Diachronous subduction to diamond- and coesite-facies conditions in the Kokchetav massif

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Abstract

The absolute and relative time of subduction of rocks is crucial information for subduction-exhumation models. We investigated the timing of subduction in one of the oldest ultra-high pressure (UHP) localities worldwide: the Kokchetav massif in Kazakhstan. SHRIMP ion microprobe dating of monazite from coesite-bearing micaschists of the Kulet unit indicates that subduction occurred between ~500-520 Ma. This new data provides evidence that the Kulet unit underwent UHP metamorphism 10-15 Ma later than the diamond-facies rocks in the nearby Kumdy-Kol unit. This time constrain excludes models that argue for a simultaneous evolution of coesite- and diamond-facies rocks, it suggest that subduction continued well after continental crust was involved, and that exhumation was not initiated by a single event such as slab break-off. The dynamic of this UHP massif also indicates that Cambrian tectonic was similar to that of recent orogenic belts.

Introduction

The study of crustal rocks that underwent UHP conditions, i.e. subduction to the coesite and diamond stability fields (> 90 Km depth) offers a unique insight into the deep Earth and the tectonic processes of subduction and exhumation. It has been proposed that the first occurrence of UHP metamorphism defines the time of onset of modern cold subduction on Earth (Brown, 2006). The Kokchetav massif in Kazakhstan contains some of the oldest known UHP rocks, which reached diamond-facies conditions indicating subduction to at least 150 km depth, at ~530 Ma (Claoué-Long et al., 1991; Hermann et al., 2001; Katayama et al., 2001). These rocks therefore provide a rare opportunity to study fundamental processes at the onset of modern plate tectonics. In addition to determining the P-T conditions recorded by the rocks, the timing of subduction and exhumation is crucial to constrain the tectonic processes responsible for UHP metamorphism. For example, it has been shown in the Kokchetav massif and in the Alps that exhumation can be as fast as subduction, acting at rates of cm/year (Hermann et al., 2001; Rubatto and Hermann, 2001). This provides strong evidence that tectonic processes and not erosion drives exhumation, and is an important constraint for exhumation models. A number of different tectonic models have been proposed to explain how crustal rocks can be subducted to, and exhumed from, such great depth (e.g. Chemenda et al., 1996; Cloos, 1993; Gerya et al., 2002; Kurz and Froitzheim, 2002). The detailed knowledge of the timing of UHP metamorphism is crucial to evaluate these different models.

The UHP rocks of the Kokchetav massif are contained within two separate zones: a diamond-bearing unit and a coesite-bearing unit. While there are abundant age data for the diamond-bearing rocks, few age constraints exist for the coesite-bearing unit, where the temperatures are too high for Ar-Ar dating but too low to produce metamorphic zircon. In this paper we show that in Ca-poor rock types of the coesite bearing unit, monazite is stable up to UHP conditions. Such monazite is dated using SHRIMP and provides evidence that UHP metamorphism is diachronous in the coesite and diamond units. This time constraint has a strong bearing on the type of tectonic model applicable to this area and is comparable to what has been documented in younger collisional belts such as the Alps.

Two contrasting UHP domains

The Kokchetav massif is located in the central part of the Eurasian craton and extends NW-SE over 150 km with a thickness of 20 km. This HP-UHP belt is composed of several metamorphic units derived from Precambrian protoliths, overlain by Devonian volcanoclastic and Carboniferous-Triassic shallow-water deposits, and intruded by Ordovician granites and gabbros (Dobretsov et al., 1995; Maruyama and Parkinson, 2000). Two contrasting UHP domains have been described in the Kokchetav massif: the diamond-bearing unit at Kumdy-Kol and the nearby coesite-bearing unit at Kulet (Dobretsov et al., 1998; Theunissen et al., 2000; Udovkina, 1985). There is mounting evidence of different P-T conditions in the two areas with P = 4- 6 GPa and T = 950-1000°C in Kumdy-Kol

(Hermann et al., 2001; Maruyama and Parkinson, 2000; Shatsky et al., 1995; Zhang et al., 1997), versus P = 3.4-3.6 GPa and T = 720-760°C in Kulet (Parkinson, 2000).

Two alternative models have been proposed for the juxtaposition of these UHP domains. The *extrusion wedge* model suggests that the two units were exhumed simultaneously by the same process and stacked together during exhumation (Maruyama and Parkinson, 2000). In contrast the *megamelange* model emphasizes different evolutions and thus exhumation processes for the diamond- and the coesite-bearing unit (Dobretsov et al., 1995; Shatsky et al., 1995; Theunissen et al., 2000). Still lacking is the time information in order to assess whether the exhumation of these UHP units is coupled or decoupled. There are several studies concerning the age of UHP metamorphism in the diamond-bearing rocks (e.g. Claoué-Long et al., 1991; Hermann et al., 2001; Katayama et al., 2001; Shatsky et al., 1999), which reached peak UHP at ~530 Ma, and then were quickly decompressed to granulite and then amphibolite-facies conditions (~525 Ma). The diamond-bearing rocks cooled below the closure of Ar-Ar system in mica at 515-517 Ma (Shatsky et al., 1999). In contrast, only Ar-Ar ages are available for the coesite-bearing rocks of Kulet: they scatter between 565-520 Ma (Theunissen et al., 2000) and ~500 Ma (Hacker et al., 2003). These ages leave the possibility open that the two UHP units were exhumed at different times.

Sample and monazite description

We have investigated in detail two garnet-bearing micaschists from the coesite-facies Kulet area, which contain different types of monazite. Sample Ku98-12 is a coarse-grained and strongly foliated micaschist consisting of garnet, quartz, phengite, kyanite, rutile, monazite and rare zircon. Garnet forms dispersed porphyroblasts up to 1 cm in diameter with common rutile and rare large polycrystalline quartz inclusions. Monazite inclusions occur throughout the garnet and are associated to chlorite, apatite and kyanite (Fig. 1a). In garnet, Mn, Y and HREE strongly decrease from core to rim whereas Mg# [Mg/(Mg+Fe)] increases in agreement with a prograde growth (Fig. DR1 and Parkinson, 2000). The pyrope-rich garnet rims are in textural equilibrium with kyanite and large oriented phengite (Si=3.38 pfu, 0.5 wt% TiO_2, Fig. DR2a) that occasionally contain monazite inclusions. Large phengite grains are surrounded by smaller laths (Si=3.28 pfu, 0.6 wt% TiO_2) indicating recrystallization during decompression. Both types of phengite recrystallized at the margins to fine-grained phengite (Si=3.21 pfu, 0.55 wt% TiO_2), which in turn is partly replaced by even finer grained muscovite (Si=3.10 pfu, 0.3 wt% TiO_2) that coexists with biotite. Biotite also replaces garnet rims and occasionally contains monazite inclusions. The textural relations and mineral compositions suggest that this micaschist documents a prograde, peak and several retrograde metamorphic stages, during all of which monazite appears to be stable.

Sample K26C is a whiteschist mainly composed of quartz and garnet with phengite (Si=3.5 pfu, 0.2 wt% TiO_2) defining a foliation. Euhedral garnet porphyroblasts, similar to those described by Parkinson (2000), contain inclusions of monocrystalline quartz in the core and typical polycrystalline palisade- or mosaic-quartz aggregates surrounded by weak radial cracks in the rim. Large anhedral garnet porphyroblasts contain inclusions of polycrystalline quartz with radial cracks and coesite relics. Fresh coesite is still locally preserved (Shatsky et al., 1998). In contrast to the first sample, where large monazite grains were found, monazite is present only in small (<100 µm) symplectite-like aggregates with apatite and phengite (Fig. 1b). Such symplectites are found within the rim of the large garnet porphyroblasts and in the matrix. The varying proportions of monazite (30-80%) and apatite (10-55%) in the symplectites suggest that the precursor mineral likely was a solid solution between apatite and monazite end-members. Similar textures (apatite-monazite symplectites after bearthite) have been observed in UHP whiteschists (Scherrer et al., 2001) and micaschists (Hermann pers. comm.) from the Dora Maira (Italy) and are interpreted to form during decompression.

The presence of coesite and coesite pseudomorphs provide evidence that the rocks experienced UHP peak conditions which, based on peak mineral compositions, are estimated to be ~2.8 GPa, ~680°C using the calibrations of Krogh Ravna and Terry (2004) and Green and Hellman (1982), respectively. This is slightly lower than what has been reported in the detailed study of Parkinson (2000), who obtained 720-760°C and 3.4-3.6 GPa for the peak conditions of the

Kulet whiteschists. The several retrograde stages documented by phengite are in agreement with an initial near isotherm decompression stage to about 1.8 GPa, 640°C followed by decompression and cooling, as outlined by Parkinson (2000).

Monazite U-Pb geochronology

U-Th-Pb analyses were obtained for monazite grains separated from micaschist Ku98-12 and for monazite contained in the symplectites of micaschist K26C. This latter was analysed directly in thin section.

Back-scattered electron images (Fig. 1c-e) of monazite from sample Ku98-12 reveal a weak zoning that is organised in a core-rim (core brighter than rim) or mosaic-like texture. Monazite contains inclusions of phengite with variable composition (Fig. DR2a), chlorite, apatite, zircon and rutile. Inclusions are equally distributed between core and rim and the inclusions, particularly phengite, are found across the core-rim boundary (e.g. Fig. 1d). This supports the textural observations that monazite was stable over a large portion of the metamorphic history of the sample.

SHRIMP analyses yielded $^{206}Pb/^{238}U$ ages between 488 and 529 Ma (Table DR1 and Fig. 2), with a scatter of data above analytical uncertainty (507±3 Ma MSWD = 7.3, N = 54, or MSWD = 5.2 excluding three extreme values). The scatter of ages somewhat correlates with the core-rim structure seen in BSE; i.e. within a crystal, cores are older or equal in age to the rims, but never younger than the rims (Fig. 1c-e). However, throughout the sample core and rim ages vary significantly and overlap (~496-529 Ma and 491-520 Ma, respectively).

There is no clear correlation between age and monazite composition as measured by EMP analysis close to the SHRIMP pits. Older monazite domains have a weak tendency to higher Y and Gd contents (Fig. DR2b). However, overall a limited chemical variation is observed in the monazite grains (Fig. DR3a). This information can be used to compare monazite to garnet growth by using empirical trace element partitioning between monazite and the different garnet growth zones (e.g. Hermann and Rubatto, 2003). The garnet in sample Ku98-12 has a bell-shaped major and trace element zoning that indicates prograde growth culminating in a rim with high Mg#, low Mn, Y and REE. The HREE distribution coefficients between the monazite composition (either core or rim) and the garnet rim composition decrease constantly from Dy (30-75) to Lu (0.8-2.2) (Fig. DR3). Similar values were reported for monazite/garnet equilibrium partitioning in granulites (e.g. Buick et al., 2006; Hermann and Rubatto, 2003; Rubatto et al., 2006). The partitioning of HREE between monazite, and the garnet core is at least an order of magnitude lower and far from any equilibrium partitioning reported. This provides evidence that the monazite dated in sample Ku98-12 is in chemical equilibrium with the garnet rim. Garnet break down is restricted to the last retrograde event, where a fine biotite rim forms around garnet. Therefore the dated monazite must have formed in the period between the last stage of prograde garnet growth and the late retrogression when biotite formed.

Some of the old monazite domains have inclusions of chlorite, which occurs as prograde mineral enclosed in garnet, but is not stable in the peak assemblage.

This suggests that at least some of the older monazite may have formed before the metamorphic peak. The composition of phengite inclusions in monazite spans the entire range documented in the rock (Si=3.1-3.4 pfu, Fig. DR2a), indicating that monazite recrystallization/formation occurred during peak and several retrograde stages. However, there is no systematic relationship between Si-content of the inclusion and the age of the monazite domain (Fig. DR2c). For example phengite with 3.4 pfu of Si is present as inclusion in a 526 Ma cores as well as in a 491 Ma domain.

The combined evidence from monazite textures, trace element composition, inclusion assemblage and ages suggests that the age spread is geologically significant and indicates growth/recrystallization of monazite over a period of time. The youngest and oldest statistically consistent (MSWD ~ 1) group of analyses within the age spread observed are at 497±2 Ma and 522±2 Ma (Fig. 2). These values can be taken as bracketing the ~25 Ma time span of monazite growth between prograde-peak metamorphic conditions and amphibolite facies retrogression.

SHRIMP U-Pb analyses on micaschist K26C was done with a small spot size (10-15 micron diameter) to maximise the chances to get clean monazite analyses. Filtering the data according to the percent of monazite versus other phases in the analysis (see analytical methods in DR) returns a main group with an average $^{206}Pb/^{238}U$ age of 508±6 Ma (MSWD 0.67, N = 7, Table DR2) and an identical concordia age (Fig. 2). In this sample, the monazite-forming reaction is likely to be the breakdown of precursor bearthite. The obtained age thus dates this reaction, which is related to the exhumation of the UHP rocks, although the exact P-T conditions of the reaction cannot be established. The HP minerals texturally associated to the symplectites indicate that the reaction occurred still at relatively HP conditions.

Monazite versus zircon behaviour during deep subduction

Zircon is known to react in various ways during deep subduction, from recrystallization in sub-solidus conditions under the influence of fluids to new growth favoured by melting (Rubatto and Hermann, 2007). An example of new zircon formation at UHP is represented by zircon found in the Kokchetav diamond-bearing unit of Kumdy-Kol (Hermann et al., 2001; Katayama et al., 2001). In contrast, the zircons contained in the coesite-bearing rocks of Kulet do not show any metamorphic domains of appreciable size (> a few μm). The difference in behaviour is likely due to the presence of a melt in the diamond-bearing unit, which favoured dissolution-reprecipitation of zircon. The coesite-bearing rocks experienced lower metamorphic conditions below the pelite solidus (Fig. 3, Nichols et al., 1994), conditions at which metamorphic zircon formation can be very limited and restricted to zones rich in fluids (see a review in Geisler et al., 2007; Rubatto and Hermann, 2007).

This study shows that monazite can be used to date UHP rocks in conditions not favourable to metamorphic zircon. As demonstrated in regional metamorphic sequences, monazite forms and/or recrystallizes at lower grade than zircon. Monazite is expected to be present at HP and UHP conditions only in Ca-poor rocks, where the stability of the most common LREE mineral, allanite, is suppressed (Hermann, 2002). We report here one of the first occurrences of UHP monazite (see also Terry et al., 2000). Finger and Krenn (2007) documented in detail HP monazite from a Al-rich, Ca-poor rock, in which monazite is stable during prograde, peak (26±3 kbar, 830±30°C) and retrograde conditions. That HP monazite is characterised by high Sr contents (Sr 0.85-1.7 wt%) indicating formation after breakdown of plagioclase. This chemical criterion is however not valid for the Kokchetav monazite (Sr 500-1000 ppm) because these Ca-poor micaschist do not contain plagioclase even at low pressures. In rocks richer in calcium, allanite or bearthite are the stable LREE phases (Hermann, 2002; Scherrer et al., 2001), and monazite will form during the decompressional break down of these phases. In either case, dating of monazite can yield time constraints on the peak and/or exhumation history of UHP rocks.

Age significance and implications

The new age data permit to construct a P-T-time diagram for the coesite-bearing UHP unit that can be compared to the known evolution of the diamond-bearing unit (Fig. 3). Based on texture, trace element composition and inclusions in monazite it is concluded that the pressures peak was reached at ~520-515 Ma. Decompression is dated by the formation of monazite symplectites in sample Ku26C at 508±6 Ma. This implies that the coesite-bearing unit underwent UHP metamorphism when the diamond unit was already exhumed at mid crustal levels (Fig. 3). The monazite ages cannot be reconciled with the scattering Ar-Ar data of

Theunissen et al. (2000) who obtained biotite and phengite ages of ~520 Ma (including and age of 519±2 Ma for our sample Ku98-12), but also an older muscovite age of 565±2 Ma for sample K26C. The monazite data fit well the internally consistent Ar-Ar ages of Hacker et al. (2003) on micas at ~ 500 Ma. There was thus a time lag of circa 15 Ma between the metamorphic evolution of the diamond and coesite-bearing units. Although the P-T evolution of the diamond-facies and coesite-facies rocks are comparable from amphibolite facies onward (Fig. 3), they are separated in time and thus juxtaposition of the two units must have occurred once the rocks were exhumed to mid crustal levels.

This timing relationship has important implications on the tectonic model for the UHP subduction and exhumation of the Kokchetav massif. Diachronous evolution of the two UHP units is incompatible with the *extrusion-wedge* model (Maruyama and Parkinson, 2000), but the *megamelange* model could accommodate this time constraints (Dobretsov et al., 1995). From our data it can also be added that continental subduction of the Kumdy-Kol unit to diamond-facies conditions did not mark the transition from subduction to collision, because UHP metamorphism occurred in the Kulet micaschists 15 Ma later. Therefore, classical models where continental collision leads to cessation of subduction and initiates exhumation (e.g. Chemenda et al., 1996; Cloos, 1993) cannot be applied to the Kokchetav massif. It also renders unrealistic models where a single event such as collision or slab break-off initiate exhumation (e.g. Hermann et al., 2001; von Blanckenburg and Davies, 1995). On the other hand, the obtained ages would be consistent with the subduction channel models of Gerya et al. (2002).

This represents an exemplar case where geochronology can directly assists tectonics in defining a workable subduction-exhumation model.

Diachronous subduction and exhumation is well documented in the Western Alps. There is evidence for different units undergoing similar subduction conditions at different times (e.g. Rubatto et al., 1998), and a recent model proposes exhumation of diachronous slices of HP rocks equilibrated at different depths inside a subduction channel (Federico et al., 2007). We can thus draw a similarity between the Cambrian tectonic represented in the Kokchetav massif and the Paleogene Alpine orogeny. This represents supporting evidence that not only modern cold subduction (Brown, 2006), but also complex and diachronous exhumation, has been acting since at least the early Paleozoic era.

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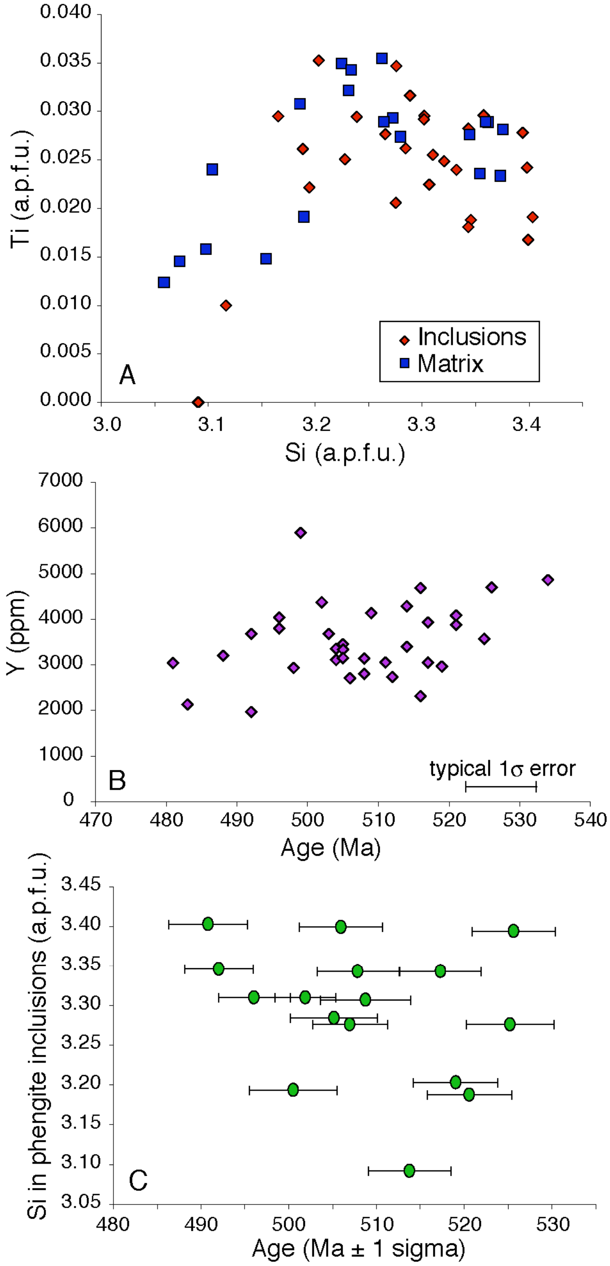
FIGURE CAPTIONS

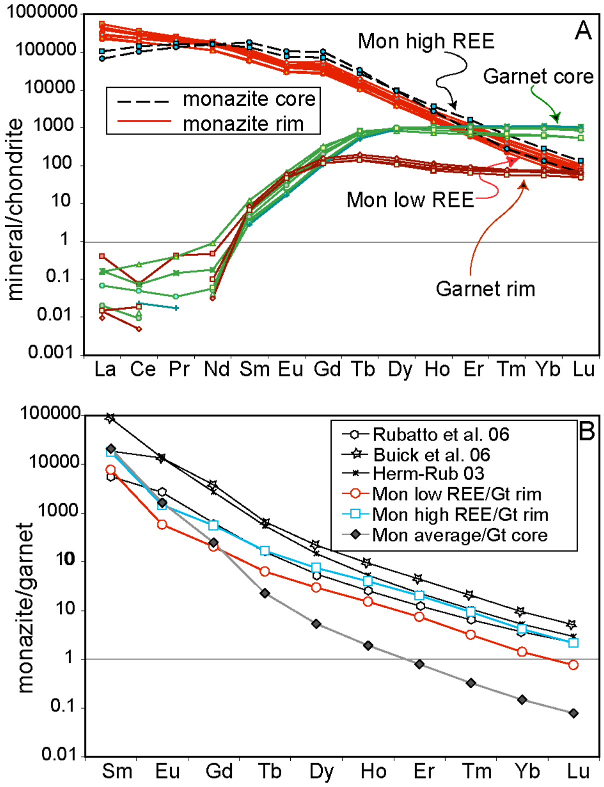
Fig. 1. Back-scattered electron images of monazite textural relationships. A) Composite inclusion in garnet consisting of monazite, apatite, kyanite and chlorite from sample Ku98-12. B) Symplectite of monazite, apatite and phengite, likely formed from decompression of bearthite in sample K26C. C-E) High contrast images of monazite crystals in sample Ku98-12. Note the core-rim structure and the inclusions of phengite with different Si contents. Circles mark SHRIMP pits for which $^{206}Pb/^{238}U$ ages (Ma ±1 sigma) are reported. Y contents from EMP analysis of the same domain are given in ppm.

Fig. 2. Monazite U-Pb geochronology. A) Plot of $^{206}Pb/^{238}U$ ages for sample Ku98-12 showing the wide age range. The statistically consistent (MSWD~1) older and younger age group are reported. B) Concordia diagram for U-Pb analyses of monazite symplectites in sample K26C. The Concordia age reported in the box is represented by the darker ellipse. Average ages are at 95% c.l..

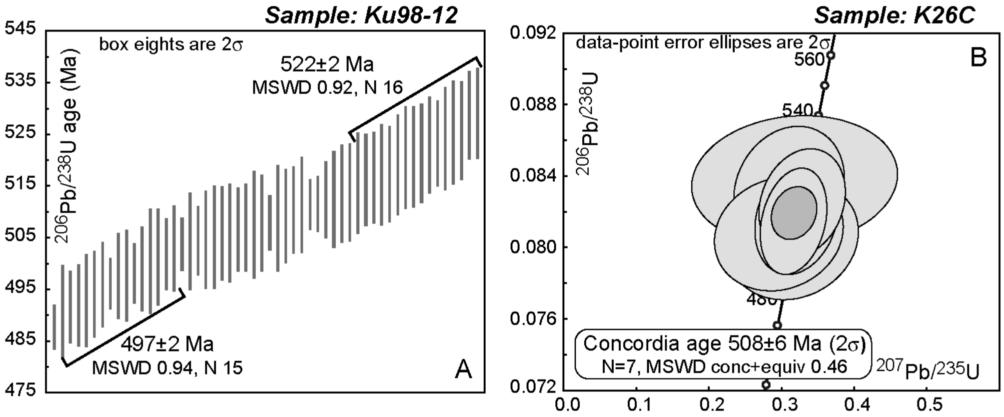
Fig. 3. P-T-time path for the two UHP units of the Kokchetav massif. Ages are given in Ma and are U-Pb on zircon (Kumdy-Kol) or monazite (Kulet) and Ar-Ar on mica (in italics). The P-T-time path for Kumdy-Kol is after Hermann et al. (2001) and references therein. For Kulet, the P-T estimates are from this work (thick black line) and Parkinson (2000) (thin black dashed line). Kulet U-Pb ages are from this work (tw), and Ar-Ar ages are from Hacker et al. (2003). Wet solidus from Nichols et al. (1994). See text for discussion.



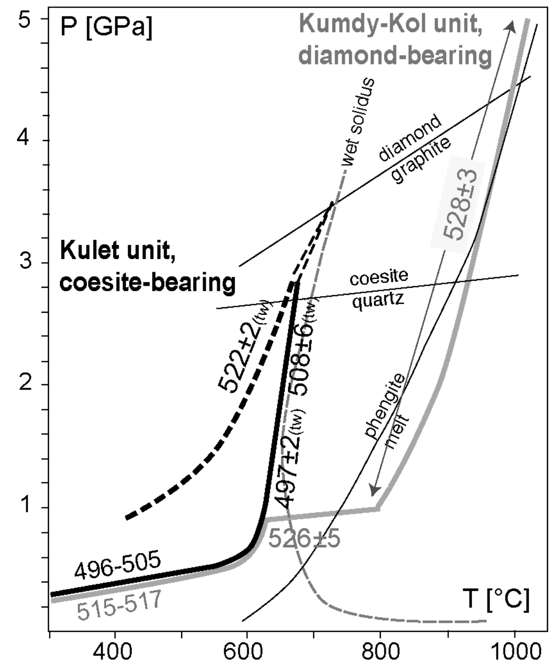
Rubatto et al. Data Repository, Fig. 2



Rubatto et al., Data Repository Fig. 3



Rubatto et al., Figure 2



Rubatto et al., Fig. 3.