Ultrarapid exhumation of ultrahigh-pressure diamond-bearing metasedimentary rocks of the Kokchetav Massif, Kazakhstan

Bradley R. Hacker, Andrew Calvert, R.Y. Zhang, W. Gary Ernst, J.G. Liou

1. Introduction

The Kokchetav Massif, Kazakhstan (Fig. 1), is a large ( ~ 10–15 x 150 km) ultrahigh-pressure terrane, distinctive because of the very unusual widespread occurrence of metamorphic diamond (e.g., Dobretsov et al., 1998; Maruyama and Parkinson, 2000; Sobolev et al., 1990) and coesite (Katayama et al., 2000; Parkinson, 2000) that formed as a result of subduction of a continental margin or microcontinent. In spite of this, its geological relationships are relatively poorly known because of geographic inaccessibility and poor outcrop. A spate of recent studies (see references quoted in this article) has, however, produced an excellent structural and petrological assessment of the

Kokchetav Massif. This paper reports new 40Ar/39Ar geochronology to complement the petrological and structural investigations and provide new time constraints on the history of this remarkable group of rocks. Unless otherwise noted, quoted uncertainties for radiometric ages are 2σ.

2. Geology of the Kokchetav Massif

The Kokchetav Massif consists of dominantly continental rocks that have most recently been divided into four flat-lying, fault-bounded, high-pressure to ultrahigh-pressure units with an aggregate thickness of ~ 2 km (Maruyama and Parkinson, 2000). Early subhorizontal structures characterized by intrafolial isoclinal folds are overprinted by late steep structures (Kaneko et al., 2000; Yamamoto et al., 2000).

Unit I, the structurally lowest unit, is composed of amphibolite, orthogneiss, and pelitic schist recrystallized at amphibolite-facies conditions of 700–815 °C,
1.2–1.3 GPa (Masago, 2000; Ota et al., 2000). Unit II, pelitic–psammitic gneiss and whiteschist, with variably retrogressed eclogite and minor pods of garnet peridotite, experienced peak metamorphism at 780–1000 °C, 3.7–6.0(?) GPa (Okamoto et al., 2000). Unit II contains the remarkable microdiamonds as inclusions in garnet, zircon, and clinopyroxene from dolomitic marble, clinopyroxene-bearing garnet quartzite, and garnet–biotite paragneiss; coesite as inclusions in eclogite, paragneiss, and whiteschist; and clinopyroxene with as much as 1.0 wt.% K2O in gneiss, marble, and eclogite (Okamoto et al., 2000). Unit III, chiefly interlayered orthogneiss and amphibolite (blocks of UHP eclogite at the base of Unit III may have been derived from Unit II), was metamorphosed at 730–750 °C, 1.1–1.4 GPa (Ota et al., 2000). Unit IV, the structurally highest unit, consists of quartzose metasediments with minor amphibolite; it experienced epidote-amphibolite facies P–T conditions of 400–500 °C, 0.9 GPa (Masago, 2000). Units I, II, and III all show a late amphibolite-facies overprint at 570–680 °C, 0.7–1.3 GPa, equivalent to the peak metamorphism of Unit IV (Masago, 2000; Ota et al., 2000).

Unit I shows top-N(W) sense-of-shear indicators (mica fish, shear bands, etc.) (Yamamoto et al., 2000), whereas Units III (Yamamoto et al., 2000) and IV (Kaneko et al., 2000) contain top-S shear indicators. Because ultrahigh-pressure Unit II overlies high-pres-
sure Unit I with top-N(W) sense of shear and underlies high- to medium-pressure Units III and IV with show top-S(E) sense of shear, Unit II is interpreted to have been exhumed upward and northward within a channel bounded by lower pressure rocks to the north and south (Maruyama and Parkinson, 2000).

These high-pressure to ultrahigh-pressure rocks are tectonically overlain and underlain by rocks metamorphosed at normal crustal pressures and temperatures. Unit I overlies the Daulet Suite, pelitic–psammitic rocks recrystallized at low pressures (500–650 °C, 0.2–0.3 GPa (Terabayashi, 1999)), along a gently N-dipping fault with top-N shear bands (Ishikawa et al., 2000). Unit IV is overlain by feebly metamorphosed clastic and carbonate rocks along a gently inclined normal fault with top-S motion (Kaneko et al., 2000). Unmetamorphosed and undeformed granitic plutons intrude Units I, II, III, and the Daulet Suite (Ishikawa et al., 2000); some of these are reportedly 420–460 Ma (Dobretsov et al., 1998) and 515–517 Ma (Borisova et al., 1995), but insufficient data are available to evaluate these ages.

3. Geochronology

High-resolution geochronologic data for the Kokchetav Massif are rather sparse. The first sensitive high-resolution ion microprobe (SHRIMP) U/Pb analyses of Kokchetav zircons with diamond inclusions yielded a mean age of 530 ± 7 Ma (Claoue-Long et al., 1991). Katayama et al. (2001) subsequently obtained more SHRIMP data on zircons from diamond-bearing gneiss, diamond-free gneiss, and a coesite-bearing eclogite. After rejecting one anomalously old age, they reported a $^{238}\text{U}/^{206}\text{Pb}$ mean age of 537 ± 9 Ma for grain cores and mantles with ultrahigh-pressure mineral inclusions; after excluding two anomalously young ages, they reported a $^{238}\text{U}/^{206}\text{Pb}$ mean age of 507 ± 8 Ma for grain rims that contain low-P mineral inclusions such as graphite, quartz, and chlorite. Note that all of their core and rim ages (aside from the three they excluded) fit a single population with an age of 519.8 ± 6.4 Ma (MSWD = 1.4), and on a statistical basis, cannot be separated into two populations. Zircon ages from ultrahigh-pressure rocks are often difficult to tie directly to the time of ultrahigh-pressure metamorphism (e.g., Hacker et al., 1998), but the textural observations of ultrahigh-pressure mineral inclusions by Katayama et al. (2001) are definitive.

Sm/Nd or Lu/Hf analyses of ultrahigh-pressure phases are a more direct means of assessing time at peak pressure, but they may be complicated by zoning (Brueckner et al., 1996) or later hydrothermal

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
<th>Rock description</th>
</tr>
</thead>
<tbody>
<tr>
<td>95K-2</td>
<td>Kumdy–Kol</td>
<td>garnet–biotite gneiss. Garnet porphyroblasts of 1- to 4-mm set in a matrix of quartz, minor plagioclase, and biotite</td>
</tr>
<tr>
<td>95K-3</td>
<td>Kumdy–Kol</td>
<td>similar to 95K-2</td>
</tr>
<tr>
<td>95K-5b</td>
<td>Kumdy–Kol</td>
<td>quartz-rich eclogite with &gt;50% garnet, 30% quartz, hornblende replacement of clinopyroxene, and minor rutile</td>
</tr>
<tr>
<td>95K-5c</td>
<td>Kumdy–Kol</td>
<td>quartz–muscovite–plagioclase–K-feldspar (?) gneiss. With minor garnet and apatite</td>
</tr>
<tr>
<td>95K-5e</td>
<td>Kumdy–Kol</td>
<td>garnet–muscovite–kyanite–quartz schist with minor feldspar, tourmaline, rutile, and zircon. Secondary biotite and chlorite replace garnet and kyanite. Strong foliation</td>
</tr>
<tr>
<td>95K-7</td>
<td>Kumdy–Kol</td>
<td>diopside-bearing dolomitic marble similar to 95K-5E, but garnet is coarser (1.5–5 mm)</td>
</tr>
<tr>
<td>95K-8a’</td>
<td>Kumdy–Kol</td>
<td>diamond-bearing gneiss with garnet, muscovite, biotite, quartz, plagioclase, and minor tourmaline. Diamonds are rare inclusions in garnet</td>
</tr>
<tr>
<td>95K-11a</td>
<td>Kumdy–Kol</td>
<td>garnet–biotite–quartz schist. Garnets (&gt;10 vol.%) contain many inclusions of biotite and quartz; some are atoll shaped</td>
</tr>
<tr>
<td>95K-21f</td>
<td>Kulet</td>
<td>garnet–muscovite–biotite–quartz schist with minor rutile; strong deformation. Strong foliation; garnets are fractured</td>
</tr>
<tr>
<td>A-12</td>
<td>Kumdy–Kol?</td>
<td>garnet–kyanite–muscovite–biotite metasediment</td>
</tr>
<tr>
<td>KZ-5</td>
<td>Kumdy–Kol</td>
<td>eclogite partially retrogressed to amphibolite</td>
</tr>
<tr>
<td>KZ-7</td>
<td>Kumdy–Kol</td>
<td>garnet–muscovite–plagioclase–quartz orthogneiss</td>
</tr>
<tr>
<td>KZ-10</td>
<td>Kumdy–Kol</td>
<td>quartzose eclogite partially retrogressed to biotite-bearing amphibolite</td>
</tr>
<tr>
<td>KZ-17</td>
<td>Sulu–Tjube</td>
<td>eclogite partially retrogressed to zoisite-bearing amphibolite</td>
</tr>
<tr>
<td>KZ-24</td>
<td>Kulet</td>
<td>pyrope–talc–kyanite schist with minor biotite</td>
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</tbody>
</table>
Table 2
Summary of 40Ar/36Ar data

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mineral</th>
<th>Size (μm)</th>
<th>Mass (mg)</th>
<th>TFA</th>
<th>WMPA</th>
<th>IA</th>
<th>40Ar/36Ar</th>
<th>MSWD</th>
<th>Steps used</th>
<th>% used</th>
</tr>
</thead>
<tbody>
<tr>
<td>95K-2</td>
<td>bio</td>
<td>90–125</td>
<td>0.39</td>
<td>483.9 ± 0.9</td>
<td>none</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>95K-3</td>
<td>bio</td>
<td>180–250</td>
<td>0.35</td>
<td>502.8 ± 0.9</td>
<td>510.3 ± 0.9</td>
<td>509.8 ± 1.1</td>
<td>467 ± 165</td>
<td>0.28</td>
<td>22–31/36</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>mus</td>
<td>180–250</td>
<td>0.55</td>
<td>505.1 ± 0.9</td>
<td>506.6 ± 0.9</td>
<td>505.9 ± 1.1</td>
<td>333 ± 30</td>
<td>2.6</td>
<td>7–31/41</td>
<td>70</td>
</tr>
<tr>
<td>95K-5b</td>
<td>hbl</td>
<td>125–180</td>
<td>2.00</td>
<td>643.4 ± 1.1</td>
<td>none</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>95K-5c</td>
<td>mus</td>
<td>355–500</td>
<td>0.45</td>
<td>526.0 ± 0.9</td>
<td>525.3 ± 0.9</td>
<td>524.6 ± 1.2</td>
<td>398 ± 99</td>
<td>1</td>
<td>12–22/39</td>
<td>33</td>
</tr>
<tr>
<td>95K-5e</td>
<td>mus</td>
<td>355–500</td>
<td>0.45</td>
<td>531.0 ± 0.9</td>
<td>529.4 ± 1.0</td>
<td>529.6 ± 1.5</td>
<td>285 ± 81</td>
<td>0.42</td>
<td>16–22/42</td>
<td>48</td>
</tr>
<tr>
<td>95K-7</td>
<td>cpx</td>
<td>350–500</td>
<td>2.6</td>
<td>578.9 ± 6.0</td>
<td>none</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>95K-8a'</td>
<td>mus</td>
<td>355–500</td>
<td>0.30</td>
<td>509.8 ± 0.9</td>
<td>509.4 ± 0.9</td>
<td>509.8 ± 1.0</td>
<td>324 ± 18</td>
<td>1.2</td>
<td>5–34/36</td>
<td>90</td>
</tr>
<tr>
<td>95K-11a</td>
<td>bio</td>
<td>106–155</td>
<td>0.55</td>
<td>502.1 ± 0.9</td>
<td>510.8 ± 0.9</td>
<td>510.1 ± 1.7</td>
<td>451 ± 199</td>
<td>0.31</td>
<td>24–28/30</td>
<td>18</td>
</tr>
<tr>
<td>95K-11c</td>
<td>bio</td>
<td>180–250</td>
<td>0.48</td>
<td>506.7 ± 0.9</td>
<td>511.4 ± 0.9</td>
<td>510.2 ± 1.0</td>
<td>503 ± 62</td>
<td>2.1</td>
<td>5–29/31</td>
<td>71</td>
</tr>
<tr>
<td>95K-21f</td>
<td>bio</td>
<td>180–250</td>
<td>0.45</td>
<td>422.4 ± 0.8</td>
<td>none</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>mus</td>
<td>180–250</td>
<td>0.48</td>
<td>495.6 ± 0.9</td>
<td>none</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>A-12</td>
<td>mus</td>
<td>355–500</td>
<td>0.26</td>
<td>510.0 ± 0.9</td>
<td>508.9 ± 0.9</td>
<td>509.1 ± 1.0</td>
<td>290 ± 20</td>
<td>1.5</td>
<td>5–27/28</td>
<td>82</td>
</tr>
<tr>
<td>KZ-5</td>
<td>hbl</td>
<td>125–180</td>
<td>2.00</td>
<td>653.0 ± 1.1</td>
<td>none</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>9–34/35</td>
<td>74</td>
</tr>
<tr>
<td>KZ-7</td>
<td>mus</td>
<td>250–300</td>
<td>0.47</td>
<td>505.3 ± 0.9</td>
<td>none</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>KZ-10</td>
<td>bio</td>
<td>125–150</td>
<td>0.21</td>
<td>521.1 ± 0.9</td>
<td>none</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>KZ-17</td>
<td>hbl</td>
<td>125–180</td>
<td>2.80</td>
<td>512.0 ± 0.9</td>
<td>none</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>KZ-24</td>
<td>bio</td>
<td>180–250</td>
<td>0.25</td>
<td>501.8 ± 1.1</td>
<td>none</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Preferred ages are in bold. Uncertainties in table are ±1σ, whereas ±2σ is quoted in the text.

a Italics indicate weighted mean ages (WMA); remainder are weighted mean plateau ages (WMPA).

b Isochron ages (IA) in italics are poor fits that have MSWD greater than expected.

To constrain the timing and path of exhumation of the Kokchetav ultrahigh-pressure rocks, we undertook 40Ar/39Ar resistance furnace dating of multigrain separates of hornblende, K-white mica (henceforth referred to as “muscovite”), biotite, and K-bearing diopside. All the samples we analyzed are from Unit II; all are from the Kumdy–Kol area (Fig. 1), except for two from the Kulet area and one from the Sulu–Tjube area. The samples include mafic eclogites, quartzose eclogites, diamond-bearing gneiss, diamond-free gneiss, and dolomitic marble (Table 1). The results are summarized in Table 2 and reported in full in the appendix.1

Unless otherwise mentioned, analytical techniques followed Calvert et al. (1999). We calculate weighted mean plateau ages (WMPA) from consecutive step ages that make up >50% of the released 39Ar and are statistically equivalent at the 95% confidence interval. We calculate weighted mean ages (WMA) from consecutive step ages that are not statistically equivalent at the 95% confidence interval, but for which a part of the spectrum is not hump shaped, saddle shaped, crankshaft shaped, or composed of serially increasing or decreasing step ages; these “non-flat” spectrum types often indicate excess Ar, in vacuo degassing of more than one mineral or domain, or recoil of 39Ar.

Interpreting the 40Ar/39Ar ages of high-pressure minerals is often difficult because of the presence of excess 40Ar or other factors (e.g., Hacker and Wang, 1995; Li et al., 1994; Scaillet, 1998). Samples may

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1 See Appendix in the online version of this article.
yield plateau that are geochronologically meaningless, either because of in vacuo homogenization or homogenously distributed excess Ar (e.g., Foland, 1983). Mixed age populations (e.g., Wijbrans and McDougall, 1986), recoil of $^{39}$Ar in chloritized biotite (Lo and Onstott, 1989; Ruffet et al., 1991), or contamination by other phases (e.g., Rex et al., 1993) can produce complexly shaped spectra. Laser microprobe $^{40}$Ar/$^{39}$Ar dating of grains can help resolve some of these issues by detailing the spatial distribution of Ar isotopes within grains (e.g., Arnaud and Kelley, 1995; Giorgis et al., 2000; Scaillet, 1998). In the absence of laser microprobe dating, however, there are several means by which one can assess the meaning of spectra. (1) Analyzing the same minerals from different rock types. Eclogites often exhibit the most excess $^{40}$Ar, presumably because their $^{40}$Ar content is small relative to the typically K-rich surrounding gneisses. If different rocks from the same locality (e.g., paragneiss and eclogite) yield different spectra, one or both spectra may be suspect. (2) Analyzing different grains or groups of grains from a single sample. Because excess $^{40}$Ar is inhomogeneously distributed, different (groups of) grains with excess $^{40}$Ar can yield quite different spectra, whereas different groups of grains without excess $^{40}$Ar should yield similar spectra. (3) Spectrum shape—either saddle- or hump-shaped—is often diagnostic of excess $^{40}$Ar (Harrison and McDougall, 1981). (4) Analyzing a suite of minerals or suite of grain sizes from a single sample should yield a range of ages that fall in a sequence dictated by closure temperature. If the suite does not produce such a sequence, some ages may be suspect. (5) Analyzing multiple minerals with different isotopic systems to assess whether the sequence of ages follows the expected sequence of closure temperatures. See, for example, Tonarini et al. (1993), Li et al. (1994), and El-Shalzy et al. (2001) for examples of some of these tests.

Six Kokchetav micas (samples 95K-3 muscovite, 95K-5e, 95K-8a, A-12, KZ-7, KZ-10) yielded relatively flat spectra (Fig. 2a) for which we calculated either weighted mean plateau ages or weighted mean ages. All have $^{40}$Ar/$^{36}$Ar ratios indistinguishable from or close to atmosphere, indicating that the WMPA is preferable to the isochron age. These samples might be affected by excess Ar, but there is no indication of such from the shapes of the spectra or from the distribution of the measured isotopic ratios.

Another four micas (95K-3 biotite, 95K-5c, 95K-11a, 95K-11c) have more internally discordant spectra (Fig. 2b). In particular, the biotite spectra all have intermediate-temperature steps with anomalously old ages and depressed K/Ca ratios, suggesting that these biotites are chloritized and that these steps are affected by recoil of $^{39}$Ar during irradiation (Lo and Onstott, 1989; Ruffet et al., 1991). It is important to note that biotite and muscovite were both analyzed from sample 95K-3, yet the biotite WMA is older than the muscovite WMA; this hints that the biotite, with a more discordant spectrum, may be affected by excess Ar in addition to recoil.

The two oldest ages (529.4 ± 2.0 Ma and 528.3 ± 1.8 Ma) of these two groups of samples derive from relatively well-behaved spectra (95K-5e and KZ-10) and are equivalent at the 95% confidence level at ~ 529 Ma. Seven of our eight younger mica ages cluster around 509.2 ± 1.7 Ma (MSWD = 4.3), and the subset of four samples with the relatively flat spectra gives a mean of 507.9 ± 2.2 Ma (MSWD = 2.4).

Two mica samples from the Kulet area (95K-21f muscovite, KZ-24) have even less well-defined spectra with anomalously low K/Ca ratios for which we provisionally estimate ages of 495.6 ± 1.2 and 504.7 ± 1.0 Ma (Fig. 2c). The isochron for KZ-24 is meaningless, with an $^{40}$Ar/$^{36}$Ar ratio of 239 ± 21. Two other mica samples (95K-2, 95K-21f biotite; not shown) and three hornblendes (Fig. 2d) yielded spectra that have no age significance but indicate the presence of excess $^{40}$Ar.

We also made a concerted effort to obtain an age on a separate of K-bearing diopside (sample 95K-7; Fig. 3). The diopside contains inclusions of K-bearing phases—K-feldspar and probably phengite (Ogasawara et al., 2000)—that are < 1-μm thick and 10- to 200-μm long. We infer that the ultrahigh-pressure stage of eclogite recrystallization produced homogeneous K-rich clinopyroxene and that lower P–T annealing resulted in exsolution of the K-feldspar and phengite. As far as we are aware, this is the first report of $^{40}$Ar/$^{39}$Ar dating of such a crystal. K-bearing clinopyroxenes hold considerable promise as thermochronometers because they are the only K-bearing phase other than K-feldspar that may not decompose during heating in the resistance furnace until relatively high temperature, conceivably...
Fig. 2. $^{40}$Ar/$^{39}$Ar spectra (step ages do not include error in irradiation parameter, J). K/Ca spectra (maximum value shown is 10,000, beyond which $^{37}$Ar/Ca cannot be distinguished from blank), and inverse isochron diagrams for hornblende and mica. Steps used to compute WMPA ages are shown in dark gray. Inset in each isochron diagram shows fit in more detail. (a) Samples with relatively flat spectra. (b) Samples with moderately flat spectra. (c) Samples with least flat spectra. (d) Hornblende separates.
Fig. 2 (continued).

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rendering them amenable to multi-domain diffusion analysis (e.g., Lovera et al., 1997). Because we suspected a complex spectrum and hoped to apply multi-domain diffusion analysis, we conducted considerable temperature-cycling steps during the analysis. The K/Ca ratios suggest that the low-temperature steps are derived chiefly from the exsolved phases and that the high-temperature steps comprise gas from dominantly K-bearing pyroxene, respectively (Fig. 3). The spread of isotopic ratios from measurements with relatively low $^{40}$Ar/$^{36}$Ar ratios is compatible with an Ar-loss event at $\sim$ 450–500 Ma.

Beyond this, we are unable to interpret the data for the K-bearing diopside.

Shatsky et al. (1999a) reported two $^{40}$Ar/$^{39}$Ar spectra from Kumdy–Kol diamond-bearing garnet–biotite gneiss (their sample K83-3); muscovite and biotite gave plateau ages of $515 \pm 10$ and $517 \pm 10$ Ma, respectively. Travin (1999) (also reported in Theunissen et al., 2000) conducted a more comprehensive $^{40}$Ar/$^{39}$Ar dating program. Four of their samples (17A, 25E, 26C, Ku98-8) from Unit II at Kulet gave ages of 565–635 Ma, prompting Travin to suggest that these samples are affected by excess...
Two other gneiss and schist samples (Ku98-20, Ku98-12) from the same area gave muscovite and biotite plateau ages of 519.3 ± 3.6 and 521.5 ± 7.8 Ma, respectively. Travin also obtained hornblende and muscovite ages from Unit IV (samples 90B and 90D) at Chaglinka of 516.6 ± 12.4 and 498.1 ± 4.4 Ma. The former is equivalent to our ~508 Ma samples from Kumdy–Kol and the latter to our ~500 Ma samples from the Kulet area. Two cordierite schists (Ku98-2, E-98-8) from the Daulet unit gave muscovite and biotite plateau ages of 396.0 ± 12.0 and 402.0 ± 10.2 Ma, respectively (Travin, 1999), indicating cooling ~100 Myr later than the bulk of the Kokchetav Massif.

4. Tectonic interpretation

Our new geochronologic data can be integrated with existing geochronology to yield a better constrained exhumation history for the Kokchetav Massif (Fig. 4). First we make the assumption that the Sm/Nd mineral isochron of 535 Ma dates the time of eclogite-facies metamorphism in Unit II. While this ingrowth of radiogenic Nd need not have happened at the peak metamorphic conditions of 780–1000 °C, 100–180(?!) km (Okamoto et al., 2000), it nevertheless must have occurred at eclogite-facies pressures. Second, because the amphibolite-facies metamorphism
that overprinted the high-pressure minerals at 20- to 40-km depth was likely too hot (570–680 °C) (Masago, 2000; Ota et al., 2000) for Ar retention, the oldest 40Ar/39Ar muscovite and biotite ages should indicate when the UHP rocks had been exhumed through the mantle and reached crustal levels. We provisionally interpret the ~529 Ma mica ages from samples 95K-5e and KZ-10 as signifying this—in which case the duration of exhumation was ~6 Myr. Accordingly, the average vertical rate of exhumation was comparable to plate tectonic rates, at 15–30 km/Myr. The grouping of mica ages around ~529 Ma from two different minerals and three different rock types—regardless of whether one chooses WMPA ages or total fusion ages—implies that this conclusion is robust. However, the presence of excess 40Ar cannot be discounted, and this study should be followed up by additional studies to assess whether these ages are reliable.

The second group of mica ages, at ~508 Ma, is a much more clearly defined population composed of a greater number of samples that yield less-disturbed spectra. This group is equivalent in age to the U/Pb SHRIMP determinations of 507 ± 8 Ma that

Fig. 2 (continued).
Fig. 2 (continued).
Katayama et al. (2001) obtained from the rims of zircons that contain low-P mineral inclusions such as graphite, quartz, and chlorite. Together, these mica and zircon ages indicate a tectonic event that caused zircon growth or Pb loss and reset some mica grains to ~ 508 Ma but did not reset other micas in the same area (i.e., the ~ 529 Ma group). The ~ 508 Ma mica samples do not exhibit any systematic difference in
style or degree of deformation from the ~529 Ma mica samples, such that perhaps a brief amphibolite-facies or greenschist-facies event with heterogeneous fluid flow that promoted local reaction is most likely. Other, perhaps, less likely possibilities are that the ~508 Ma ages reflect (i) cooling following the regional amphibolite-facies metamorphism mentioned above, (ii) cooling following regional plutonism at 515–517 Ma (Borisova et al., 1995), or (iii) partial Ar loss associated with the intrusion of local 500–505 Ma gabbro–pyroxenite intrusions (Dobretsov et al., 1998).

Katayama et al. (2001) interpreted the same data set, without our 40Ar/39Ar ages, as indicating much slower exhumation of the Kokchetav Massif over a 30 Myr timeframe from ~537 to ~507 Ma. We prefer the interpretation that exhumation of the ultrahigh-pressure rocks through the mantle was finished by 529 Ma, however, because of the mica samples that began to retain radiogenic Ar at that time.
Further measurements of the cooling history and exhumation rate are warranted, however, to see whether this interpretation finds other supporting evidence.

5. Conclusions

New $^{40}$Ar/$^{39}$Ar data, in conjunction with existing Sm/Nd and U/Pb ages, suggest that the ultrahigh-pressure Kokchetav Massif may have been exhumed from 180-km depth to crustal depths within ~6 Myr. The exhumation rate—tens of kilometers per million years—may have been comparable to rates of plate spreading and subduction. The best documentations of similarly fast exhumation rates for other ultrahigh-pressure rocks are the Zermatt–Saas ophiolite (Amato et al., 1999) and the Dora Maira massif (Rubatto and Hermann, 2001).

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