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Eclogites and garnet clinopyroxenites in the Anrakhai Complex, Central Asian Orogenic Belt, Southern Kazakhstan: P-T evolution, protoliths and some geodynamic implications.

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Abstract

The Anrakhai Metamorphic Complex (AMC), located in the SE part of the Chu-Ili Mountains of Southern Kazakhstan in the western part of Central Asian Orogenic Belt, exhibits occurrences of HP metamorphic rocks in the form of eclogites and garnet clinopyroxenites with peak metamorphic conditions of 750 – 850° and 15 – 19 kbar estimated with both conventional geothermobarometric methods and phase diagram modeling. P-T estimates as well as intimate field relations evidently imply a common metamorphic history for eclogites and garnet clinopyroxenites of the AMC. These high-pressure, medium temperature eclogite facies P-T conditions are indicative of a collision or subduction tectonic setting. Major and trace element geochemistry suggests that they probably had a common magmatic origin as part of a suite of differentiated tholeiitic intrusions. Furthermore, distinctive mineral and chemical compositions of these eclogites and garnet clinopyroxenites correspond to the Fe-Ti type of ultramafic rocks suggesting that they may have been derivatives of intraplate tholeiitic melts, introduced into continental crust before HP metamorphism.

Key words: HP metamorphism; Central Asian Orogenic Belt; eclogite; garnet pyroxenite; geothermobarometry; tectonics.

Introduction

High-pressure (HP) and ultrahigh-pressure (UHP) metamorphic complexes occur in many orogenic belts, where they are believed to have formed as a result of tectonic burial or transient subduction of oceanic or thinned continental lithosphere to depths below the normal Moho, followed by fast exhumation (Coleman & Wang, 1995). These processes are considered to accompany subduction of a passive continental margin and its subsequent collision with an island arc or an opposing continental margin (Ernst et al., 2007; Degtyarev, 2012). Therefore, identification of HP-UHP lithologies in a metamorphic complex indicates that subduction and/or

collision processes are likely to have occurred, providing important information for detailed paleotectonic reconstructions.

It is commonly the case, when studying HP-UHP rocks, that attention is devoted to P-T parameters and timing of metamorphism. However, the protolith compositions and provenances of HP and UHP rocks are also important when attempting to understand the tectonic assembly and thermal regimes of orogens. In this regard mafic and ultramafic metamorphic lithologies such as eclogites and garnet-bearing ultramafites are highly significant, not only because they tend to preserve HP and UHP mineralogy more often than felsic rocks (Heinrich et al., 1986; Proyer, 2003), but also because they have a range of possible origins prior metamorphism. Mineralogical, geochemical and isotopic data from mafic-ultramafic rocks in different HP-UHP complexes reveal distinct features of their protoliths and genesis. For example, they may have been fragments of oceanic or continental crust, or cumulates of mafic melts intruded into continental crust, or mantle rocks introduced into the subducting lithosphere (Carswell et al., 1983, Coleman & Wang, 1995; Brueckner, 1998; Medaris et al., 1999; Ernst et al., 2007; Reverdatto et al., 2005). Each of these has different implications for the origins and tectonic assembly of a HP-UHP terrain.

In this paper evidence for a HP eclogite-facies history of the Anrakhai Metamorphic Complex within the Chu-Ili region (Southern Kazakhstan) is presented. Pressure (P) and temperature (T) for the prograde (only for eclogites) and peak metamorphic stages in eclogite and garnet clinopyroxenite are estimated for the first time. Moreover, identification of the protoliths and provenance of these ultramafic rocks based upon bulk rock geochemistry has been undertaken in order to provide insights into their pre-orogenic settings.

1. Geological outline

Among the Paleozoic complexes of the western part of the Central Asian Orogenic Belt (CAOB) (Fig. 1), a very large and long-lived accretionary orogen, large blocks comprising Proterozoic continental crust are separated by Paleozoic nappes consisting of oceanic and island-arc

complexes. HP-UHP formations, including bodies of mafic and ultramafic composition are usually present within the metamorphic complexes that make up the blocks with Proterozoic crust. They are associated with narrow tectonic zones, which do not extend for more than 150 km.

The most well-known (and the largest) structures of this type are related to the Kokchetav massif (Northern Kazakhstan) and the Makbal and Aktyuz blocks of Northern Tian Shan (Reverdatto et al., 2005; Konopelko et al., 2012; Rojas-Agramonte et al., 2013; Meyer et al., 2014) (see discussion below). In these zones metamorphic rocks form packages of tectonic slices consisting of schists, gneisses of various types, amphibolites, eclogites, garnet and spinel peridotites.

Within the Chu-Ili region (Southern Kazakhstan) blocks containing Proterozoic crust frame the Early Paleozoic Dzhalair-Naiman ophiolite zone (Fig. 1A) (here and in the following the timescale after Gradstein, Ogg et al. (2004) was used). The zone extends to the NW by more than 500 km and consists of tectonically accreted Early Cambrian ophiolites as well as other basaltic and silicic formations (Ryzantsev et al., 2009; Degtyarev, 2012). In the Dzhalair-Naiman ophiolite zone Ordovician terrigenous, carbonate and volcanogenic formations are exposed.

The Anrakhai massif is located NE of the Dzhalair-Naiman zone (Fig. 1A). The Anrakhai block (Fig. 1B) is characterized by orthogneisses and gneissic granites (the Uzunbulak series). Geochronological data indicate widespread development of Paleoproterozoic complexes represented by orthogneisses with a protolith age of 1841±6 Ma (Tretyakov et al., 2016b), and Neoproterozoic (c. 800 Ma) formations having highly similar compositions (Kröner et al., 2007).

A metamorphic complex containing HP rocks has been identified within the NE part of the Anrakhai complex, where HP lithologies form a band trending NW with breadth varying from 50 m to 1.5 km. This has been attributed to the Koyandy series (Efimov et al., 1983). These HP rocks have been overthrust from the SW by Precambrian orthogneisses and gneissic granites of the Uzunbulak series. Also, Cambrian (?) ultramafics and gabbroids and Middle Cambrian (508±3 Ma) granitoids (Alexeiev et al., 2011) have been thrust from the NE onto the Koyandy series.

In the Koyandy series, schists having variable compositions are predominant. In the NE part (Fig. 1B) they are mainly biotite and biotite-muscovite schists with layers of meta-psammite and marble. In the SW part of the series garnet-biotite gneisses enclose bodies of amphibolite, mylonitized acid granulites (containing relics of Kfs and Ky) and gneissic granites as well as extensive (up to 200 m) blocks of serpentinized dunite and wherlite.

Garnet-biotite gneisses in the Koyandy series are metasedimentary rocks. This is confirmed by the presence of detrital zircons that have yielded range of ages from 694 Ma to 2257 Ma (Alexeiev et al., 2011). In some places bodies of eclogite and garnet clinopyroxenite occur within garnet-biotite paragneisses (Efimov et al., 1983; Alexeiev et al., 2011). Ion microprobe (SHRIMP II) U-Pb isotopic analyses of zircons from garnet-clinopyroxene rocks gave an age of 489±9 Ma corresponding to the Late Cambrian-Early Ordovician boundary. This date has been interpreted as the age of HP metamorphism rather than the protolith age (see Alexeiev et al., 2011 for details).

2. Field relationships and petrography of eclogites and garnet clinopyroxenites

Anrakhai complex HP rocks are characterized by superficially similar mineral assemblages, namely Cpx + Grt + Rt; but the clinopyroxenites are distinctively different from the eclogites in their petrography and phase compositions. Both of these lithologies occur as lensoid bodies (pods) that are normally enclosed within Grt-Bt gneisses. They form pods from 0.4 m to 4 m in size. Peripheral parts of the pods typically consist of amphibolite and garnet amphibolite, whereas assemblages with Grt + Cpx are found only as remnants in the central parts of the pods. Garnet clinopyroxenite may be the only lithology in a pod, or it may be intercalated with eclogite.

Eclogite displays fine- to medium-grained, granoblastic textures. All eclogite pods are highly altered, with eclogite-facies mineral assemblages preserved only rarely in the central parts of pods. Microscopically, the peak mineral assemblage consists of almost colorless Grt from 0.2 to 1.5 mm in size containing abundant mineral inclusions (Fig. 2a); slightly greenish Omp as elongated anhedral grains up to 0.7 mm but in most cases replaced by plagioclase-diopside symplectites (Fig.

2d); Rt, surrounded by sphene pseudomorphs, and Qz. Later stage minerals are Amp, which is predominant in the matrix of eclogites where it typically encloses relics of garnet and symplectite (Fig. 2b, c) as well as coexisting with plagioclase in the symplectite (Fig. 2c) and forming coronas around garnet grains (Fig. 2e, f); Ep, and Czo form large poikiloblastic grains enclosing relics of garnet or form monocrystal rims around garnet grains. Accessory minerals are apatite, zircon and ilmenite as either needles within garnet grains or separated grains within the matrix, normally replaced by Spn. It should be noted that eclogites possess different extents of alteration; almost all investigated samples contain carbonates and chlorites, which fill cracks in the matrix or form separated grains in some samples.

Garnet clinopyroxenites display medium to coarse grained, granoblastic textures and comprise Grt, Cpx, Rt and Amp. In contrast to eclogites the peak mineral association is pale reddish Grt from 0.7 mm to 2 mm (containing inclusions of Di (Fig. 2h) and a lesser amount of Amp); colorless Di, which is the predominant matrix mineral (Fig. 2g). Grain sizes vary from 1mm to 1.5 mm, and Spn, as pseudomorphs after rutile. Retrogression of the rocks is expressed by minor amphibole development at the expense of matrix Cpx (Fig. 2i). Minor plagioclase, epidote or chlorite is present. Similarly to eclogites, some of the samples contain carbonate, developing in the cracks or rarely forming the separated grains. Accessory minerals are apatite, zircon and ilmenite. In addition, monomineralic agglomerations of rutile or apatite up to 1 mm in size are typical for garnet clinopyroxenites.

3. Whole-rock geochemistry and mineral chemistry

In order to determine the geochemical affinities and magmatic environment of the protoliths to the HP rocks of the Anrakhai complex, and to provide compositional data to aid pseudosection analysis, bulk-rock major and trace element analyses and mineral chemistry determinations of selected eclogites and garnet clinopyroxenites have been obtained. In order to minimize the compositional effects of metasomatic alteration or element loss, the samples of eclogites and

garnet clinopyroxenites were selected from the cores of lenses. Also, some representative XRF analyses of HP lithologies collected by D.V. Alexeiev and A.V. Ryazantsev (Alexeiev et al., 2011) were used. However, despite the applied accuracy with the selection all collected samples show LOI in the range of 2-9 wt.%, implying the strong influence of volatile components on the rocks compositions.

3.1. Analytical procedures

Major element analysis was carried out in the chemical-analytical laboratory of the Geological Institute of the Russian Academy of Sciences (RAS). Sodium, magnesium, aluminum, silicon, phosphorus, potassium, calcium, titanium, iron oxide, manganese were determined by XRF using a Bruker Pioneer^{TM} spectrometer with data reduction using «Spectra-Plus^{TM}» software. Intervals of analyzed contents in recalculation on oxides (mass fraction %): silicon – 0.01-1.0, titanium – 0.01-5.0, aluminum – 1.0-60.0, iron oxide – 1.0-40.0, manganese, calcium – 1.0 -50, magnesium – 0.1- 40, sodium – 0.1-10.0, potassium – 0.1-10.0, phosphorus – 0.01-5.0. Certified standards (GSO, OSO, MSO) with similar matrices to the analyzed samples (felsic, medium and basic rocks) were used as samples for comparison. Fifty standard samples of different composition were used for construction of calibration graphs. The Fe_2O_3 fraction of the total Fe oxides was carried out by a titrimetric dichromatic method. Trace elements were analyzed in the Institute of Mineralogy and Geochemistry of Trace Elements, RAS, by XRF on a Russian ARF-6 quantographer in the concentration range 0.001 – n% and by ICP-MS on a Perkin Elmer ELAN 6100 DRC as well as by atomic emission spectrometry with ICP-MS (ICAP-61, Thermo Jarrell Ash; X-7, Thermo Elemental, USA) in the Analytical Centre of the Institute of Microelectronics Technology and High-Purity Materials, RAS.

The electron microprobe measurements of mineral composition were carried out at the Laboratory of Mineral Substances Analysis, Institute of mineralogy, geochemistry and petrography of Russian Academy of Sciences, on a JEOL-8200 electron probe microanalyzer and on a JEOL JXA-8230

electron probe microanalyser (EPMA) at the Institut des Sciences de la Terre (ISTerre), University Grenobles Alpes, France (Batanova et al., 2015). These were equipped with five wavelength dispersive spectrometers and an energy dispersive (EDX) spectrometer at an accelerating voltage of 20 kV, probe current of 20 nA, beam diameter of 1 micron.

Ferric iron was calculated for garnets, clinopyroxenes and amphiboles, based on charge balance and stoichiometry (after Droop, 1987); all iron in clinozoisites was recalculated as Fe^{3+} in accordance with the mineral formula of Czo. All mineral abbreviations are after Whitney & Evans (2010).

3.2. Whole-rock geochemistry

Eclogites and garnet clinopyroxenites are characterized by contents of SiO_2 (37.37-42.91 wt. %) less than 45 wt.% (according to the standard definition of "ultramafic" - "mafic" boundary) and $\Sigma(Na_2O+K_2O)$ in the range 0.21-1.71 wt. % (see Table 1). The rocks also contain notably high contents of FeO ($FeO_{tot}/ (FeO_{tot} + MgO)$ = 0.57-0.76) and TiO_2 (1.88-4.28 wt. %). As a result, mineral phases of both eclogites and garnet clinopyroxenites (see section 3.3 below) are also remarkably Fe-rich, whereas MgO contents are unusually low in comparison to the typical mineral assemblages of ultramafics (as in Carswell et al., 1983; Bodinier &Godard, 2003) and are more similar to typical metabasic HP assemblages (as in Demina et al., 2005; Li et al., 2015). However, SiO_2 contents in the rocks are low (even recalculating the analyses to "dry" basis – in this case only TS 1044 shows SiO_2 = 46.65 wt.%) and correspond an ultramafic composition. Taking into account the extensive alteration of these rocks (indicated by low analysis totals without LOI (90 – 98 wt.%) and abundant late-stage retrogressive minerals including hydrous and carbonate-bearing phases) it is possibly to presume the partial desilication of the rocks (when during metamorphism at HP conditions the mafic/ultramafic rocks were dehydrating and losing silica (particularly with respect to eclogites) and thermodynamic potential influenced on the gain-loss of the mobile and inert components (Marakushev, 1991)). However, it is needed to take into account an emplacement

of the rocks pods among silicic gneisses that may have undergone dehydration reactions (phengite breakdown or even partial melting); therefore, it suggests that eclogites and garnet clinopyroxenites could have experienced an inward flux (i.e. gain from outside) of water and perhaps dissolved metal species rather than a loss to the exterior, at least in relation to the retrogressive metamorphic stage. At the same time, possible desilication could be related to the diluting effect of volatiles on the analyses (particularly carbonate fluids, since carbonation reactions could cause mobilization and probably loss of silica from the rocks) and partly to metamorphic differentiation in response to external processes, associated with shearing stress or another deformation (Gray, 1977). On the other hand, the obtained data on trace elements contents, especially on high field strength elements (Nb, Y, etc.) should be considered as robust and significantly less dependent from the metamorphic alteration, since they are characterized by lower mobility during retrograde metamorphism (Pearce & Norry, 1979; Meschede, 1986).

The concentrations of Al_2O_3, TiO_2, Nb and Th of eclogites and garnet clinopyroxenites show a negative correlation with MgO. Covariations of Al_2O_3 and (to a lesser extent) P_2O_5 and FeO_{tot} covary positively with TiO_2 (Fig.3). Such trends usually characterize magmatic differentiation (Middlemost & Romey, 1968; Janney & Castillo, 1997; Xu et al., 2003). Both eclogites and garnet clinopyroxenites toile in the field of tholeiites in an AFM plot (Fig.4A). Furthermore, garnet clinopyroxenites have lower Na_2O than eclogites ($Na_2O_{grt-cpxt}$ = 0.06-0.81 wt. %; Na_2O_{ecl} = 1.05-1.29 wt. %); hence Na_2O contents discriminate well between these two lithologies. However, it should be noted that as discussed earlier, bulk compositions of eclogites and garnet clinopyroxenites may have been modified during metamorphism. In particular, Na_2O, K_2O and CaO, tend to be mobile (Winchester & Floyd, 1976). At the same time the rocks are very similar in their REE contents and are generally characterized by relatively high total concentrations of REE (ΣREE = 86-234 ppm) (Fig.4B, C). Most of the samples demonstrate enrichment in LREE relative to HREE ((La/Yb)$_n$ = 1.6 – 12.0).

3.3.Mineral chemistry

In the tables 2 - 6 results of electron microprobe analyses of garnet clinopyroxenite and eclogite minerals are provided. Compositions of the main minerals of HP rocks, along with microstructural observations, were used to delineate mineral parageneses and deduce the metamorphic evolution of these rocks. It should be noted that the analyzed mineral phases in eclogites are from both a highly retrogressed variety (TS 1048/2) and relatively less altered one (TS 1086). Minerals of garnet clinopyroxenites from the all samples are almost equal in composition.

3.3.1. Garnet

Eclogite garnets have 48-63% Alm, 11-21% Prp, 23-32% Grs, 1-2% Sps (Table 2, Fig. 5 A, B). Garnet grains are characterized by prograde zonation (Spear, 1995); Alm decreases from core to rim and Prp increases in the same direction, whereas Grs displays an almost flat distribution (particularly in the sample TS 1086) but with a decrease closer to rims. They contain numerous inclusions of clinozoisite (Czo), amphibole (Amp), represented by ferropargasite, concentrated in the inner parts of garnet. Rutile (Rt) with ilmenite (Ilm) and quartz (Qtz) inclusions are located mostly within the outer parts of garnet grains.

Garnets in garnet clinopyroxenites have compositions ranging from 40-46% Alm, 25-34% Prp, 18-31% Grs, 0.5-1 % Sps (Table 2, Fig. 5C). Porphyroblasts of garnet in garnet clinopyroxenites, in contrast to eclogites, show another type of zonation, in which both Alm and Prp increase from core to rim and Grs shows a notable decrease within the grain rims. $Fe^{2+}/ (Fe^{2+} + Mg)$ ratio in garnets tend to decrease closer to rims; in doing so interior of the grains is characterized by "flat" profiles of magnesium and iron contents. Both core and rims of the garnet contain micro-inclusions of clinopyroxene or amphibole.

It should be noted that the very high iron contents of the garnets in both rock-types are not typical of medium-T eclogites and ultramafites, but are caused by very high bulk-rock Fe (Table 1).

3.3.2. Clinopyroxene

In eclogites there are at least two varieties of Cpx, represented by omphacite with Jd = 22-31% (Fig. 6A, Table 3) and diopside (Jd = 6-13%), forming a symplectic intergrowth with sodic plagioclase indicating the decomposition of omphacite under decompression.

Clinopyroxene in garnet clinopyroxenites forming the matrix of the rocks is diopsidic with higher magnesium than the omphacite in eclogites (Fig. 6A, Table 3). Inclusions of Cpx within garnets of the garnet clinopyroxenites are monotonous with compositions similar to groundmass Cpx.

3.3.3. Amphibole

Amphibole in eclogites is present in several textural generations, namely greenish edenite (Si = $6.5 - 6.8$; Mg/(Mg + Fe^{2+}) = $0.58 - 0.62$) in one assemblage with oligoclase as symplectites; bluish pargasite and ferropargasite (Si = $5.6 - 6.4$; Mg/(Mg + Fe^{2+}) = $0.44 - 0.65$), rimming garnet grains as coronas with andesine intergrowths; and green magnesiohastingsite (Si = $6.0 - 6.4$; Mg/(Mg + Fe^{2+}) = $0.63 - 0.66$; giving Al^{VI} < Fe^{3+}), making up the groundmass and replacing the symplectites (Table 4; Fig. 6B).

In garnet clinopyroxenites amphibole is less abundant and represented by high-magnesium hornblende (Si = $6.6 - 6.9$; Mg/(Mg + Fe^{2+}) = $0.82 - 0.97$) (Table 4; Fig. 6B), replacing matrix diopside. In some cases amphibole microinclusions are enclosed within garnet grains. All amphiboles (both inclusions and groundmass minerals) show monotonously equal compositions.

3.3.4. Other minerals

Plagioclase, quartz and clinozoisite were identified (and analyzed) only in eclogites; however, in garnet clinopyroxenites minor plagioclase in the matrix is present, but its affinity to any stage is unclear. Plagioclase in eclogites is represented by several varieties from albite-oligoclase in various symplectites with diopside and amphibole to labradorite in the matrix (Table 5).

Clinozoisite (Table 5) and quartz are contained as inclusions within garnet grains in eclogites and occur in the matrix as separated crystals.

Rutile and apatite are widespread in garnet clinopyroxenites and eclogites; high Zr contents in rutile are notable (Table 6), indicating its relatively high temperature of formation (Zack et al., 2004; Watson et al., 2006; Ferry et al., 2007).

4. P-T peak estimations

For eclogites as well as garnet clinopyroxenites the P-T path has been reconstructed by both conventional geothermobarometric methods and pseudosection modeling using the Perple_X software package version 6.7.3 (Connolly, 1990; Connolly, 2005). Mineral and chemical compositions features could show differences in the minerals forming during prograde and retrograde metamorphism, caused by the different bulk compositions of the eclogites and clinopyroxenites; it may mean that each lithology recorded different P-T points along the P-T-t path. Absence of orthopyroxene, phengite or kyanite in both lithologies is a major constraint on the application of conventional geobarometry, particularly with regard to garnet clinopyroxenites, which have only diopside, garnet, rutile, ilmenite and little amphibole in their compositions.

4.1. Conventional geothermobarometry

The different mineral assemblages of eclogites and garnet clinopyroxenites requires the use of different types of geothermometers and geobarometers. For both lithologies Grt-Cpx geothermometry, based on Fe-Mg exchange (Krogh Ravna, 2000), is possible. The presence of omphacite with elevated Jd contents coexisting with quartz in eclogites allows an application of Jd-in-Cpx geobarometers (e.g. Holland, 1980; Perchuk, 1992), whereas owing to the absence of appropriate minerals (Opx, Omp, Ky or phengite) pressure estimation for garnet clinopyroxenites by conventional barometry methods is impossible. Zr-in-rutile was used for temperature estimation (after Ferry et al., 2007), however this geothermometer is only relevant for Qz-bearing rocks (i.e.

eclogites for this case). Nevertheless the content of ZrO_2 for some rutile grains in garnet clinopyroxenites were provided as well (Table 6).

For eclogites and garnet clinopyroxenites representative garnet-clinopyroxene pairs (presumed to be in equilibrium in accordance with their chemical compositions and zonation) were selected and isopleths of P-T dependencies were constructed. Since this geothermobarometry is sensitive to the oxidation state of iron, two types of plot with either total Fe or calculated Fe^{2+} in Grt and Cpx for both eclogites and garnet clinopyroxenites were constructed.

4.1.1. Eclogites

Application of Fe-Mg exchange geothermometer (Krogh Ravna, 2000) and Jd-in-Cpx geobarometer (Perchuk, 1992) for pressure range from 13 to 20 kbar for 4 representative pairs of Grt and Omp (see tables 2, 3) showed an intersection in the interval T = 760 – 800°C and P = 18 – 19 kbar with total iron and T = 660 – 740°C and P = 15 – 16.5 kbar with divided ferrous and ferric iron in Grt and Cpx (Fig. 7A). Zr-in-Rt geothermometry (after Ferry et al., 2007) showed temperature range T = 700 – 760°C (Fig. 7C).

4.1.2. Garnet clinopyroxenites

As mentioned above, garnet clinopyroxenites have a mineral assemblage that only allows Grt-Cpx exchange thermometry. Therefore any conventional P-T estimations for garnet clinopyroxenites are highly arbitrary and based primarily on structural and spatial proximity with eclogites (taking into account the intercalation of the rocks). Isopleths for 4 pairs of coexisting Grt and Cpx (see tables 2, 3) were plotted, with the pressure values taken from those determined for eclogites (Fig. 7B). For P = 18 – 19 kbar temperature varies from 735 to 755°C with total iron in Cpx and Grt and T = 660 – 760°C for divided ferric/ferrous iron in the minerals. Although an application of the Zr-in-Rt geothermometer in garnet clinopyroxenites is restricted due to the absence of Qz, the

contents of ZrO_2 in rutile are remarkably similar to the contents in rutile from eclogites (Table 6, Fig. 7C).

4.2. P – T pseudosection modeling and isopleths geothermobarometry

Construction of pseudosections for eclogites and garnet clinopyroxenites was carried out by means of the Perple_X software package (version 6.7.3; Connolly, 1990; Connolly, 2005) in conjunction with the internally consistent thermodynamic database of Holland and Powell (Holland & Powell, 1998). Two representative samples of eclogites (highly retrogressed eclogite (TS 1048/2) (Fig.8B) and a less altered variety (TS 1086) (Fig.8A) and one sample of garnet clinopyroxenite (P 56/4) (Fig.9) were analyzed and modeled. The model system Na_2O-CaO-TiO_2-FeO-Fe_2O_3-MgO-MnO-Al_2O_3-SiO_2-H_2O (NCTiFMMnASHO) was used for the phase diagram calculations. K_2O contents were neglected from the systems since potassium does not control any phases in the rocks, comprising only amphibole and plagioclase as admixture.

4.2.1. Effective bulk composition

Two samples of eclogite (TS 1086 and TS 1048/2) show similar mineral assemblages (with slightly different chemical compositions (Tables 2 & 3). Symplectitic and coronitic reaction microtextures are developed in both varieties (Fig. 2 c, d, e, f). However, sample TS 1048/2 possesses considerably more extensive development of symplectites and kelyphites after garnet, indicating a higher extent of retrogressive alteration, whereas in sample TS 1086 direct contacts between garnet and omphacite of the peak stage are sometimes preserved and Cpx-Pl symplectites are less abundant. Nevertheless, the presence of such microtextures implies that equilibrium was achieved only on a domain-scale. Therefore the compositions of such domains should be calculated (see examples in Cruciani et al., 2008; Groppo et al., 2015). Effective bulk compositions (EBC) of the domains for both samples with Grt-Omp assemblages, surrounded by Cpx-Pl symplectites, were measured using of the method of calculation of mineral densities (taking into account each component), multiplied by the percent by volume and chemical composition of each phase (garnet

(rim), omphacite, diopside, etc.) for domains of about 800 × 800 μm. The obtained EBC's are used in modeling (Table 7). It is noteworthy that in this case the transition from Grt-Omp to Grt(?)-Di-Pl is described by modeling, therefore the results are consistent not with the peak conditions, but with the beginning of retrogression (i.e. near-peak conditions).

As shown in section 3.3, the compositions of minerals in garnet clinopyroxenite are monotonous, especially with respect to pyroxenes and amphiboles; therefore XRF data could probably reflect the reacting bulk during the post-peak evolution of the rock. However, the correction of FeO/Fe_2O_3 after Irvine & Baragar (1971) was applied (Table 7).

4.2.2. Pseudosection calculations

For eclogite samples TS 1086 and TS 1048/2 NCTiFMMnASHO model systems were constructed as pseudosections for the temperature range 500 - 1000° C and pressure range 5 kbar -20 kbar, using the effective bulk compositions (Table 7; Fig.8 A, B). H_2O was recalculated by using the CORK equation of state (Holland & Powell, 1998). For both cases the solution models for Gt (WPH) (White et al., 2000), Pl (h) (Newton et al., 1980) and Amph (DHP) (Dale et al., 2000) and Omph (GHP) (Green et al., 2007) were applied.

For the bulk composition of garnet clinopyroxenite sample P 56/4 (Table 7) the NCTiFMMnASHO model system was also implemented to construct the pseudosection (Fig. 9). The model system was calculated assuming saturation of an H_2O fluid (also with using of CORK equation of state). The pseudosection was calculated with solution models for Gt (WPH) (White et al., 2000), Cpx (HP) (Holland, Powell, 1996), Pl (h) (Newton et al., 1980) and Amph (DHP) (Dale et al., 2000).

Near-peak P-T conditions of eclogites and garnet clinopyroxenite were determined by application of isopleth geothermobarometry (e.g. Wei et al., 2008; Groppo and Castelli, 2010; Lü et al., 2013;

Meyer et al., 2013; Li et al., 2015). All isopleths were plotted with PyWerami software (Lexa, 2011).

4.2.2.1.Eclogites

P-T pseudosections for eclogites TS 1086 and TS 1048/2 are given in Fig. 8 A, B. According to the mineral composition of eclogites, including microinclusions within garnet grains, the obtained pseudosections reflect all observed mineral assemblages. However due to the inevitable shortcomings of the thermodynamic data for ferric iron minerals magnetite or hematite appear as an additional Fe^{3+}-bearing phases in some fields of the model system. On Fig. 8A garnet isopleths of $X_{Fe2+/(Fe2+ +Mg)}$, X_{Prp} and X_{Grs} (Table 2) along with $X_{Ca/(Ca+Na)}$ and $X_{Mg/(Mg+ Fe2+)}$ in Omp (Table 3) isopleths intersect within pretty narrow field (P = 15 – 16.5 kbar; T = 750-840°C). On Fig. 8B $X_{Fe2+/(Fe2+ +Mg)}$, X_{Prp} and X_{Grs} (Table 2) along with $X_{Ca/(Ca+Na)}$ and $X_{Fe2+/(Fe2+ +Mg)}$ in Omp (Table 3) isopleths have an intersection at P = 14.5 – 16 kbar ; T = 720-780°C. Thus the (near-) peak stage of metamorphism corresponds to the eclogite facies P-T field.

4.2.2.2.Garnet clinopyroxenites

As mentioned earlier, mineral compositions of garnet clinopyroxenites are indeed monotonous, therefore pseudosection (Fig. 9) for the sample P 56/4 contains mostly large fields with similar phases. Similarly to the eclogites, magnetite or hematite are also present as additional Fe^{3+}-bearing phases in most of the fields. In accordance with garnet zonation (Fig. 5C) $X_{Fe2+/(Fe2+ +Mg+Ca)}$, $X_{Mg/(Fe2+ +Mg+Ca)}$ and $X_{Ca/(Fe2+ +Mg+Ca)}$ isopleths, corresponding to the garnet core (Table 2), along with X_{Fe}^{2+} isopleths of Cpx (Table 3) intersect at P = 16.5-17.5 kbar ; T = 800-860°C. Despite the evident difficulties in P-T assessments for garnet clinopyroxenites related to the absence of the critical mineral phases (e.g. omphacite or Opx), the results of isopleths geothermobarometry indicate near-peak P-T conditions in the eclogite facies field similar to those for the eclogite samples.

5. Discussion

5.1. Evolution of metamorphism

Eclogites and garnet clinopyroxenites in the Koyandy series of the Anrakhai complex have undergone extensive re-equilibration to lower pressure mineral assemblages. However, the relict eclogite facies minerals (mainly omphacite and pyrope-rich garnet in association with rutile and quartz in eclogites and magnesian garnet along with Mg-rich Cpx and rutile in garnet clinopyroxenites) are retained. Moreover, garnet grains in eclogites exhibit prograde zonation (as discussed further below) expressed in their chemical zonation and regular distribution of mineral inclusions.

5.1.1. Eclogites

Chemical zonation of representative garnet grains in eclogites is characterized by cores relatively enriched in Fe and Ca and rims enriched in Mg (Fig.5 A, B). This is typical of normal growth zonation in metamorphic garnets (Spear, 1995) manifested by their increase in Prp component from core to rim while the Alm component decreases in the same direction. This zonation is consistent with the arrangement of mineral inclusions. Thus within the internal Fe-Ca-rich zone inclusions of Amp (ferropargasite) and Czo are observed (Tables 4, 5), while the outer Mg-rich zones enclose sporadic inclusions of Qz and Rt. We argue that this correlation of the solid inclusion pattern with chemical zonation is because the inclusions enclosed within the core zone represent the matrix phases that were in equilibrium with garnet during the early stages of its growth. This early paragenesis would, then, have comprised amphibolite. This is confirmed by plotting of mineral inclusion compositions with associated garnet compositions into a tetrahedral ACFM (Al_2O_3 – CaO – FeO_{tot} – MgO) diagram (Fig. 10). The assemblage Czo + Amp + ferriferous Grt core represents an amphibolite facies stage (with estimated P = 9 – 9.5 kbar; T = 600 – 640 ºC (Hammarstrom & Zen, 1986; Hollister et al., 1987; Krogh Ravna, 2000)) while the more magnesian Grt with Omp and Qz is, by definition, an eclogite facies paragenesis. Intersection of

the Grt-Amp-Czo field with the Grt-Omp tie-line (Fig. 10) indicates formation of eclogite facies minerals at the expense of the earlier amphibolite facies assemblage, hence garnet amphibolite was likely the protolith for eclogite.

The post-peak retrogression in eclogites is characterized by several stages; the earliest changes involve formation of sodic Pl (An_{10-14}) with Cpx (Di_{60-65}) (Tables 3, 5; Fig. 2d), corresponding to granulite facies field (10-14 kbar at 700-750 °C; Krogh Ravna, 2000; Newton & Perkins, 1982). The subsequent stage involved the growth of amphibole at the expense of diopside in these symplectites and by amphibole-plagioclase coronas formation around garnet under amphibolite facies conditions (8-10 kbar at 600-650 °C; Krogh Ravna, 2000; Kohn & Spear, 1990). Amphibole of the former assemblage has edenite composition and Pl composition is An_{20} (Tables 4, 5; Fig. 2c). Amphibole, rimming garnet, is represented by bluish pargasite and ferropargasite; the associated Pl varies from An_{26-36} (Tables 4, 5; Fig. 2 e, f). Amphibole of the groundmass is greenish magnesiohastingsite with labradorite plagioclase (An_{53}) (Tables 4, 5), epidote and clinozoisite.

5.1.2. *Garnet clinopyroxenites*

Garnet in the garnet clinopyroxenites show another type of chemical zonation that differs from the eclogites; the core is characterized by "flat" Alm, Prp and Grs compositional profiles, while closer to the rim garnet is of significantly more magnesian composition and Grs is decreased (Fig. 5C). Garnet grains contain numerous inclusions of Cpx and Amp, which are similar to the groundmass Cpx (Di) and Amp on their compositions (Tables 3, 4). Within Ca-Mg-Fe-rich garnet cores there are abundant Di and Amp inclusions with sizes up to 0.02 mm. The rims of garnet contain larger inclusions of Cpx (Di) and Amp (0.1-0.3 mm), generally altered to magnesiohornblende. Both types of microinclusions as well as Amp and Cpx crystals of the matrix have similar compositions, hence it is likely that the core of garnet could be apparently formed in equilibrium with the same matrix paragenesis throughout and could grow from a large reservoir of source components; therefore, fractionation and depletion were not a significant influence on garnet composition,

accounting for the "flat" major elements distribution. From here mineral associations of the inferred earlier metamorphic stages could be represented by the same mineral assemblages of Grt, Amp and Cpx (Di); however, it is a nontrivial task to be proved. The post-peak retrogression of garnet clinopyroxenites is expressed mainly in replacement of clinopyroxenes by magnesiohornblende amphibole (Table 4; Fig. 2i) and abundant retrograde garnet growth under apparently amphibolite facies conditions.

5.2. *Protolith compositions reconstruction*

Petrochemical characteristics of the Koyandy series eclogites and garnet clinopyroxenites (see section 3.2. above) indicate that their protoliths were tholeiitic ultramafic (mafic?) rocks. Close correspondence of the obtained metamorphic P-T paths of these rocks (Fig. 7 – 9), similar REE distribution characteristics (Fig. 4 B, C) and the spatial proximity and intercalation of eclogites and garnet clinopyroxenites imply that they shared their entire metamorphic evolution. Furthermore, the geochemical data indicate a genetic link between their protoliths, hence they probably comprised a single magmatic complex. Covariations of major and trace elements (Section 3.2 and Fig.3) generally resemble fractionation trends of primary igneous minerals during magmatic differentiation, which could indicate that the protoliths of eclogites and garnet clinopyroxenites belonged to a single group of differentiated tholeiitic igneous rocks (Fig. 4A). It is noteworthy that many well-studied layered ultramafic-mafic complexes (e.g. Skaergaard massif, East Greenland (McBirney, 1996), Chineiskii massif, Northern Transbaikalia (Gongalsky et al., 2008)), possess very similar chemical characteristics of their ultramafic differentiates. It also should be noted that on the Al_2O_3 vs. TiO_2 diagram eclogites and garnet clinopyroxenites of the AMC tend to lie in the basalt field (Fig.11), indicating the limited role of olivine or plagioclase fractionation (Konzett et al., 2012).

HP-UHP metamorphic complexes commonly exhibit a heterogeneous structure, reflecting juxtaposition of rock masses with crustal or mantle derivation during subduction and exhumation

(Zhang et al. 1995b, 2000; Medaris et al., 1995). In this respect the issue of paleotectonic location and provenance of eclogites and garnet clinopyroxenites is of great interest. Mafic and ultramafic rocks involved in HP and UHP metamorphic belts may represent metamorphosed fragments of oceanic or continental crusts, or could be considered as exhumed mantle fragments (Ernst et al., 2007). Distinguishing which of these different origins applies to such rocks is crucial to understanding the tectonic organization and assembly of accretionary and collisional orogens.

In previous studies, on the basis of petrochemical characteristics, mantle derivation of garnet pyroxenites for the rocks of Anrakhai complex was proposed (Alexeiev et al., 2011). However, the data presented in this contribution imply another paleotectonic interpretation of their protoliths. It has been shown that the evolution of eclogites included a stage of prograde metamorphism under increasing pressure and temperature during burial or subduction to the maximum depth of at least 60 km. This means that before metamorphism the protoliths of eclogites and garnet clinopyroxenites (genetically related to eclogites) were at normal mid-to-lower continental crustal levels, or a shallow oceanic subduction level, corresponding to amphibole+clinozoisite stability (7-8 kbar).

The enrichment by LREE relative to HREE, as well as the generally high concentrations of REE ($\Sigma REE = 86 - 234$ ppm), comparable to OIB type basalts, imply an enriched source of the melts that generated the eclogite and garnet clinopyroxenites protoliths. This is also indicated by ΔNb (Fitton et al., 1997) (Fig. 12A): the rocks display positive values of ΔNb for the range $0.23 - 1.83$ (with the exception of P 56/4 with slightly negative $\Delta Nb = - 0.005$) (Table 1) implying that a plume component took part in their formation, whereas rocks derived by partial melting of depleted mantle possess stable negative values of ΔNb. Furthermore, the range of ΔNb values for eclogites and garnet clinopyroxenites could result from contamination by continental crust matter, showing negative ΔNb values (Fitton et al., 1997).

Close results are depicted on the diagram Th/Yb vs. Nb/Yb (Pearce, 2008) (Fig. 12B), where most of the analyses are located in proximity to E-MORB and OIB compositions, indicating an enriched composition of the source. In addition, some of the samples are characterized by higher Th contents, which indicated an involvement of the continental crust material.

Continental derivation of the eclogites and garnet clinopyroxenite protoliths is also indicated on a La/10 – Y/15 – Nb/8 diagram (Cabanis & Lecolle, 1989) (Fig. 13A) in which the samples lie predominantly within the continental basalt or continental rift fields. However, some caution is necessary here, since there is a large overlap between the fields (see Li et al., 2015 for details) and especially for highly altered or metasomatically reworked rocks.

The observed geochemical characteristics, taking into account the high contents of TiO_2 and FeO_{tot} (Table 1; paragraph 3.2) imply the affinity of eclogites and garnet clinopyroxenites of Koyandy series to Fe-Ti type of garnet ultramafics (after Carswell et al., 1983). Ultramafic formations with such a geochemical signature are typical of many HP and UHP metamorphic complexes, including Western Norway (Carswell et al., 1983), the Bohemian Massif (Medaris et al., 1995), Dabie Shan of Eastern China (Zhang et al. 1995b, 2000) and the Kokchetav massif of Northern Kazakhstan (Reverdatto et al., 2005). All of these are considered to have had magmatic origins in which they were intruded as tholeiitic mafic melts into lower and middle levels of continental crust (Ernst et al., 2007). This emplacement often long preceded the insertion of their present host continental crustal rocks into a subductional channel.

In the western part of the CAOB, formations with similar geochemical features were identified within Kokchetav massif in Northern Kazakhstan where the rocks are represented by garnet and spinel peridotites and pyroxenites (Reverdatto et al., 2005). As shown in Fig. 13B Koyandy series rocks of AMC are considerably more enriched by LREE than the Fe-Ti ultramafics of Kokchetav massif. Both massifs manifest similar patterns of REE distribution, although the Koyandy series formations have higher concentrations of all REE. Thus the geochemical features indicate that the

eclogites and garnet clinopyroxenites were intrusive tholeiitic rocks with enriched trace element compositions, emplaced into continental crust prior to tectonic burial. Formation of the tholeiitic melts was evidently related to intraplate magmatism.

The issue of the protolith age (and consequently the age of intraplate magmatism) for eclogites and garnet clinopyroxenites of Koyandy series is debatable. Alexeiev et al. (2011) obtained an age for the HP metamorphism of 489±3.1 Ma, which allows a pre-Ordovician age of the protolith of the garnet ultramafics. There is abundant evidence for anorogenic magmatism during the pre-Ordovician history of the Western part of CAOB including anorogenic granites, alkaline-ultramafic and layered massifs ranging in age from Paleoproterozoic to Late Cambrian (see Kröner et al., 2017; Tretyakov et al., 2012; Tretyakov et al., 2015; Tretyakov et al., 2016a, b; Tretyakov et al., 2017 (in press)). Thus it may be proposed that the formation of protoliths of eclogites and garnet clinopyroxenites of Koyandy series is related to one of these magmatic episodes.

5.3. *Geodynamic implications*

Rarely-preserved relics of HP mineralogy in mafic and ultramafic bodies indicate that metamorphism of the Koyandy series of the Anrakhai massif reached HP-eclogite facies conditions. The HP rocks were eclogites and garnet clinopyroxenites that experienced peak P-T conditions of at least 15-19 kbar at 750-850°C with the metamorphism age estimated as 489±3.1 Ma (Alexeiev et al., 2011).

Similar P-T parameters and timing of HP metamorphism as well as similar protolith compositions of HP and UHP lithologies are identified within another metamorphic complexes of Kazakhstan and Tien Shan (Fig. 14).

In Northern Kazakhstan HP and UHP formations are related to the Precambrian Kokchetav massif, where eclogites, pyroxenites, garnet and spinel peridotites of Fe-Ti type are present among para- and orthogneisses. The metamorphic peak for the rocks was estimated as 780-1000°C at 40-60

kbar; eclogites and other HP and UHP formations were interpreted to have been formed after dykes of mafic rocks among upper continental crust (Katayama et al., 2001, 2003; Reverdatto et al., 2005, 2008).

In the western part of the Tien Shan, HP rocks comprise the Precambrian Makbal metamorphic complex, mainly comprising metasedimentary rocks. They contain eclogites, garnet amphibolites and Grt-Cld-Tlc schists. The peak of metamorphism (550-600°C at up to 15 kbar (and 600°C at 25 kbar)) was reached in the Late Cambrian – Early Ordovician (~ 509 – 470 Ma) (Tagiri et al., 2010, Konopelko et al., 2012, Rojas-Agramonte et al., 2013). Most researchers consider the protoliths for HP lithologies to have been dykes and sills of mafic rocks among upper crustal terrigenous and carbonate formations (Rojas-Agramonte et al., 2013, Dergtyarev et al., 2013, Konopelko & Klemd, 2016). However, some have concluded that they have been formed by metamorphism of oceanic crust (Meyer et al., 2014).

In the central part of the Northern Tien Shan HP rock outcrop, represented mainly by Neoproterozoic orthogneisses and gneissic granites with bodies of amphibolites and eclogites, is the Aktyuz metamorphic complex. HP metamorphism (550-660°C at 21-23 kbar) was occurred here in Early Ordovician (474±2 Ma); the protolith for HP eclogites is considered to have been mafic dykes intruded into continental crust (Kröner et al., 2012, Rojas-Agramonte et al., 2013, Klemd et al. 2014).

The origin of the HP and UHP formations in all of the mentioned complexes, and their subsequent emergence at the present-day surface, is considered to be related to subduction of thinned Precambrian continental crust followed by exhumation (Reverdatto et al., 2005, Degtyarev et al., 2013, Alexeiev et al., 2011, Klemd et al., 2014, Rojas-Agramonte et al., 2013, Konopelko & Klemd, 2016 etc.).

Current geodynamic models imply that the Anrakhai block represented part of the large Northern Tien Shan microcontinent (for example Alexeiev et al., 2011; Klemd et al., 2014). This is

confirmed by the predominant presence within the Koyandy series of garnet-biotite gneisses containing detrital zircons with ages ranging from 934 Ma to 1316 Ma, which are close to "Grenville" magmatic ages and are widely developed in Northern Tien Shan (Degtyarev et al., 2013; Kröner et al., 2013). However, within the Anrakhai block only Early Precambrian and Neoproterozoic formations were identified, whereas Grenville (or Mesoproterozoic) magmatic rocks are absent. The Uzunbulak series has the structurally lowest position within the Anrakhai complex and consists of Early Precambrian (1841±6 Ma) orthogneisses and gneissic granites as well as Neoproterozoic (~800 Ma) ortho- and paragneisses, amphibolites and gneissic granites (Tretyakov et al, 2016b; Kröner et al., 2007). The Late Neoproterozoic Koyandy series is emplaced structurally higher than the Uzunbulak series and consists of metasedimentary Grt-Bt gneisses and schists, containing detrital zircons with ages ranging from 694 Ma to 2267 Ma (Alexeiev et al., 2011). Gneisses and schists of the Koyandy series contain bodies of eclogites and garnet clinopyroxenites, indicating HP metamorphism in Early Ordovician (489±9 Ma), as well as slightly metamorphosed serpentinites and gabbroids of ophiolitic sequence (Ryazantsev et al., 2009). These data indicate that the Anrakhai complex represents a package of tectonic slices, made up by mainly formations of Precambrian continental crust from the different structural levels as well as small fragments of oceanic crust.

A comparison of Anrakhai complex lithologies with metamorphic formations of other Precambrian microcontinents of Southern Kazakhstan and Northern Tien Shan shows that the rocks of Anrakhai complex have most in common with the Precambrian rocks of the Chu-Kendyktas microcontinent (Fig. 14), comprising Aydaly and Aktyuz metamorphic complexes. Widespread development of Neoproterozoic orthogneisses and gneissic granites is characteristic for the Anrakhai, Aktyuz and Aydaly metamorphic complexes. The Aydaly complex, located in NW part of Chu-Kendyktas microcontinent, is made up of gneissic granites with ages ~800 Ma, containing bodies of orthogneisses of tonalitic composition with the age of magmatic protolith 769±2 Ma (Tretyakov et al., 2016a). Orthogneisses and gneissic granites with magmatic protolith

ages 844±9 Ma and 778±6 Ma (Kröner et al., 2012) form part of the Aktyuz complex in the Northern Tien Shan, located in SE part of Chu-Kendyktas microcontinent. It should be noted that within both the Chu-Kendyktas and the Anrakhai blocks the Neoproterozoic rhyolite-basalt Kopi formation with the age of magmatic protolith 776±1 Ma (Kröner et al., 2007) is developed.

Thus obtained data on the structure, compositions and ages of Precambrian formations imply that in the earlier Precambrian the Anrakhai, Aktyuz and Aydaly blocks represented parts of Chu-Kendyktas rather than Northern Tien Shan microcontinent.

Starting in the Late Precambrian to Early Cambrian, rift-driven processes led to formation of the Dzhalair-Naiman (Fig. 1A) oceanic basin, the complexes of which divide Chu-Kendyktas microcontinent and Anrakhai block (Ryazantsev et al., 2009).

Following evolution of this region included the inception of subduction of the Dzhalair-Naiman oceanic crust under the Anrakhai block margin in Late Cambrian, which led to the emergence of an ensialic island arc, marked by granitoids formation with the age ~ 509 Ma (Alexeiev et al., 2011).

The age of HP metamorphism (489±9 Ma) of eclogites and garnet clinopyroxenites indicates that in the Early Ordovician the thinned margin of the Anrakhai block continental crust was buried to depths corresponding to eclogite facies.

6. Conclusions

In accordance to all considered data the following conclusions are:

1.   At least two types of HP metamorphic rocks are present within the Koyandy series of the Anrakhai complex, namely eclogites and garnet clinopyroxenites, as defined by their mineral and whole-rock compositions;

2.   Minimum temperature and pressure estimates derived from the eclogite and garnet clinopyroxenite mineral assemblages yield peak metamorphism in the HP eclogite facies field of 750 - 850°C and 15-19 kbar; the prograde stage for eclogite is estimated at 600 - 640°C and 9-9.5 kbar.

3.   The protoliths of eclogites and garnet clinopyroxenites constituted evidently a single coherent structure, represented by group of differentiated tholeiitic igneous rocks;

4.   Features of mineral and chemical compositions of eclogites and garnet clinopyroxenites correspond to the Fe-Ti type of ultramafic rocks, which, by comparison with similar occurrences in other HP-UHP terrains, are derivatives of intraplate tholeiitic melts, introduced into continental crust.

Acknowledgments

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Figures captions

Fig. 1. A. Scheme of geological structure of SE part of Chu-Ili Mountains; B. Scheme of geological structure of Anrakhai Mountains.

Fig. 2. Photomicrographs of eclogites (a – f) and garnet clinopyroxenites (g – i) main minerals: a) Anhedral porphyroblast of garnet with microinclusions of Czo, Amp and quartz in eclogite (crossed nicols); b) Porphyroblastic microtexture of eclogites (crossed nicols); c) Amphibole-plagioclase symplectites in eclogites (crossed nicols); d) Relic of omphacite among diopside-

plagioclase symplectites in eclogites (plane light); e, f) Amphibole-plagioclase corona, surrounding garnet of eclogites (crossed nicols); g) Oriented microtexture, composed by diopside crystals of garnet clinopyroxenites (crossed nicols); h) Diopside microinclusions within garnet porphyroblast of garnet clinopyroxenites (crossed nicols); i) Groundmass diopside, replaced by amphibole (plane light).

Grt – garnet; Omp – omphacite; Di – diopside; Czo – clinozoisite; Amp – amphibole; Pl – plagioclase; Qz – quartz.

Fig. 3. Variation diagrams of SiO_2, TiO_2, Al_2O_3, Nb, Th to MgO and Al_2O_3, $FeO_{(tot)}$, P_2O_5 to TiO_2.

Fig. 4. Whole-rock geochemistry of eclogites and garnet clinopyroxenites: A – Triangular Na_2O+K_2O-Al_2O_3-MgO diagram (after Irvine & Baragar, 1971);

B – Chondrite- and C – Primitive mantle- normalized spectrums (N-MORB, E-MORB, OIB compositions are after Sun S.-S., McDonough W.F., 1989).

Fig. 5. Main components distribution in garnets of eclogites (A and B) and garnet clinopyroxenite (C) and Mg and Fe element maps for eclogites. X_{Alm} – Fe^{2+}/ $(Fe^{3+}+Fe^{2+}+Mg+Ca+Mn)$; X_{Grs} – $Ca/(Fe^{3+}+Fe^{2+}+Mg+Ca+Mn)$, X_{Prp} – $Mg/(Fe^{3+}+Fe^{2+}+Mg+Ca+Mn)$, X_{Sps} – $Mn/(Fe^{3+}+Fe^{2+}+Mg+Ca+Mn)$, X_{Adr} – $Fe^{3+}/(Fe^{3+}+Fe^{2+}+Mg+Ca+Mn)$. Peach-colored areas are suggested peak metamorphism fields.

Fig. 6. A – Clinopyroxenes compositions Q $(Fe^{2+} + Ca + Mg)$ – Jd $(NaAlSi_2O_6)$ – Ae $(NaFeSi_2O_6)$ (after Morimoto et al., 1988);

B – Amphiboles compositions (after Leake et al., 1997). Circles – amphiboles of garnet clinopyroxenites; squares – amphiboles of eclogites.

Fig.7. Results of the conventional geothermobarometry methods. A – P-T peak estimations for eclogites, based on Grt-Cpx thermometry (Krogh Ravna, 2000) and Jd-in-Cpx barometry (Perchuk, 1992) (calculated with total (left) and divided (right) iron in Cpx and Grt);

 B – P-T peak estimations for garnet clinopyroxenite, based on Grt-Cpx thermometry (Krogh Ravna, 2000) for eclogite pressure assessments (calculated with total (left) and divided (right) iron in Cpx and Grt); C – Zr-in-rutile temperature assessments (after Ferry et al., 2007).

Fig.8. P-T pseudosections for lower retrogressed (A) and highly altered (B) eclogites (near-peak assessments).

Fig. 9. P-T pseudosection for garnet clinopyroxenite (near-peak assessments).

Fig. 10. Tetrahedral ACFM (Al_2O_3-CaO-FeO-MgO) diagram, depicting the transition from garnet amphibolite of the prograde stage (yellow circles) to eclogite (the peak stage; pink circles) assemblage (after Torres-Roldan R.L. et al., 2000).

Fig. 11. Emplacement of eclogites and garnet clinopyroxenites compositions on the Al_2O_3 to TiO_2 diagram (after Konzett et al., 2012).

Fig. 12. A – Nb/Y to Zr/Y diagram; PM — primitive mantle (McDonough, Sun, 1995) and N-MORB, E-MORB, OIB (Sun, McDonough, 1989). ΔNb (Fitton et al., 1997) = log (Nb/Y) + 1,74 - 1,92×log(Zr/Y);

B – Th/Yb to Nb/Yb diagram (after Pearce, 2008); N-MORB, E-MORB, OIB are after Sun, McDonough, (1989).

Fig. 13. A – La/10-Y/15-Nb/8 diagram (after Cabanis & Lecolle, 1989). 1 – Volcanic arcs basalts (1A – calc-alkaline basalts; 1B – calc-alkaline basalts and island-arc tholeiitic formations; 1C – island-arc tholeiitic formations); 2A – continental basalts; 2B – back-arc basins basalts; 3A

– alkaline intracontinental rifts basalts; 3B – enriched basalts of E-MORB type; 3C – slightly enriched basalts of E-MORB type; 3D – N-MORB basalts.

B – Chondrite-normalized distribution of REE. 1 – eclogites and garnet clinopyroxenites of Koyandy series (Anrakhai complex); 2 – garnet, spinel peridotites and pyroxenites of Kokchetav massif (Reverdatto et al., 2008); 3 – average and maximum concentrations of REE in Fe-Ti type pyroxenites (Reverdatto et al., 2008); 4 – average and maximum concentrations of REE in Fe-Ti type peridotites (Reverdatto et al., 2008).

Fig. 14. Principal outcrops of Precambrian rocks in relation to early Paleozoic and middle to late Paleozoic assemblages in the western part CAOB. Precambrian blocks: AY – Aktau-Yili, CT – Chinese Central Tien Shan, E-N – Erementau-Niyaz, IS – Issyk-Kul, K – Kokchetav, I – Ishkeolmes, ANR – Anrakhai, Ch – Chatkal, Ch-K – Chu-Kendyktas, K-D – Karatau-Dzhebagly, K-T – Karatau-Talas, N-S – Naryn-Sarydzhaz, Ul – Ulutau (after Degtyrev et al., 2017).

Tables captions

Table 1. Selected chemical analyses of eclogites and garnet clinopyroxenites (the samples were selected by A.V. Ryazantsev (P 56/3, 4, 5, 6) (Alexeiev D.V. et al., 2011); A.V. Pilitsyna with A.A. Tretyakov (TS 1044, 1048/2, 1075/3, 1048/6). Major elements are in wt.%, trace elements are in ppm. Mg# = MgO/(MgO + FeO(tot)); Fe# = FeO(tot)/(FeO(tot) + MgO); Kal = (2CaO + Na_2O + K_2O - Al_2O_3)/2CaO; Ka = (Na_2O + K_2O)/Al_2O_3; $FeO_{(tot)}$ = $0.9Fe_2O_3$ + FeO;

Table 2. Selected microprobe analyses of garnet of eclogite and garnet clinopyroxenite (calculated on the basis O = 12);

Table 3. Selected microprobe analyses of clinopyroxene of eclogite and garnet clinopyroxenite (calculated on the basis O = 6);

Table 4. Selected microprobe analyses of amphibole of eclogite and garnet clinopyroxenite (calculated on the basis O = 23);

Table 5. Selected microprobe analyses of plagioclase (calculated on the basis O = 32) and clinozoisite (calculated on the basis O = 13) of eclogite;

Table 6. Selected microprobe analyses of rutile of eclogites and garnet clinopyroxenites;

Table 7. Effective bulk compositions (in wt.%) for pseudosection modeling of the near-peak conditions for eclogite and garnet clinopyroxenite (corrected bulk for garnet clinopyroxenite is after Irvine & Baragar (1971) for highly oxidized rocks).