et al., 2007; Su et al., 2010; Meyer et al., 2013; He et al., 2014a; Klemd et al., 2015). The significance of these high-pressure rocks depends on whether they indicate collision between terranes, or ongoing subduction, thereby giving insights into different facets of crust building and geodynamic processes (O'Brien and Rötzler, 2003; Volkova and Sklyarov, 2007; Ota and Kaneko, 2010; Manton et al., 2017). Because eclogites can form during double thickening of the crust (e.g., Gilotti et al., 2004; Nutman et al., 2008) or via the subduction of passive continental margin beneath overriding active margin (e.g., Tso Morari eclogite; de Sigoyer et al., 2000), they do not necessarily signify fragments of a consumed ocean, and hence the origin of each eclogite occurrence needs to be reviewed on a case by case basis.

The Beishan Orogen in north western China is a southern-most extension of the CAOB. It is one of the last accretionary segments in the CAOB, before the final cratonic amalgamation in the latest Permian to Early Triassic (Fig. 1; Xiao et al., 2010). The Beishan Orogen thus contains important information about the tectonic interactions between the peri-Gondwanan Tarim and North China cratons and the Siberian Craton. Consequently, the Beishan Orogen has become the focus of studies investigating closure of the Palaeo-Asian Ocean that marked the final stage of the CAOB growth (Mao et al., 2012b).

Long-lasting debate over Early Paleozoic (Zuo et al., 1990; Gong et al., 2003) *versus* Late Paleozoic (Guo et al., 2012; Zhang et al., 2015a; Kröner et al., 2017) closure of the Palaeo-Asian Ocean played an important role in research into the Beishan Orogen. Final ocean closure and continental collision between Siberia, Tarim and North China cratons is thought by some to be a Late Paleozoic to Early Mesozoic termination (e.g., Windley et al., 2007; Xiao et al., 2010; Xiao et al., 2015). Nevertheless, previous studies as well as this one, reveal that orogenesis in the Beishan was a multistage process involving multiple ocean basins (Liu et al., 2010; Xiao et al., 2010; Qu et al., 2011; Song et al., 2013b). This study focuses on the formation of the mafic Gubaoquan eclogite and its relationship to the associated quartzofeldspathic gneisses and granitic veins. In this paper, we present the field relationships along with geochemistry and geochronological data to show that the Gubaoquan eclogite has an intra-continental origin; i.e. it formed by transient high pressure brought by tectonic thickening of continental crust during a collisional event. In light of this, we provide a re-evaluation of the tectonic evolution of the

Beishan Orogen and the significance of this to the evolution of the Central Asian Orogenic Belt in general.

2. Geological history and terrane overview of the Beishan Orogen

The Gubaoquan eclogites in the Beishan Orogen (Fig. 2) were first reported by Mei et al. (1999) and were studied in detail by Liu et al. (2010) and Qu et al. (2011). The Beishan Orogen is bounded by ancient and active fault systems that partition it from the adjacent orogens. Its western boundary is the Xingxingxia Fault that separates it from the Tianshan Orogen, whereas in the east, it is bounded by the active Altyn Tagh Fault separating it from the Mongolia-Xing'anling Orogen. To the north, the Beishan Orogen is confined by the Southern Mongolian Accretionary System, and to the south by the Dunhuang Block, that is often referred to as a north-eastern extension of the Tarim Craton. However, the true relationship between these two units is unknown, due to the Quaternary sediment that covers much of the craton, with outcrops limited to the margins of the terrane. Similarities in terms of shared orogenic history suggests that the Dunhuang Block was involved in the Ordovician Beishan orogeny (Zong et al., 2012; He et al., 2014b; Yuan et al., 2015; Zhao et al., 2016, this study).

Neoproterozoic to Early Mesozoic collisional and subduction-accretion processes led to amalgamation of discrete terranes that together constitute the CAOB. The Beishan Orogen is important because it is located at the contact between the Tarim and North China cratons to the south and the previously accreted terranes of the CAOB to the north (Fig. 1). It represents one of the first periods of continental growth onto the northern margin of the Tarim Craton in the Early Paleozoic (Liu et al., 2010; Song et al., 2013a). Numerous Precambrian continental ribbons occur between Tarim and Siberian cratons, but provenance and origin of these is not always well established due to high-grade metamorphic overprint.

Some early interpretations of the CAOB involved the development of a single, massive "Turkic-type" accretionary complex and arc (Kipchak Arc) along the southern margin of Siberian Craton (Sengör and Natal'in, 1996). However, detailed geochronology of various ophiolites and arcs throughout the CAOB has shown that continental growth did not operate as accretion or a "one-by-one" terrane collision onto a single continental margin scenario, but as multi-stage inter-terrane amalgamation onto multiple microcontinental blocks situated between the Tarim, North China and Siberian cratons (Coleman, 1989; Buckman and Aitchison, 2004; Xiao et al., 2008).

The geology of the Beishan Orogen is complicated by varying metamorphic grades across the terranes and extensive faulting and dislocation associated with successive docking of blocks and microcontinents onto the margins of Tarim and Siberian cratons. Inconsistent classification or differentiation of blocks, terranes, Groups and Formations and no distinction between ancient sutures and active faults has resulted in wildly varying interpretations of the same rock units and a multitude of subduction zones used to explain the separation of each and every isolated outcrop of the Precambrian basement. Therefore, further characterisation of Precambrian blocks as peri-Siberian or peri-Gondwana and intervening intra-oceanic terranes is needed to constrain better the tectonic evolution of this complex region. According to Xiao et al. (2010), the main regionally correlated units from north to south include:

1) The Queershan unit is referred to as a complex, arc or block, and is located on the southern margin of the Siberian accretionary complex. It is the most northern unit in the Beishan Orogen, and it comprises Ordovician to Permian mafic to intermediate arc-related volcanic and

volcaniclastic rocks. Late Carboniferous to Permian granites of calc-alkaline affinity intrude the Queershan unit (Xiao et al., 2010).

2) The Hongshishan complex is referred to as a suture or an ophiolite. This complex stretches along the Hongshishan fault zone. The ophiolitic rocks were considered to be Carboniferous to Permian in age (Xiao et al., 2010). Recent work by Shi et al. (2017a) provided first U-Pb zircon ages for this ultramafic complex. The gabbro yielded an age of 357 ± 4 Ma, whereas andesite and basaltic andesite yielded 322 ± 3 and 304 ± 2 Ma ages respectively, indicating Early to Late Carboniferous generation of ophiolite-arc crust (Shi et al., 2017a).

3) The Heiyingshan arc (Heiyingshan-Hanshan Unit), this magmatic arc is intruding into the Hanshan unit and is composed of calc-alkaline felsic volcanic rocks, limestone, volcaniclastic rocks and minor cherts (Xiao et al., 2010). High-pressure metamorphic rocks occur within the centre of Hanshan unit, for which metamorphic age is not well established but they are intruded by numerous Carboniferous to Triassic granites (Nie et al., 2002).

4) The Xingxingxia-Shibanjing unit consists of disrupted ophiolitic rocks mixed with blocks of turbidite, gneiss, schist, migmatite and marble that were incorporated into a highly attenuated and sheared mélange. Many of the ophiolitic fragments underwent amphibolite facies metamorphism but the age of this event is unknown (Zhou et al., 2001). The first chronological control was based on the fossils within sedimentary rocks, providing Ordovician to Silurian ages (Zuo et al., 1990; Zuo and He, 1990; Zuo et al., 2003). However, a more recent study provided the first U-Pb zircon ages from a gabbro of the Xingxingxia-Shibanjing ophiolitic complex which yielded an age of 535 – 516 Ma (Shi et al., 2017b).

5) The Mazongshan Block (arc, unit) consists of Proterozoic to Cambrian high-grade metamorphic gneisses, schists and migmatites, Early to Middle Paleozoic volcanic rocks and Late Paleozoic sedimentary rocks (Xiao et al., 2010 and references therein). This Precambrian basement is considered to be a rifted fragment of the Tarim Craton by Zheng et al. (2013). The Mazongshan Block is devoid of any volcanic rocks until the Ordovician, marking an onset of an active continental margin (Zheng et al., 2013). Xiao et al. (2010) interprets the Mazongshan Block to have collided with the Hanshan Arc at the Ordovician-Silurian boundary, to produce the composite Mazongshan-Hanshan Arc that was then active from the Silurian to Devonian.

6) The Hongliuhe-Niujuianzi-Xichangjing unit (mélange, ophiolite). This ophiolitic mélange consists of highly disrupted ophiolitic rocks mixed with Cambrian, Ordovician and Silurian clastic and pyroclastic rocks. Block of gabbro from the Hongliuhe ophiolite yielded a middle Silurian U-Pb zircon age of ~426 Ma (Yu et al., 2000; Yu et al., 2006; Tian et al., 2014).

7) The Shuangyingshan-Huaniushan unit, also named Liuyuan microcontinent by Liu et al. (2010). The Shuangyingshan unit refers to the Precambrian basement, whereas Huaniushan unit is an magmatic arc intruding into the Shuangyingshan basement in the Ordovician. It consists of Late Proterozoic to Early Paleozoic clastic rocks and carbonates. Xiao et al. (2010) and Qu et al. (2011) included the Gubaoquan eclogite and augen gneisses in the Huaniushan arc, developing on the southern margin of the Mazongshan Block. These units consist of high grade metamorphic rocks, which comprise orthogneisses and paragneisses containing the Gubaoquan eclogite as lensoidal bodies (Liu et al., 2010; Qu et al., 2011). Some researchers have grouped the Permian pillow basalts located just to the south of the eclogite locality, as well as rare ultramafic and gabbro occurrences as well as the Ordovician Beishan eclogites as part of the

Liuyuan ophiolitic mélange (Xiao et al., 2010; Qu et al., 2011). This led to their interpretation of the Beishan eclogites as subducted oceanic crust allochthonous to the enveloping gneisses.

8) The Shibanshan unit (arc) is the southernmost unit in the Beishan Orogen, which abuts the Dunhuang Block to the south (Xiao et al., 2010). From existing literature or maps it is unclear as to the relationship between the Dunhuang Block, Shibanshan and Huaniushan units. Most regional geology maps show a faulted contact between the two units, suggesting they may be unrelated tectonic entities. The Shibanshan unit contains granitic gneisses, schists and migmatites. The protolith ages range from ~1,450 - 880 Ma with εHf isotopic signatures indicating contribution of the continental crust in melt generation (Jiang et al., 2013; He et al., 2015a; He et al., 2015b). Jiang et al. (2013) have recognized anatexis events at *ca.* 295 Ma which they postulate to occur in a post-collisional rift setting. This event has now been recognised in several locations in southern Beishan area (see below and discussion).

9) The Dunhuang Block is considered to be the north-eastern extension of the Tarim Craton and marks the southern boundary of the Beishan Orogen (Qu et al., 2011). It consists of both high-grade metamorphic rocks including HP granulites, paragneisses, orthogneisses, migmatites, amphibolites, quartzites, schists and marbles as well as domains of low-grade meta-sedimentary rocks. These range in age from Neoarchean-Paleoproterozoic to Paleozoic (Zuo and He, 1990; Zuo and Li, 1996; Wei et al., 2000; Zong et al., 2012; Zhao et al., 2016).

Final ocean closure and continental assembly in the CAOB is thought by some to be as late as Late Permian to Early Triassic (Xiao et al., 2010), constrained by the presence of Permian island arc and ophiolitic rocks along the Solonker Suture further east (Jian et al., 2010). In the study area, a Permian sequence of voluminous greenschist-grade pillow basalts with minor occurrences of chert, tuff, limestone, gabbro ultramafic rocks have been interpreted as the

"Liuyuan ophiolite mélange" (Fig. 2; Zuo et al., 1990; Zuo et al., 1991), and zircons from single gabbro intruding into basalts yielded an age of 286 ± 2 Ma (Mao et al., 2012b). One of these related ultramafic intrusions in the southern Beishan were dated at 232 Ma (SHRIMP U-Pb zircon, our unpublished data, Fig. 3; See Saktura, 2015), and between 220 Ma and 240 Ma using K-Ar and ^{40}Ar-^{39}Ar methods (Zhang et al., 2011). This rift-related magmatism is host to important volcanogenic massive sulfide copper deposits which form in post-orogenic extensional environments (Zhang et al., 2011; Wang et al., 2016b).

3. Analytical methods

Eclogite and leucogranitic vein samples used for major and trace element chemical analyses had any weathered surfaces removed prior to the pulverization. Major element data was attained on fused glass discs by a Phillips PW 4400 X-ray fluorescence (XRF) spectrometer. Based on the analyses of international reference materials, the analytical precision for all major oxides by XRF is estimated to be better than 1%. Trace element (including REE) data was obtained by inductively coupled plasma mass spectrometry (ICP-MS) using a VG Elemental PQII Plus system, according to the procedures described by Qi et al. (2000). The results of standard analyses are consistent with their reference values and within the published error ranges; the differences for trace elements (including REE) range between 5-10%. All major and trace element analyses were conducted at the National Research Centre for Geoanalysis, Chinese Academy of Geological Sciences, Beijing.

Mineral identification in polished thin sections and inclusions in zircons was facilitated by Raman spectroscopy and the Energy Dispersive X-ray Spectrometry (EDS) at the University of Wollongong. The Raman was equipped with Green Diode Solid-State Laser using wavelength of

532 nm with output power of 42 mW and the spot size range of 0.5-1 μm. The EDS investigation was performed using a JEOL JSM-6490LV SEM. The analyses were run under low vacuum to avoid ionization and the need for conductive coating with operating voltage set to 15 kV and spectrum count rate between 52,000 and 60,000 cps. Analyses of inclusions within the zircons were always supported by one background check on every zircon crystal analysed to assure accurate responses from the detector.

Zircon grains were extracted by conventional density and isodynamic methods from 1-10 kg rock samples, depending on composition. Obtained zircon concentrates were handpicked and ~150 grains from each rock type and 20 grains of the standards TEMORA-2 (Black et al., 2004) and 10 grains of OG1 (Stern et al., 2009) standards were cast into an epoxy resin mount. The encapsulated grains were ground to expose a mid-section through them and then polished with 1 μm diamond paste. The mount was mapped using reflected light and cathodoluminescence imaging (CL). The U-Pb zircon dating was conducted at the Australian National University (ANU) in Canberra using the SHRIMP RG instrument. Analytical procedures followed those described by Williams (1998). The analytical spot size was ~20 μm; the reduction of the raw data was conducted using the ANU software 'PRAWN' and 'Lead'. The $^{206}Pb/^{238}U$ ratio of the unknowns was calibrated using measurements of TEMORA-2 (U–Pb ages concordant at 417 Ma; Black *et al.* 2004) undertaken after every 3 analyses of the unknowns. U and Th abundance was calibrated using measurement of the reference zircon SL13 (U=238 ppm) located in a set-up mount. The reduced and calibrated data were assessed and plotted using the ISOPLOT Excel™ software add-in of Ludwig (2003).

Rare earth element (REE) analyses of the zircons was undertaken using LA–ICP–MS at GEMOC, Macquarie University, Australia. New Wave UP213 Nd:YAG 213 nm laser ablation instrument coupled with an Agilent 7700 quadrupole ICP–MS was used to perform the analyses. Jackson et al. (2004) provides through description of the analysis and analytical procedures for *in situ* LA–ICP–MS zircon analysis. The data were calibrated against NIST 612 glass. Laser ablation spots were located atop of the SHRIMP pits.

4. Field occurrence and petrography

4.1 Field occurrence

The Gubaoquan site (40°59'17.80" N, 95°02'20.29" E; WGS84 datum) has the largest and the best-preserved eclogite bodies in the Beishan region (Figs. 2 and 3). Eclogites occur as mafic rock boudins and tabular bodies ranging from a metre to hundreds of metres in length within orthogneiss. The largest bodies are mineralogically zoned, where cores preserve altered eclogite mineral assemblage of garnet + omphacite + accessory minerals; whereas their margins and smaller bodies are retrogressed to amphibolite facies assemblages with relict textural evidence of a previous eclogite assemblage by decompression textures in omphacite. The orthogneiss host rocks to the eclogite have well-developed augen texture and a steeply-inclined foliation (Fig. 3e). The eclogite boudins align with the general foliation trend, and the margins of the eclogite bodies have the foliation impressed on them, whereas cores remain largely non-foliated. This suggests that the eclogite bodies were continuous units prior to superimposed amphibolite facies metamorphism and deformation, during which they were dismembered into the lenticular forms now observed. Their form and interpreted history indicates their protoliths were dykes intruded into the orthogneisses and paragneisses.

The Gubaoquan eclogites are concentrated in proximity of the Gubaoquan-Hongliuyuan fault and a transition zone between augen orthogneisses and paragneisses; interpreted as a tectonically modified contact between a granite intrusion and a sedimentary sequence. Individual augen vary in size from 1 to ~5 centimetre in diameter. Strain in the orthogneiss is heterogeneous, with the highest strain zones displaying augen porphyroclasts largely dismembered to form mylonitic bands, whereas zones of lesser deformation preserve the largest augen and a semblance of an igneous texture.

The leucogranitic vein shown in Figure 3 intrudes the largest eclogite body and orthogneiss. It does not display any signs of deformation or metamorphism, suggesting that its emplacement occurred after these events. Its width varies, and reaches up to 1.7 metres. At its thickest point the vein contains several enclaves of the country rocks.

4.2 Petrography

4.2.1 Eclogite

All eclogite samples reveal pronounced textural and mineralogical evidence of retrogression. Two samples, 14GBQ1 and BS02, were studied, and the latter was chosen for most detailed petrography due to its relatively better preservation state. The original eclogite mineral assemblage consists of garnet, omphacite, quartz and rutile (Fig. 4a). These minerals were subjected to a retrogressive breakdown where garnet rims were replaced by a symplectite of amphibole + plagioclase, and omphacite by a symplectitic lower Na-Al clinopyroxene + plagioclase. This indicates decompression at high temperature (e.g., Nutman et al., 2008). Additional later-stage amphibolite facies overprint is evident by amphibole growth within the matrix and amphibole + plagioclase veining cross-cutting the rock. These observations are consistent with the previous petrographic examinations of Liu et al. (2010) and Qu et al. (2011).

4.2.2 Orthogneiss

The representative orthogneiss samples 14GBQ8 and 14GBQ10 consist of microcline, quartz, plagioclase, muscovite, minor biotite and tourmaline (Fig. 4b). Abundant large prismatic zircons are present. Moderate to high effects of alteration are present in the form of sericitization and chloritization of feldspars, especially plagioclase. The porphyroclastic augen in the rock consist of microcline, whereas the foliation is defined by muscovite, quartz ribbons and to a lesser extent biotite (Fig. 4c).

Myrmekite, a symplectite of a plagioclase + quartz was found within the orthogneisses. Figure 4b shows the symplectite that is embedded between plagioclase and microclines. The convex boundary of the myrmekite towards the microcline indicates that it formed from that mineral in the replacement reaction. This mineral reaction and its good preservation indicates formation under retrogressive regime at upper amphibolite facies in the process of fluid infiltration (Ashworth, 1986; Menegon et al., 2006). This feature has significant implications for this terrane and it will be further examined in the Discussion.

4.2.3 Leucogranitic vein

Sample 14GBQ2 was collected from the largest leucogranitic vein shown in Figure 3. The rock consists of plagioclase, quartz, muscovite and minor K-feldspar, with overall equigranular texture (Fig. 4d). The feldspars display an advanced sericitization evident by the sericite overprint and a “dusty” texture, and by chloritization along the feldspar grain boundaries.

The mineral assemblage is purely igneous with some hydrothermal effects, but with no evidence of regional metamorphism or deformation.

5. Results

5.1 Major and trace element geochemistry

Seven eclogite samples were analysed (Table 1) and were compared with another 7 samples collected by Qu et al. (2011). Two of our samples came from the core and retrogressed margin of a single body, and remaining 5 correspond to more garnet-rich samples. The leucogranitic vein sample was collected from the largest intrusion (Fig. 3).

5.1.1 Eclogite

The major element chemistry of the eclogites indicates a basic protolith, in accordance with the interpretation of the bodies as tectonically-dismembered dykes. High field strength elements (HFSE) including REE remain relatively immobile at UHP conditions (Tang et al., 2007; Xiao et al., 2012; Xiao et al., 2016), therefore our investigation of the geodynamic setting is based on this suite of elements (e.g. Ti, Th, Nb and Yb). Nevertheless, mobilization is possible when partial melting has occurred (Jiang et al., 2005; Szilas et al., 2014). However, there is no textural evidence for this in the eclogites of this study.

To assess element mobility in retrogression from eclogite facies our data from the largest boudin is compared with data from smaller boudins studied by Qu et al. (2011). This revealed a significant enrichment in Zr, Hf, Y, Nd, Sm and Yb in the smallest bodies. This was accompanied by an enrichment in SiO_2 and a significant increase in LOI values, which are on average 0.44 wt.% for the large eclogite boudins and 2.43 wt.% for the smallest, indicating significant fluid inundation. For this reason, results from the Qu et al. (2011) geochemical data should not be used for detailed geochemical interpretation.

All eclogite samples show similar whole rock composition, except outlier 14GBQ5-1 which seems to be either enriched or depleted in different major elements. Eclogite samples have SiO_2 content of ~47 wt.%, and the outlier is 50 wt.%. The FeO content of the outlier is 15.07 wt.% in comparison to average 12 wt.% for the rest of the samples. However, its MgO and CaO content (5.59 and 7.46 wt.%, respectively) is less than in the rest of the samples, which averages at 7.04 and 10.95 wt.%, respectively. This variation between the samples could be driven by small differences in garnet concentration in the bulk sample, as heterogeneity within the rock was observed prior to pulverization. The TiO_2 concentration varies between 1.40-1.81 wt.%, with only a slight enrichment in 14GBQ5-1, whereas Al_2O_3 concentration is largely consistent across all samples, averaging 14.12 wt.%. The Na_2O and K_2O concentration for this eclogite is ~2.23 and 0.21 wt.% respectively.

Within the TAS (Le Bas et al., 1986) and the AFM (Irvine and Baragar, 1971) diagrams (Supplementary material) the Gubaoquan eclogite precursor is classified as a tholeiitic basalt. Within the Shervais (1982) Ti-V diagram the eclogite samples fall within the field of MORB, with one outlier in the ARC field (Fig. 5a). In the Nb/Yb-Th/Yb diagram of Pearce (2008) the sample suite falls to the right of N-MORB field (Fig. 5b), indicating either igneous fractionation (F) or Th loss during metamorphism (e.g., Szilas et al., 2014).

In a chondrite normalized rare earth element (REE) plot (Fig. 6a) all elements are enriched relative to chondrite, with slight enrichment in LREE, without significant Eu anomalies. In the primitive mantle normalized patterns (Fig. 6b) there is no significant fractionation of Nb relative to La or Ti relative to Eu or Dy. In agreement with the trace element discrimination diagrams (Fig. 5) this indicates that anhydrous decompression melting rather than fluxing by fluids is the origin of the protolith magmas. The trace elements show less consistent pattern, there is an overall tendency to show enrichment in K relative to La, negative Th and Zr anomalies. The Th negative anomaly might have been caused by Th loss during eclogite facies metamorphism, as during high-grade metamorphism Th can be mobilized, as was argued by Szilas et al. (2014). This is further evident by low Th/Yb ratios falling below MORB field on Th/Yb vs. Nb/Yb plot of Pearce (2008). No significant Ti or Nb negative anomalies were observed, further indicating that formation in a suprasubduction zone environment was unlikely. Overall trend in the patterns points to either fractionation processes or mild contamination of the magmas by granitic crust.

5.1.2 Leucogranitic vein

The granitic vein has SiO_2 content of 76 wt.% and its major and minor oxide composition confirms this granitic body as a calc-alkaline and strongly peraluminous granite, according to Le Bas et al. (1986) and Sylvester (1989) classification schemes (Supplementary material). On the granite tectonic discrimination diagram of Pearce et al. (1984) sample 14GBQ2 straddles the syn-collisional and volcanic granite fields (Supplementary material).

5.2 Zircon U-Pb geochronology

5.2.1 Zircon morphology

Zircon grains from the eclogite sample 14GBQ1 are mostly equant and multifaceted with some displaying irregular shapes. Their length ranges from 70 to 250 μm with an average length-to-width ratio of 2:1. The cathodoluminescence (CL) imaging revealed cores and mantling rims (Fig. 7). The irregular shapes of the cores imply that these domains were subjected to dissolution and/or recrystallization during metamorphism. Both domains have homogenous texture with varying luminescence, with cores generally brighter in CL relative to the mantling rims. The metamorphic rim development is limited, and generally cores constitute the majority of the grain mass. The process of corrosion/recrystallization is evident by etched cavities within the cores (Fig. 7), across which overgrowth became the most pronounced. These embayments provided enough surface area for a microprobe U-Pb analysis, whereas most of the zircon rims are too narrow to be analysed.

Zircons from the orthogneiss sample 14GBQ10 are prismatic and characteristic of igneous grains and display only restricted modification during metamorphism. The grain lengths range from 80 to 350 μm with variation in aspect ratios from 1:1 to 3:1, where 2:1 is the most dominant. The CL imaging reveals broad and oscillatory zoning, with the latter being the most dominant (Fig. 7). Most grains display textural modifications in the form of a convolution of banding and homogenization overprinting the oscillatory zoning, which is thought to be caused by late magmatic to post magmatic recrystallization (e.g., Corfu et al., 2003). Since no metamorphic growth was observed on orthogneiss zircon grains, the obtained U-Pb ages represent crystallization age of the granitic protolith.

Zircons from the leucogranitic vein sample 14GBQ2 display prismatic to equant morphology with oscillatory zoning characteristic of an igneous zircon. The grains vary between 40 and 300 μm long, with highly diverse aspect ratios ranging between 1:1 and 5:1, with an average of 3:1. The CL imaging reveals oscillatory zoning to be a dominant internal texture (Fig. 7). However, several inherited zircons have homogenous cores and some grains also display broad zoning. The luminescence intensity is highly variable, as some grains are extremely dark with slight zoning, whereas others were intensely light, masking any internal structures. In many grains, there is disruption to oscillatory zoning, taking the form of irregular shapes, convoluted zones and highly luminescent patches. This is attributed to processes similar to those causing recrystallization within the orthogneiss zircons.

5.2.2 Mineral inclusions

Several mineral inclusions were observed within the zircon core and rim domains of the eclogite sample 14GBQ1. These include garnet, pyroxene, quartz, rutile, plagioclase and apatite; as were identified using EDS. This mineral assemblage present within both zircon domains was also identified in previous study of Liu et al. (2010), who concluded that zircon growth occurred in both eclogite and the amphibolite facies metamorphism.

5.3 Zircon U-Pb ages

5.3.1 Eclogite

Thirty one analyses were performed on 24 zircon grains from the eclogite sample 14GBQ1 (Table 2). Twenty-eight spot analyses were performed on core domains and only 3 spots on overgrowth rims as majority of the rims were too narrow to be analysed. Additionally, domains in 3 zircon grains have been completely reset, giving Cenozoic ages (Fig. 7; discussed in section 6.4), these were not considered during assessment of the timing of the eclogite facies metamorphism. Another five analyses (1.1, 10.1, 11.1, 11.2 and 12.1) were discarded, as these sites were judged to contain both core and rim domains, due to narrowness of the rims. The core domains have Th = 0.4-73 ppm and U = 12-279 ppm, and Th/U ratios range between 0.01 and 0.26. Plotted prior to correction for common Pb, all 19 analyses form a tight cluster close to concordia (Fig. 8a). Regression of this data anchored by a Zartman and Doe (1981) common Pb $^{207}Pb/^{206}Pb$ ratio appropriate for an early Neoproterozoic orogenic system yielded a concordia intercept of 860 ± 18 Ma (n=19; MSWD = 1.02). Three analyses performed on the rim domains revealed abundance range of Th = 0.06-0.18 ppm and U = 30-33 ppm with Th/U ratio range between 0.002 and 0.006 with mean of 0.003 (Table 2). Following correction for common Pb the rims plot near concordia and have a weighted mean $^{238}U/^{206}Pb$ age of 466 ± 60 Ma (n=3; MSWD = 1.3). Regression of the data anchored with the same common Pb composition resulted in a concordia intercept age of 466 ± 27 Ma (MSWD = 0.95), and is interpreted to represent the age of Palaeozoic metamorphism (Fig. 8b).

5.3.2 Orthogneiss

Twenty analyses were performed on 19 zircon grains from the orthogneiss sample 14GBQ10 (Table 2). Analysis sites were aimed at undisturbed conformable oscillatory zoning and several convoluted zones in order to determine the age of the imposed disturbance. However, the disturbance to the trace element distribution within zircons was shown to have no effect on the U-Pb isotopic system, as all ages are indistinguishable within error, suggesting late magmatic modification of the oscillatory-zoned zircon. Analyzed zircons have Th = 158-654 ppm and U = 125-1287 ppm with Th/U ratio range between 0.19 and 1.26 (Table 2). The analyzed sites produced a tight cluster on the concordia diagram where all gave Precambrian $^{206}Pb/^{238}U$ ages ranging from 799 to 946 Ma. The weighted mean $^{238}U/^{206}Pb$ age was established at 920 ± 14 Ma (n= 20; MSWD = 0.19) for the orthogneiss protolith zircons (Fig. 8c).

5.3.3 Leucogranitic vein

Sixteen zircon grains from the leucogranitic vein sample 14GBQ2 were analyzed (Table 2). They have Th = 157-377 ppm and U = 439-1131 ppm and Th/U ratios range between 0.31 and 0.59. Twelve analyzed sites produced U-Pb ages indistinguishable from each other weighted mean $^{238}U/^{206}Pb$ age at 424 ± 8.6 Ma (n= 12; MSWD = 0.25) and are interpreted as the time of magmatic emplacement (Fig. 8d). The remaining four analyses are interpreted to be inherited from the country rock, as they all have Precambrian ages similar to those of the local orthogneisses.

5.4 LA-ICP-MS zircon geochemistry

Eleven laser ablation ICP-MS trace element analyses were performed on zircons from the eclogite sample 14GBQ1; these correspond to prior SHRIMP U-Pb analyses of six cores and five rims. The results are presented in Table 3 and chondrite-normalized rare earth elements (REE) patterns are shown on Fig. 9.

The cores show progressive enrichment in heavy REE (HREE) by three orders of magnitude in comparison to the light REE (LREE). All analyses show positive Ce anomalies characteristic of terrestrial rocks (Thomas et al., 2003) along with negative Eu anomaly of varying degrees (Eu/Eu* = 0.28-0.40). These patterns indicate zircon growth in equilibrium with plagioclase in environment devoid of garnet; diagnostic of igneous zircon (e.g., Rubatto, 2002). The Ti concentration in core domains does not vary significantly; it is within range of 7.83–9.78 ppm. Ti-in-zircon thermometry calculations based on Watson et al. (2006) provided temperature range of 720–739°C for the igneous cores, with the mean temperature 731 °C. These temperatures match well estimates of Liu et al. (2010), however the results could be underestimated as protolith cores most likely crystallized in rutile-absent environment and instead in the presence of other Ti-bearing phases such as titanite or ilmenite. Work of Watson and Harrison (2005) have shown that most igneous melts that are capable of crystallizing zircons will have TiO_2 activity of ~0.5 what will result in underestimate by at most 70°C. Therefore, eclogite protolith core temperature estimates using Ti-in-zircon thermometer should be used as an approximate result.

From five analyses performed on zircon rims, three correspond to the sites used in U-Pb age determination (3.1, 4.1 and 5.1), whereas remaining two (10.1 and 12.1) were excluded in dating process due to slightly high ages caused by analytical spot overlapping both cores and rim domains (see Section 5.2.1). This was avoided during LA-ICP-MS analysis by decreasing spot size and analysing farther away from the core. Relative to core analyses, the patterns show less enrichment in HREE by two orders of magnitude in comparison to the LREE (Fig. 9). Importantly, there are no negative Eu anomalies present in any of the analysed rims (Eu/Eu* = 0.60-1.34); these two characteristics are diagnostic of zircon growth in presence of garnet and environment devoid of plagioclase. The Ti concentration within rim domains ranges from 1.83 to 5.42 ppm. Ti-in-zircon thermometry calculations based on Watson et al. (2006) provided temperature range of 611–690°C for the mantling rims, with the mean temperature 659 °C. These results are regarded as accurate, given that the rims crystallized in the presence of quartz and rutile.

6. Discussion

6.1 Timing of the Gubaoquan eclogite facies event

The field occurrence of the eclogite bodies indicates that they represent mafic dykes or sills intruded into continental granitic rocks that subsequently were dismembered during synkinematic high-grade metamorphism (Fig. 3a-e). The geochemical analyses show that mafic metamorphic rocks of the Gubaoquan have precursor composition resembling tholeiites formed by decompression melting. These rocks underwent eclogite facies metamorphism, evident by the mineral assemblage of garnet + omphacite + quartz + rutile, which subsequently was significantly altered during high temperature decompression. U-Pb SHRIMP zircon dating of the metamorphic rim domains provided an age of 466 ± 27 Ma which supports previous age determinations (Liu et al., 2010; Qu et al., 2011). The REE LA-ICP-MS study on zircon rims which show subdued HREE enrichment caused by growth in presence of garnet and the absence of negative Eu anomalies indicating an environment devoid of plagioclase (Fig. 9). Presence of garnet and lack of plagioclase in the system is a diagnostic feature of eclogite facies metamorphism (Rubatto, 2002). Ti-in-zircon thermometry of Watson et al. (2006) used in this study indicates a temperature range 611-690 °C at the time of eclogitic zircon growth. Pressure estimations were previously attempted using pseudosection calculations and indicate > 15.5 kbar (Qu et al., 2011).

6.2 Intra-continental protolith of the Beishan eclogite and its tectonic association

In previous studies, the Gubaoquan eclogite was interpreted as a fragment of oceanic crust which was subducted, metamorphosed to eclogite facies and then exhumed during the Early Paleozoic (Liu et al., 2010; Qu et al., 2011). This interpretation was based on whole rock geochemical MORB signatures and positive whole rock initial ε_{Nd} isotopic signatures obtained by Qu et al. (2011). Those interpretations formed the basis of tectonic models developed for the orogen. However, this protolith classification is inconsistent with field relationships and the protolith ages of this terrane. Our alternative interpretation is based on geological context of the eclogites as well as robust zircon ages and geochemistry, which indicate that the high-pressure regime forming the Gubaoquan eclogite was not generated by subduction of oceanic crust, but instead, partial subduction and tectonic thickening of continental crust cut by dolerite dykes or sills, during Middle Ordovician collisional orogeny. The inherited Proterozoic zircons in the eclogite and zircons in the surrounding gneisses indicate that the continental protolith is Neoproterozoic.

High metamorphic grade of the eclogite-bearing gneiss units led to the interpretation of the gneisses and eclogites as a separate microcontinent, the Liuyuan microcontinent by Liu et al. (2010), or the Shuangyingshan unit by Xiao et al. (2010). Instead, we suggest that the Neoproterozoic Gubaoquan eclogite and surrounding gneisses are equivalents of the adjacent Dunhuang Block, and not an allochthonous assemblage as proposed in previous studies. Collision of the Dunhuang Block with southern terranes of the Beishan Orogen was previously postulated (Liu et al., 2010; Wilhem et al., 2012; Wang et al., 2014), but the eclogite protolith was interpreted as oceanic in origin (Liu et al., 2010; Qu et al., 2011), and Cenozoic faults were interpreted as reactivated sutures that dissect the orogen into multiple blocks requiring multitude of subduction zones to accommodate all these terranes. Here, we have considered several similarities between the Dunhuang Block and southern high-grade Beishan terranes. Eclogites from the Gubaoquan (Liu et al., 2010; Qu et al., 2011, this study) and recently identified eclogite in the mélange of the Dunhuang Block (Wang et al., 2017a) and previous studies of the Dunhuang HP granulites (Zong et al., 2012; He et al., 2014b; Wang et al., 2017b) have shown that these rocks underwent high-grade metamorphism in proximal space and time (see section 6.5). Additionally, the Shuangyingshan unit and Dunhuang Block were shown to have the same geothermal gradients at the time of metamorphism (Qu et al., 2011; Wang et al., 2017b). The

Early Paleozoic high-grade metamorphism and migmatization of the Shibanshan Block which is wedged between the Dunhuang Block and Shuangyingshan unit (He et al., 2014b; He et al., 2015b; Wang et al., 2016a), implies that similar tectonic conditions span across all these three terranes. Furthermore, lack of extensive I-type magmatism along the margin of the Dunhuang Block suggests that southward subduction underneath the Dunhuang Block during Ordovician is unlikely, whereas widespread Carboniferous granitic magmatism across both the Dunhuang Block and Mazongshan-Hanshan Block (Huaniushan Arc) implies collision, suturing and subduction flip by Silurian (Fig. 10). Shared post-Ordovician geological histories across the Dunhuang, Shibanshan and Shuangyingshan led us to conclude that these terranes are part of a composite microcontinent experiencing southward subduction throughout the Carboniferous and until final closure of the Solonker Ocean and amalgamation of the CAOB in the Late Carboniferous to Early Permian (Han et al., 2015; Kröner et al., 2017).

Previous studies suggested that the Dunhuang Block and southern Beishan terranes differ from each other, because Archean zircons have not been found in the latter (He et al., 2013; Zong et al., 2013; Yuan et al., 2015). Resemblance in meta-igneous zircon populations across these terranes was previously used to separate the Dunhuang Block from southern Beishan terranes (Jiang et al., 2013; He et al., 2014b; He et al., 2015b), which in turn were correlated with Central Tianshan Terranes (He et al., 2015a). However, in our model the southern Beishan terranes are equivalents of Proterozoic active margin of the Dunhuang Block which would have experienced extensive magmatism, as evident by the abundance of orthogneisses. This magmatism is likely to have diluted Archean zircon abundance, making them rare in this part of the block, and in this manner the hinterland appears distinct from the active margin. This is exemplified by studies of Song et al. (2015), Song et al. (2016) and Ao et al. (2016), where only few Paleoproterozoic and Archean zircons have been found in the Beishan terranes, and the dominant signatures are of *ca.* 1,400 and 900 Ma. This implies that basement in southern Beishan contained Archean rocks just as Dunhuang Block, but it has been overprinted by Proterozoic magmatic events. Zong et al. (2013) identified Proterozoic and Paleozoic tectonothermal events within Dunhuang Block which could be responsible for Pb-loss and recrystallization in rocks *ca.* 1,760 Ma and older in the study conducted by He et al. (2013). Our orthogneiss and other Mesoproterozoic to Neoproterozoic rocks in southern Beishan do not record such effects (Jiang et al., 2013; Liu et al., 2015). Therefore, it could be possible that these effects are not present in younger meta-igneous rocks because their intrusion into the Paleoproterozoic crust is sole cause of the Pb-loss and recrystallization. Additionally, absence of these effects in the southern Beishan Precambrian rocks, excludes Paleozoic collision as the possible cause. This leaves the *ca.* 1,400 Ma and *ca.* 900 Ma magmatic and tectonic events as the probable cause, implying proximal co-existence of these the Dunhuang Block and southern Beishan high-grade rocks during Neoproterozoic.

A continental origin for the eclogites has significant implications for the tectonic evolution of the orogen, because it implies partial subduction of the continental crust beneath another continent or continental arc terrane and therefore, provides timing of *closure* for an ocean basin. This is significant because subduction-related eclogites can be formed at any time during subduction of an extant ocean basin, whereas continental eclogites reflect a collisional event that terminates the life of an ocean and subduction zone. Other similar examples of such Palaeozoic continental eclogites have been documented in the Caledonian of North East Greenland (Gilotti et al., 2004), the As Sifah eclogites beneath the Semail Ophiolite in Oman

(Searle et al., 1994), and the Tso Morari eclogite along the Indus Suture in the Himalaya Orogen (de Sigoyer et al., 2000).

The MORB-like signatures obtained on the eclogite do not necessarily imply an ocean crust protolith. The MORB signatures for basaltic and/or gabbroic rocks are reported in crustal intrusions (Rubatto, 1998), and in eclogites with a confirmed continental origin (Casado et al., 2001; Wang et al., 2013; Park et al., 2014). The Gubaoquan eclogite bodies are distributed along a contact zone between orthogneiss and paragneiss. These gneissic rocks are strongly deformed, displaying augen and mylonitic textures. The lensoidal morphology of an eclogite bodies is parallel to foliation of the country rock (Fig. 3a-c), indicating the eclogitized dykes and the orthogneisses underwent post-eclogite, late stage amphibolite facies overprint. Petrographically, this is evident by amphibole + plagioclase symplectites and microveins within the eclogite, and plagioclase + quartz symplectite in the orthogneiss. Both eclogite and host rocks show syn-metamorphic and syn-deformational textures, that are indicative of co-existence prior to collisional event responsible for the formation of these textures. This implies coexistence of the protoliths prior to the eclogite forming event and coeval exhumation, contrary to the allochthonous ophiolitic origin previously postulated (Liu et al., 2010; Qu et al., 2011). Importantly, the gneisses enveloping the eclogite bodies do not consist of mélange. Wang et al. (2017a) reported Silurian-Devonian mélange in other parts of this region, which could be a probable mechanism for diapiric emplacement of oceanic eclogites into the crust. However, the geological setting of the Gubaoquan eclogites has a greater resemblance to eclogites hosted in high-grade continental rocks (e.g., As Sifah or Tso Morari) which represent partially subducted margin of a continent (Arabia and India, respectively; Searle et al., 1994; de Sigoyer et al., 2000). Emplacement of these partially subducted continental rocks usually involves exhumation of deep “core complexes” rather than diapiric rise of an ophiolitic mélange. Therefore, we suggest that the tectonic double thickening of the continental crust to be most probable mechanism for onset of eclogite facies metamorphism.

The SHRIMP U-Pb zircon ages can provide additional constraint on the protolith type. The zircon core domains in the eclogite provided an age of 860 ± 18 Ma. This is most likely the age from xenocrystic zircons, based on the large quantity of zircons present in this mafic rock. Thus 860 ± 18 Ma is a minimum age for protolith formation. This leaves approximately 400 million years between the protolith formation and the eclogite facies metamorphism, which equates to two or even three times an average maximum ocean crust age (Müller et al., 2008). Additionally, eclogites of ophiolitic origin are typically not much younger than the ophiolitic protolith (e.g., Manton et al., 2017). Therefore, ophiolitic origin for the Gubaoquan eclogite is unlikely.

The whole rock $\varepsilon_{Nd}(T)$ isotope values were previously used by Qu et al. (2011) to support oceanic affinity of the Gubaoquan eclogite. The array of reported $\varepsilon_{Nd}(T)$ values consists of 7 eclogite samples, where only GBQ1 and GBQ2 show positive signatures of +6.4 and +6.3 (respectively), whereas remaining samples are slightly negative. However, this approach is questionable for this rock. There is ample opportunity for isotopic contamination during intrusion into older crust or at the time of metasomatic retrogression. In the latter case, substantial fluid ingress was identified, affecting the eclogite and the gneissic country rocks. Therefore, we contend that these whole rock Nd isotopic signatures indicate modification of a positive ε_{Nd} values, and that they do not record faithfully the character of the igneous protolith of the eclogite.

6.3 Constraint on the termination of high grade metamorphism and ductile deformation

The leucogranitic vein (14GBQ2) lacks any textural evidence of metamorphism or deformation, indicating its late- to post-kinematic emplacement. The U-Pb zircon age of 424 ± 8.6 Ma corresponds to its timing of crystallization and indicates that major tectonothermal processes had ceased by the Late Silurian in this part of the Beishan Orogen. Leucogranites are typically formed in collisional orogens, where particularly pelitic rocks in overthickened crust undergo partial melting in a hot decompressional segment of the clockwise *P*,*T*,t path (Nabelek and Liu, 2004). In which case, the age of 424 ± 8.6 Ma marks a late stage of the exhumation, with reduced tectonic activity following the collisional event, which gave rise to the 466 ± 27 Ma eclogite facies metamorphism.

6.4 Cenozoic thermal zircon resetting

Three zircons of ages 44-41 and 14 Ma were found in the eclogite sample 14GBQ1 (Fig. 7 and Table 2). These did not show any effects of internal damage in CL images, but their U-Pb systems has been reset. There is no magmatic or metamorphic activity recorded in the Beishan during this period. Thus, a different external force must be operating. We suggest that large-scale Cenozoic faulting could be a potential mechanism, as heat generation from shear alone can increase temperature to e.g., 100° or 200° C at 5 and 35 km depth, respectively (Leloup et al., 1999). Furthermore, high content of impurities within zircon (Hoskin and Black, 2000), and/or metamict zircons are susceptible to recrystallisation or resetting, especially in the presence of fluids where required temperatures for reset can drop to 200-120° C (Hoskin and Schaltegger, 2003). Shearing and transpressional forces associated with the sinistral Altyn Tagh Fault system may be responsible for resetting some zircons since extensive network of parallel faults have severely dissected and deformed the Beishan Orogen (Fig. 2). These reset ages are possibly related to Cenozoic faulting associated with far-field subduction of Indian continental crust beneath Asia resulting in onset of continental collision (Aitchison et al., 2007), and the extrusion of east Asia (Tapponnier et al., 1982). The 44-41 Ma ages correspond to Himalayan eclogites (55-43 Ma) emplaced south of the Indus Suture (de Sigoyer et al., 2000; Donaldson et al., 2013). This indicates advanced continental collision, and suggests major fault propagation through Asia as it was previously postulated (Tapponnier et al., 1982; Yin et al., 2002). The ca. 14 Ma age can be correlated with significant displacement along Altyn Tagh Fault, when a drastic change in mode the of sedimentation was observed (Sun et al., 2005). Furthermore, Coleman and Hodges (1995) determined accelerated uplift of Tibetan Plateau at this time from E-W extensional faulting, which would cause increased tectonic activity along extrusion fault network. Our reset zircon ages correspond to significant tectonic events associated with the India-Asia collision and development of strike-slip fault systems such as the Altyn Tagh Fault. We tentatively suggest that Cenozoic transpressional faulting in the Beishan Orogen may be responsible for resetting of susceptible zircons in our sample.

6.5 Tectonic model, setting and implications

Results in the literature and those obtained in this study reveal pronounced magmatic activity on a continental margin (most likely Rodinian) that produced the Proterozoic granitic protoliths of the Beishan orthogneisses (Liu et al., 2015; Yuan et al., 2015). From the Paleozoic geological history of the Beishan Orogen, we interpret current data on the Gubaoquan eclogite to show that a first collision occurred between the leading edge of the Dunhuang Block, and the active continental margin of the Mazongshan-Hanshan Block (Huaniushan Arc) with a subduction to the north (Fig. 10, stage C). The continental margin of the Dunhuang Block was shown to be passive at this time (Wang et al., 2016a), and the subduction polarity and development of the Huaniushan Arc prior to collision (Fig. 10, stage B), is evident by extensive magmatism beyond eclogite locality and the presence of adakites and Nb-enriched basalts which imply slab melt contribution to the active continental margin magmatism (Mao et al., 2012a).

In the process of collision between Dunhuang and Mazongshan-Hanshan blocks, we contend that at 466 ± 27 Ma the thinned, continental crust of the Dunhuang Block was drawn beneath the Proterozoic basement of the active Huaniushan Arc (Mazongshan-Hanshan Block), and was metamorphosed to eclogite facies by at least double thickening of the continental crust. It is here suggested, that the Gubaoquan eclogite and surrounding gneisses are the metamorphic equivalents of the Dunhuang Block as shown by the evidence in *section 6.2* (Fig. 10, stage C). During this process, the deep crust underwent high-pressure metamorphism and deformation, which was responsible for eclogitization followed by dismembering of the intrusions into lenticular and tabular bodies, and development of the augen and mylonitic textures in the orthogneisses and paragneisses. The eclogite facies assemblages have only developed in the mafic intrusions. The quartzofeldspathic orthogneisses do not record mineral phase changes at eclogite facies due to reduced availability of reaction catalysing fluids sequestrated within micas, which have shown stability across high-pressure and ultrahigh-pressure metamorphic regimes. This is typical for the continental terranes undergoing high-pressure metamorphism during collisional events (e.g., Gilotti et al., 2004 and references therein).

The *P*-*T*-t paths of the eclogite metamorphism have been described by Qu et al. (2011), their work has also provided retrogression age using $^{40}Ar/^{39}Ar$ dating method on biotite from the gneissic country rock, which shows a well-defined plateau age at 428.9 ± 3.8 Ma. This retrogression age, which is associated with the exhumation, coincides with the HP metamorphism observed in the Dunhuang Block to the south (Fig. 2 and 10, stage C). Thorough work of Zong et al. (2012), He et al. (2014b) and Wang et al. (2017a) revealed prolonged peak HP granulite facies metamorphism in the Dunhuang Block during *ca*. 440 – 430 Ma and eclogite facies at *ca*. 411 Ma. This supports our interpretation of the eclogites, orthogneisses and paragneisses of the Shuangyingshan unit as being part of the Dunhuang Block. These conclusions are further based on the similarities in metamorphic grades, general proximity, exhumation *P-T* paths and geothermal gradients across these terranes (Qu et al., 2011; He et al., 2014b; Wang et al., 2017b, this study). The broad difference in range of metamorphic ages in this region can be attributed to formation from different protoliths and in different settings. The Gubaoquan eclogite formed within subducted continental crust in early stage of continental collision, whereas the Dunhuang eclogite is oceanic and embedded within a mélange (Wang et al., 2017a), most likely forming in the later stage, when compressional forces decreased enough for mélange to be emplaced. We suggest that slab detachment of the down-going Dunhuang Block is responsible for rapid exhumation of the buoyant continental crust containing eclogitized dykes and the production of late to post-kinematic leucogranitic veins (Fig. 10, stage D). This links these two HP metamorphic episodes, which were previously thought to be a part of two distinct orogenic episodes, and adjoins the Dunhuang Block to the Beishan Orogenic collage.

These linked orogenic events closed the ocean basin between them, but we do not suggest that this was final Palaeo-Asian Ocean closure. Instead, we interpret this as final termination of an ocean basin between the Dunhuang Block to the south (northern extension of the Tarim Craton) and the Mazongshan-Hanshan Block to the north. Another ocean existed between the Mazongshan-Hanshan Block and the active southern margin of the Siberian Craton. We postulate that a subduction flip occurred following the collision of the Dunhuang and Mazongshan-Hanshan Blocks resulting in southward subduction beneath the Dunhuang-

Mazongshan-Hanshan composite block and development of shared Silurian to Carboniferous arc magmatism across all three blocks, due to one subduction zone with varying dip angle over its lifespan (Fig. 10, stage E). This simpler explanation reduces the need to invoke three separate arc systems (Shibanshan, Huaniushan or Heiyingshan) of the same age developing separately on each block as outlined by the model of Xiao et al., (2010).

We do not agree with models suggesting reopening of the new ocean basin in the Permian or interpretation of the Liuyuan pillow basalts as ophiolitic, or as being part of mélange as previously suggested (Xiao et al., 2010; Mao et al., 2012b; Zhang et al., 2015b). These models involving Permian ocean closure are contradictory to the presence of the Ordovician HP metamorphic rocks studied in this current paper. Our field observations, unpublished SHRIMP U-Pb zircon data on lamprophyre dyke (232 Ma; Fig. 3; See Saktura, 2015, p. 84) and interpretation of series of events in the southern Beishan Orogen is instead consistent with work of Li et al. (2013) and Wang et al. (2016b) who proposed presence of the rift zone, but not an ocean basin, and more likely a terrestrial lacustrine depression (Fig. 10, stage E). It is possible that this Permian rift basin was situated behind the Silurian-Carboniferous arc and was related to roll-back extension caused by a retreating, south-dipping Solonker Ocean slab. Finally, there was amalgamation of the Central Asian Orogenic Belt, as the active margin of Siberian Craton collided with North China and Tarim cratons, consuming the Solonker Ocean by the Late Carboniferous to Early Permian (Han et al., 2015; Kröner et al., 2017). This may account for supra-subduction zone geochemical affinity of the pillow basalts in the Permian rift basin basalts in the Beishan (Mao et al., 2012b; Zhang et al., 2015b).

7. Conclusions

This study resulted in the following conclusions:

- The Gubaoquan eclogite and surrounding gneisses are continental parts of the Dunhuang Block, based on field relationships, geochemistry and inherited zircon geochronology. The eclogite is a mafic dyke/sill intruded into Neoproterozoic (920 ± 12 Ma) orthogneiss. Therefore, the eclogites are not fragments of subducted oceanic crust incorporated into a mélange as previously interpreted.
- The continental origin of the eclogite implies orogenesis at the termination of subduction, with closure of an ocean basin between colliding arc and continental terranes. This is contradictory to the previous oceanic origin, in which the inception or cessation of subduction is unconstrained.
- The age of 424 ± 8.6 Ma for a post-kinematic granitic vein constrains termination of metamorphic and deformational. It probably formed during high temperature exhumation of the eclogite and orthogneisses following slab detachment after collision.
- Similar minimum protolith ages and coeval formation of Gubaoquan eclogite with HP granulites in the Dunhuang Block indicate a shared metamorphic history. Hence, we suggest the Gubaoquan eclogite and surrounding orthogneisses and paragneisses are equivalents of the Dunhuang Block metamorphic basement.
- A single south dipping subduction zone eliminates the need for 3 separate arcs (Shibanshan, Huaniushan and Heiyingshan arcs) developing contemporaneously but independently on the Dunhuang, Mazongshan and Hanshan blocks.

- Final closure of the Paleo-Asian Ocean is not related to the Gubaoquan eclogite in southern Beishan Orogen.

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Figure Captions

Figure 1. Simplified tectonic map of the Altaids showing cratons, orogens and major active faults, modified after Sengor et al. (1993) and Liu et al. (2010).

Figure 2. a) Terrane map of the major units in the Beishan Orogen and adjacent orogens, modified after Li and Xu (2007). **b)** A geological map of the Gubaoquan area showing major tectonic units in the southern Beishan (modified after Li and Xu, 2007). The HP granulite ages are sourced from Zong et al. (2012) and He et al. (2014b). Ages highlighted in red were acquired in this study.

Figure 3. a) Far view of the eclogite (14GBQ1) and orthogneiss host-rock outcrop; **b)** Close-up of the site where eclogite 14GBQ1 and leucogranitic vein 14GBQ2 samples were collected; **c)**

View of the orthogneiss country rock from the eclogite outcrop, dolerite dyke swarms severely dissect the local geology; **d)** Close-up of the orthogneiss outcrop; **e)** Outcrop of the orthogneiss country rock, showing augen texture and steeply aligned foliation; **f)** Orthogneiss 14GBQ10 sample collection site, and preferentially weathered lamprophyre dyke (see Saktura (2015) for more details).

Figure 4. Photomicrographs of rocks investigated in this study. Abbreviations sourced from Kretz (1983). **a)** Eclogite showing retrogressed eclogite mineral assemblage; **b)** XPL photomicrograph of the orthogneiss showing mineral assemblage and myrmekite symplectite replacing the microcline; **c)** PPL photomicrograph of the orthogneiss showing augen and foliation fabric; **d)** Leucogranitic vein with mineral assemblage consisting of quartz, K-feldspar, plagioclase and muscovite.

Figure 5. a) The Ti/1000-V diagram of Shervais (1982) showing the Gubaoquan eclogite sample spread on the basalt discrimination diagram; **b)** Th/Yb - Nb/Yb classification diagram of Pearce (2008) for basalts, showing down drift from the MORB field for all eclogite samples. (SC- subduction component, CC- crustal contamination, WPE- within-plate enrichment, F- fractionation).

Figure 6. Chondrite (**a**) and primitive mantle (**b**) normalized patterns for the Gubaoquan eclogite, red patterns are from this study and blue from the study of Qu et al. (2011). Geochemical data for the reference materials (OIB, N-MORB and E-MORB) are from Gill

(2010). Chondrite normalizing values are from Boynton (1984) and primitive mantle are from Sun and McDonough (1989).

Figure 7. The cathodoluminescence (CL) images of analyzed zircons. Circles and numbers indicate SHRIMP analysis spots; all ages and errors are given as Ma.

Figure 8. Tera-Wasserburg concordia diagrams for U-Pb ratios of SHRIMP analyzed zircons. **a)** 14GBQ1 eclogite core domains; **b)** 14GBQ1 eclogite rim domains; **c)** 14GBQ10 Orthogneiss sample, the protolith zircons; **d)** 14GBQ2 Leucogranitic vein sample, also showing zircon inheritance.

Figure 9. Chondrite normalized REE patterns for the sample 14GBQ1 zircon core and rim domains. Normalizing values are from McDonough and Sun (1995).

Figure 10. The schematic model for the tectonic evolution of the Beishan Orogen.

Table Captions

Table 1. The geochemistry data for the eclogite samples and leucogranitic vein, and comparison data from Qu et al. (2011).

Table 2. SHRIMP U-Pb zircon data from the analyses in this study.

Table 3. LA-ICP-MS trace elements data of the zircon core and rim domains from eclogite sample 14GBQ1.