

A New Occurrence and New Data on Akdalaite, a Retrograde Mineral from UHP Whiteschist, Kokchetav Massif, Northern Kazakhstan

SHYH-LUNG HWANG,¹

Department of Materials Science and Engineering, National Dong Hwa University, Hualien, Taiwan, ROC

POUYAN SHEN,

Institute of Materials Science and Engineering, National Sun Yat-sen University, Kaohsiung, Taiwan, ROC

HAO-TSU CHU,

Central Geological Survey, P.O. Box 968, Taipei, Taiwan, ROC

AND TZEN-FU YUI

Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, ROC

Abstract

Akdalaite ($5\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$), as well as hogbomite, kyanite, Zn-bearing staurolite, Mg-chlorite, gahnite, hercynite, quartz, apatite, and zircon, are present as submicrometer-size minerals associated with rutile aggregates occurring as inclusions in garnet porphyroblasts of whiteschist from the Kulet Kol region, Kokchetav Massif, northern Kazakhstan. The akdalaite crystals, ~ 0.5 to $1 \mu\text{m}$ in size, are subhedral to euhedral, and are bounded by (0001), (0001), $\{\bar{1}\bar{1}00\}$, $\{\bar{1}\bar{1}01\}$ facets. EDX analyses show minor Si, Ti, Cr, Fe, Mg, Zn, and Ga, in addition to the major component Al. Electron diffraction data yield the following crystal structural information: space group $P6_3mc$, and $a = 5.58(1) \text{ \AA}$, $c = 8.86(2) \text{ \AA}$, which are similar to those of synthetic tohdite, but are distinctly different from those reported for the type specimen of akdalaite ($P6_3$ or $P6_1$, $a = 14.97 \text{ \AA}$, $c = 12.87 \text{ \AA}$). The akdalaite type specimen, stored in the museum of the All-Russian Institute of Mineral Resources (VIMS) in Moscow, had also been re-examined; it has crystallographic parameters similar to tohdite. It is therefore concluded that crystallographic data of the akdalaite type specimen derived from powder X-ray experiments are in error, and that akdalaite is the natural counterpart of tohdite.

Introduction

AN ALUMINA HYDRATE phase with the stoichiometry $5\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ was first synthesized in hydrothermal experiments by Yamaguchi et al. (1964) at 450–500°C and ~ 0.3 kbar vapor pressure. This synthetic phase was named as “tohdite” after “the University of Tokyo” (Yamaguchi et al., 1964). Since then, this name has been widely used in scientific literature/books on physics, chemistry, and materials science. The naturally occurring alumina hydrate phase similar to tohdite in optical, physical, and powder X-ray diffraction characteristics was first discovered in 1965 from the Solnechnoye fluorite deposit of the USSR (Shpanov et al., 1970), and was named “akdalaite” after the Kazakh name for the deposit.

Despite the fact that akdalaite is similar to tohdite in almost all aspects, the reported unit cell parameters, space group, and reported stoichiometry ($4\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$) of akdalaite are different from those of tohdite (Yamaguchi et al., 1964; Shpanov et al., 1970). On the other hand, based on powder X-ray diffraction experiments, Tilley and Eggleton (1994) reported evidence that “tohdite” is an important phase of some bauxites in northern Australia. Despite the apparent discrepancies in the reported chemical/structural data of akdalaite and tohdite, the Commission on New Minerals and Mineral Names (CNMMN) discouraged the usage of the nomenclature “tohdite” in the paper, probably because akdalaite was the approved name for the natural alumina hydrate phase with composition/structure presumably corresponding to tohdite (Tilley and Eggleton, 1996). In this paper, we report

¹Corresponding author; email: slhwang@mail.ndhu.edu.tw

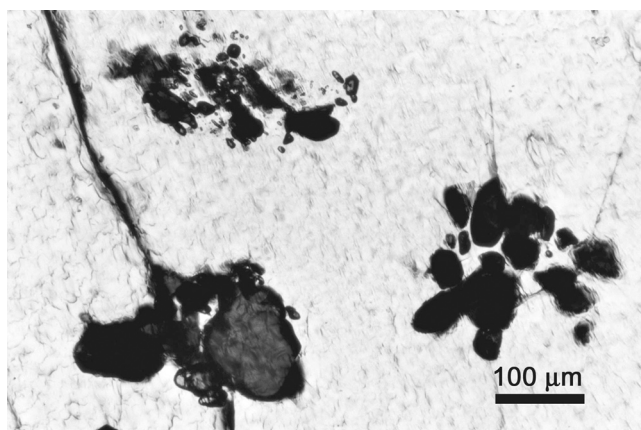


FIG. 1. Optical micrograph under transmitted light (open polarizer), showing rutile aggregates (dark and grey) of various sizes and shapes in garnet host.

the first unambiguous identification of a natural alumina hydrate phase equivalent to synthetic tohdite (i.e., akdalaite) as inclusions in garnet from the ultrahigh-pressure (UHP) whiteschist from the Kulet Kol region of the Kokchetav Massif, Kazakhstan, by analytical electron microscopy (AEM). Based on comparative AEM study of the type specimen of akdalaite stored in the museum in the All-Russian Institute of Mineral Resources (VIMS) in Moscow, we also conclude that the reported data for the akdalaite type specimen are in error (Shpanov et al., 1970). Akdalaite is in fact structurally/compositionally equivalent to synthetic tohdite.

Samples and Analytical Methods

Akdalaite from northern Kazakhstan occurs as submicrometer-size (~ 0.5 – 1.0 μm) inclusions in garnet porphyroblasts of whiteschists from the Kulet Kol region ($N53^{\circ}00'35.2''$; $E69^{\circ}30'51.6''$) of the Kokchetav Massif. The Kokchetav Massif is a large (300×150 km), fault-bounded metamorphic complex of Proterozoic protolith age. In the central part of this massif, several tectonic mélange units, resulting from collision between the Siberian platform and the Vendian-Ordovician island arc, contain high-pressure and ultra-high pressure (HP/UHP) rocks that consist of a variety of crystalline schist, gneiss, eclogite, amphibolite, garnet-pyroxene rocks, quartzite, marble, and rare garnet peridotite (Shatsky et al., 1995). Abundant *in situ* microdiamonds have been found as inclusions in garnet, zircon, and clinopyroxene in biotite gneiss, garnet-

pyroxene rock, and dolomite marble (see Parkinson et al., 2002 for details). Most of the protoliths of UHP rocks were supracrustal rocks with a 2.2–2.3 Ga Sm-Nd model age (Shatsky et al., 1999). The peak metamorphic P-T conditions have been estimated around 5.8–6.5 GPa and 900–1100°C. The age of the peak metamorphism has been determined around 530–540 Ma (e.g., Claoué-Long et al., 1991).

The whiteschist sample KL-1 containing garnet porphyroblasts with submicrometer-size akdalaite inclusions is from the Kulet Kol region of the Kokchetav massif. The rocks in this area are composed of whiteschist, eclogite, amphibolite, and minor quartz schist. Distinct foliation/lineation was developed in the whiteschists by parallel arrangement of phengite/kyanite. The trends of foliation and lineation are generally concordant with the elongation directions of enclosed eclogite masses. Kulet Kol eclogite consists of omphacite + garnet + rutile + quartz \pm hornblende \pm zoisite \pm phengite. Whiteschist is composed mainly of phengite, quartz, talc, kyanite, and garnet, with minor amounts of amphibole, chloritoid, apatite, zircon, rutile, and graphite. Garnet occurs as porphyroblasts ranging in diameter from a few millimeters to several centimeters and contains inclusion aggregates of rutile of various sizes and shapes (Fig. 1). In addition to rutile, inclusions of minerals in garnet porphyroblasts formed from prograde, peak, and retrograde stages occur in core, mantle, and rim domains (for details, see Parkinson et al., 2000); major micrometer-size mineral inclusions include quartz/coesite, ilmenite, kyanite, staurolite, chloritoid, talc, phengite,

TABLE 1. Representative Semi-quantitative Chemical Compositions of Submicrometer-Size Inclusions¹ in Garnet of Whiteschist, Kokchetav Massif, Kazakhstan

Mineral:	Hogbomite	Staurolite	Gahnite	Hercynite	Chlorite
SiO ₂	–	29.0	–	–	33.1
TiO ₂	8.6	1.1	–	–	–
Al ₂ O ₃	68.3	58.0	60.9	62.0	26.4
Cr ₂ O ₃	trace	trace	–	–	trace
Ga ₂ O ₃	1.0	trace	–	–	–
FeO	4.8	6.6	4.3	29.8	10.2
MgO	4.7	3.8	6.6	5.6	30.3
ZnO	12.6	1.5	28.2	2.6	–
	31(0)	48(0)	32(0)	32(0)	28(0)
Si	–	7.98	–	–	5.56
Ti	1.23	0.23	–	–	–
Al	15.42	18.81	16.18	16.15	5.23
Cr	trace	trace	–	–	trace
Ga	0.12	trace	–	–	–
Fe	0.76	1.52	0.81	5.51	1.43
Mg	1.35	1.56	2.22	1.84	7.59
Zn	1.78	0.31	4.69	0.42	–

¹Wt% on an anhydrous basis.

phlogopite, zircon, zoisite, graphite, apatite, chlorite, and margarite. Microdiamond inclusions are absent. Garnet is compositionally zoned. Parkinson (2000) suggested that the garnet core, high in grossular and spessartine, formed at $T = 380\text{--}580^\circ\text{C}$ at $P < 10$ kbar, and the garnet mantle, high in almandine and pyrope, at $T = 720\text{--}760^\circ\text{C}$ and $P = 34\text{--}36$ kbar. Detailed petrographic aspects of some Kulet Kol whiteschists can be found in Zhang et al. (1997) and Parkinson (2000).

In addition to akdalaite from northern Kazakhstan, two tiny rock chips with the dimensions of $\sim 1 \times 1 \times 0.3$ mm from the type specimen of akdalaite stored in the VIMS museum in Moscow were kindly provided by Drs. I. Pekov and Ye. P. Shpanov and were re-examined in the present study.

Thin foils for AEM were prepared from petrographic thin sections. Garnet grains with akdalaite inclusions were first clamped between two copper rings to ensure sample integrity, followed by argon-ion-beam milling (Gatan, PIS) to perforation (operating conditions: 4.0 kV, 9° incident angle). A carbon

coat was applied to the specimens after ion thinning. Microstructure, mineralogy, and compositions of minerals were obtained using a transmission electron microscope (JEOL JEM-3010) operated at 300 kV. The transmission electron microscope was equipped with an energy dispersive X-ray (EDX) spectrometer (Oxford EDS-6636) with an ultra-thin window and a Si(Li) detector, capable of detecting elements ranging from boron to uranium. Selective area electron diffraction (SAED) patterns were taken along various zone axes to determine the crystal system and d-spacings. The d-spacings measured from SAED patterns were used for least-squares refinement of the lattice parameters. The error of the d-spacing measurements on SAED patterns taken at a camera length of 120 cm was estimated to be ± 0.02 Å. Semi-quantitative chemical analysis was based on the Cliff-Lorimer thin-film approximation with experimental k-factors obtained from natural minerals for K, Al, Na, Ca, Mg, Fe, and Ti, and with factory preset k-factors (Link Virtual Standard Pack) for other elements (Lorretto, 1994).

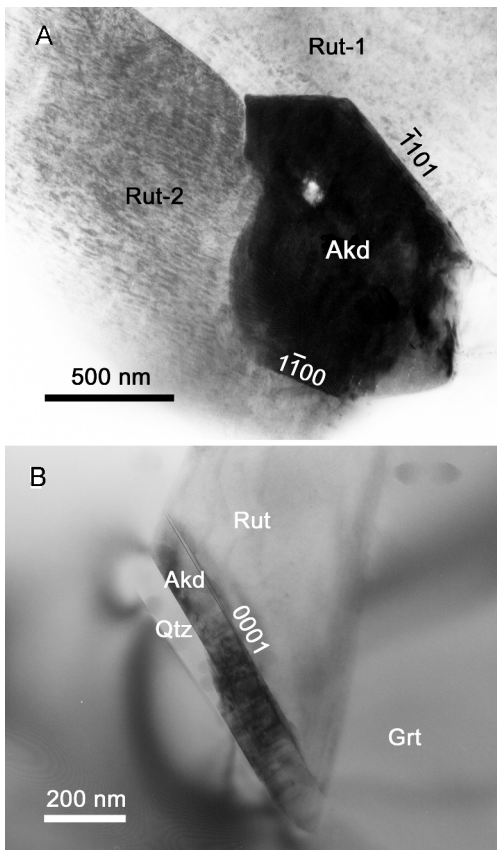


FIG. 2. TEM bright-field images showing akdalaite (Akd) crystal at the boundary of (A) rutile (Rut) crystals, and (B) rutile/garnet (Grt). The akdalaite crystal in (A) was in the exact zone axis $[11\bar{2}0]$.

Results

Akdalaite from the Kokchetav Massif, Kazakhstan

In the studied whiteschist sample KL-1, garnet displays compositional zonation, with decreasing spessartine/grossular and increasing pyrope components, from core ($\text{Alm}_{72}\text{Pyr}_{18}\text{Grs}_{3}\text{Sps}_{6}$) to rim ($\text{Alm}_{65}\text{Pyr}_{34}\text{Grs}_{<0.5}\text{Sps}_{<0.5}$). According to detailed AEM analyses, submicrometer-size akdalaite, as well as hohobomite ($(\text{Mg}_{1.4}\text{Fe}_{0.4}\text{Zn}_{1.8}\text{Al}_{1.4})\text{Al}_{14}(\text{Fe}_{0.4}\text{Ti}_{1.2}\text{Ga}_{0.1}\text{Cr}_{<0.1})\text{O}_{30}(\text{OH})_2$), Zn-bearing staurolite ($(\text{Mg}_{0.8}\text{Fe}_{0.8}\text{Zn}_{0.14})(\text{Al}_{9.4}\text{Ti}_{0.1}\text{Cr}_{<0.1}\text{Ga}_{<0.1})\text{Si}_4\text{O}_{22}(\text{O},\text{OH})_4$), gahnite ($(\text{Mg}_{0.3}\text{Fe}_{0.1}\text{Zn}_{0.6}\text{Ti}_{<0.1})\text{Al}_2\text{O}_4$), hercynite ($(\text{Mg}_{0.23}\text{Fe}_{0.69}\text{Zn}_{0.05})\text{Al}_2\text{O}_4$), Mg-chlorite ($(\text{Mg}_{7.6}\text{Fe}_{1.4}\text{Al}_{2.8}\text{Cr}_{<0.1})(\text{Si}_{5.6}\text{Al}_{2.4}\text{Ti}_{<0.1})\text{O}_{20}(\text{OH})_{16}$), kyanite, quartz, zircon and apatite, were identified as associated with micrometer-size rutile aggregates

TABLE 2. Average Chemical Compositions¹ of Four Analyses of Akdalaite from Kokchetav, Kazakhstan

	Weight (%)	Range (wt%)
SiO_2	0.6	0.1–1.6
TiO_2	4.2	2.2–5.1
Al_2O_3	91.0	90.3–92.2
Cr_2O_3	0.2	0.1–0.2
FeO	1.6	1.3–2.0
MgO	1.3	1.2–1.4
ZnO	0.3	0.2–0.4
Ga_2O_3	0.8	0.7–1.0
15(O)		
Si	0.05	
Ti	0.28	
Al	9.30	
Cr	0.01	
Fe	0.13	
Mg	0.18	
Zn	0.02	
Ga	0.05	

¹Normalized to an anhydrous basis.

(~0.7 wt% FeO, and traces of V_2O_5 and Cr_2O_3) in garnet (Table 1). Among all the studied submicrometer-size mineral inclusions, akdalaite was found in both core and rim of garnet. It occurs either at rutile/rutile or at rutile/garnet boundaries (Fig. 2). In general, akdalaite crystals are subhedral to euhedral, and are bounded by (0001), $\{1\bar{1}00\}$, $\{1\bar{1}01\}$ facets.

Chemical analyses were carried out by means of an EDX spectrometer. Despite the minute size, akdalaite was not compositionally uniform, containing various amounts of TiO_2 , FeO, MgO, SiO_2 , ZnO, Cr_2O_3 , and Ga_2O_3 as solid solution in different parts of the akdalaite crystal (Fig. 3). Although AEM-EDX could not determine the cation charge state, Fe in akdalaite most probably carries +2 charge, as required to compensate for the substitution of Ti^{+4} for Al^{+3} in the akdalaite lattice. The average of four analyses normalized to an anhydrous basis is shown in Table 2. The empirical formula, on an anhydrous basis, is $5(\text{Al}_{1.86}\text{Ti}_{0.06}\text{Fe}_{0.02}\text{Mg}_{0.03}\text{Ga}_{0.01}\text{Si}_{0.01}\text{Cr}_{<0.01}\text{Zn}_{<0.01}\text{O}_3)$. The simplified formula should be $5\text{Al}_2\text{O}_3$

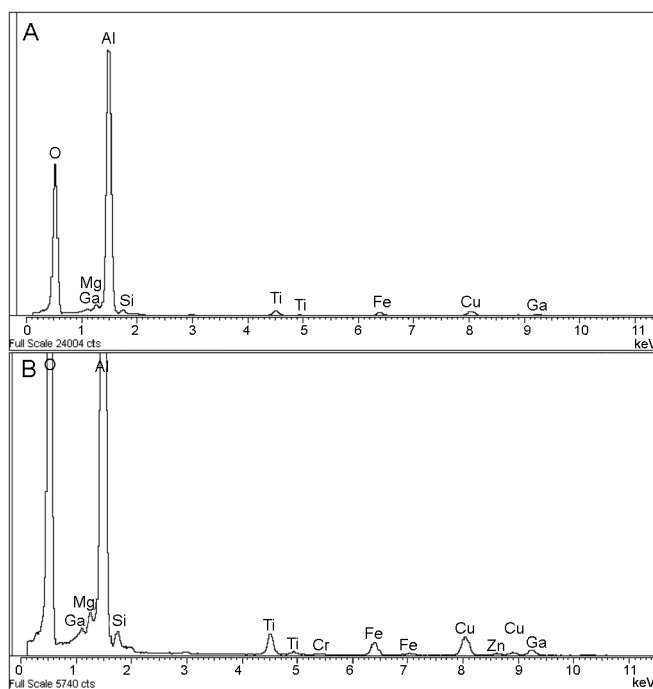


FIG. 3. AEM-EDX spectrum of akdalaite from Kazakhstan. A. Whole spectrum. B. Spectrum with a different intensity scale to better show the weak X-ray peaks. The Cu peak was from a copper grid.

(on an anhydrous basis). However, based on unit cell parameters and unit cell changes caused by dehydration during prolonged AEM observations, as addressed below, akdalaite is hydrous with the formula $5\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$, following the work of Yamaguchi et al. (1964) on synthetic tohdite.

All SAED patterns obtained from akdalaite crystals are distinct from the calculated patterns of all other natural alumina or alumina hydrate (Fig. 4). Unit-cell parameters were refined from measured d-spacings on electron-diffraction patterns (Table 3): $a = 5.58(1) \text{ \AA}$, $c = 8.86(2) \text{ \AA}$, $c/a = 1.588$, $V = 238.91 \text{ \AA}^3$ with $Z = 1$. Note that the crystallographic data of akdalaite in the present study are different from those reported for the type akdalaite: $a = 14.97 \text{ \AA}$, $c = 12.87 \text{ \AA}$, $c/a = 0.860$ (Shpanov et al., 1970), but are close to those of tohdite: $a = 5.575 \text{ \AA}$, $c = 8.761 \text{ \AA}$, $c/a = 1.571$ (Yamaguchi et al., 1964) (Table 4). The systematic absences of the reflections $hh(-2h)l$, $l = 2n+1$, as shown in $[10\bar{1}0]$ zone axis pattern in Figure 4, are the same as those observed in the X-ray reflections of tohdite, and are therefore consistent with the reported $P6_3mc$ space group of tohdite (Yamaguchi et al., 1964; Yamaguchi and Okumiyu, 1969).

Note that the hexagonal lattice parameters, as well as the c/a ratio of the akdalaite resemble those of tohdite, but are substantially different from those of dehydrated tohdite, i.e., κ' - Al_2O_3 (Table 4), indicating that the investigated akdalaite retained water in its structure, although it might have been partially dehydrated during the preparation of thin foil for AEM analyses. This conclusion can be further substantiated by the observation that after prolonged electron-beam (300 keV, ~2 hrs) exposure, the lattice parameters of akdalaite changed to: $a = 5.55 \text{ \AA}$, $c = 9.04 \text{ \AA}$, $c/a = 1.629$, which resemble those reported for tohdite dehydrated at 700–800°C: $a = 5.544 \text{ \AA}$, $c = 9.024 \text{ \AA}$, $c/a = 1.628$ (i.e., κ' - Al_2O_3) (Okumiyu et al., 1971; Okumiyu and Yamaguchi, 1971). Epitaxy between akdalaite and rutile was also noted: $(100)_{\text{Rut}} // (0001)_{\text{Akd}}$, $[010]_{\text{Rut}} // [\bar{1}100]_{\text{Akd}}$.

Re-examined akdalaite type specimen

Subhedral akdalaite crystals with the (0001) and $\{\bar{1}10\}$ facets are associated with fluorite and minor topaz in the Ar-ion-thinned edge of the type specimen (Fig. 5). EDX investigation revealed that akdalaite contains Mg, Si, Ca, Fe and Zn as impuri-

ties (Fig. 6). Minor amounts of σ - Al_2O_3 (synthetic, cubic, $a = 7.94 \text{ \AA}$) and margarite were identified at the fluorite/akdalaite interface of some akdalaite crystals by EDX and SAED (Fig. 7). The hexagonal lattice parameters ($a = 5.59(1) \text{ \AA}$, $c = 8.82(1) \text{ \AA}$, $c/a = 1.578$) (Table 5) derived from SAED patterns of the akdalaite type specimen are inconsistent with the unit cell originally reported by Shpanov et al. (1970) ($a = 14.97 \text{ \AA}$, $c = 12.87 \text{ \AA}$, $c/a = 0.860$), but are consistent with those of tohdite documented by Yamaguchi et al. (1964) and Kazakhstan akdalaite as reported above (Table 4). It is obvious that the reported crystallographic data of the akdalaite type specimen based on powder X-ray diffraction experiments (Shpanov et al., 1970) are incorrect. In their powdered sample, Shpanov et al. (1970) might have overlooked the presence of these trace phases, i.e., σ - Al_2O_3 and margarite. In fact, the additional reflections other than those of tohdite (akdalaite) in Shpanov et al. (1970) can be satisfactorily assigned to fluorite, σ - Al_2O_3 , or margarite as shown in Appendix 1. To account for the entire set of observed d-spacings, Shpanov et al. (1970) then derived an incorrect unit cell. As for the absence of $10\bar{1}0$ reflection with d-spacing of $\sim 4.84 \text{ \AA}$ in the X-ray data of Shpanov et al. (1970) obtained using a powder camera, it might be due to the very weak intensity of the $10\bar{1}0$ reflection (see the powder diffraction pattern in Yamaguchi et al. 1964) or for other unknown reasons.

The chemical composition of the akdalaite type specimen was not determined quantitatively in the present study. Presumably, the stoichiometry of akdalaite should be $5\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$, like that of tohdite, but not $4\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$, as reported by Shpanov et al. (1970), because the former was determined using the synthetic powders of high purity. The errors in the chemical compositions of the museum akdalaite from the USSR determined by Shpanov et al. (1970) would also be due to the presence of impurity phases.

Discussion

Origin of akdalaite in Kokchetav whiteschist, Kazakhstan

As mentioned above, akdalaite, hogbomite, kyanite, Zn-bearing staurolite, Mg-chlorite, gahnite, hercynite, quartz, apatite, and zircon are common submicrometer-size minerals associated with rutile aggregates as inclusions in garnet porphyroblasts of whiteschist from the Kulet Kol

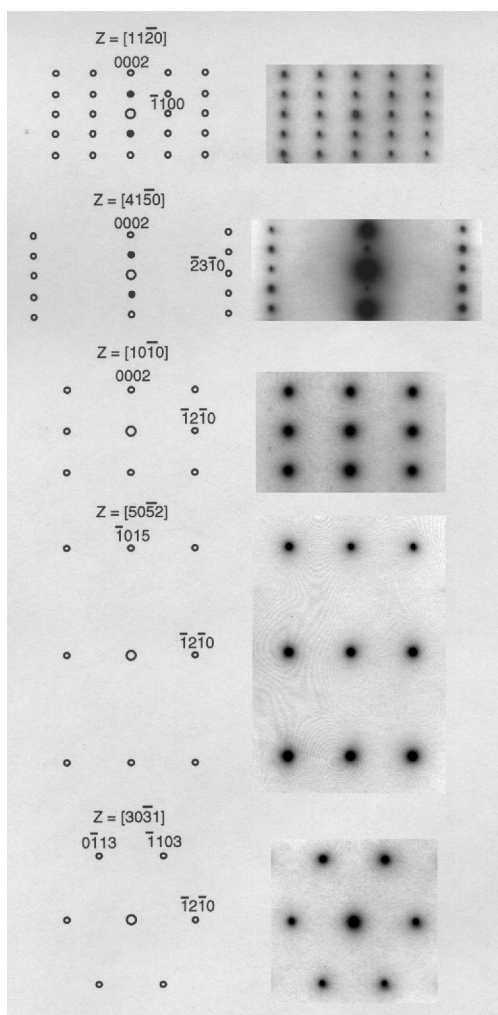


FIG. 4. SAED patterns taken by tilting the akdalaite crystal in Figure 2A from $[10\bar{1}0]$ zone axis around a -axis to zone axes $[50\bar{5}2]$ and $[30\bar{3}1]$, and around c -axis to zone axes $[41\bar{5}0]$ and $[11\bar{2}0]$. Solid circles in the schematic indexing represent double diffraction spots.

region of the Kokchetav Massif. Most of these minerals are not stable under the metamorphic peak P-T conditions of whiteschist, i.e., $T = 720\text{--}760^\circ\text{C}$ and $P = 34\text{--}36 \text{ kbar}$ (Parkinson, 2000). They were, therefore, either prograde minerals included during garnet growth, or were formed during retrograde metamorphism. It is noted that, in addition to akdalaite, submicrometer-size hogbomite, Zn-bearing staurolite, gahnite, and hercynite all contain substantial amounts of $\text{Zn} \pm \text{Ga}$, whereas

TABLE 3. Observed (obs), Refined (ref), and Calculated (cal) d-spacings (Å) of Akdalaite from Kokchetav, Kazakhstan

hkl	d(obs) (Å)	d(ref) (Å) ¹	d(cal) (Å) ²
100	4.84	4.83	4.828
002	4.42	4.43	4.381
101	4.23	4.24	4.229
110	2.78	2.79	2.788
103	2.53	2.52	2.499
112	2.36	2.36	2.352
105	1.67	1.66	1.647
205	1.44	1.43	1.418
106	1.42	1.41	1.398

¹ The refined hexagonal lattice parameters are: $a = 5.58(1)$ Å, $c = 8.86(2)$ Å, $c/a = 1.588$.

² Calculated based on tohdite: $a = 5.575$ Å, $c = 8.761$ Å, $c/a = 1.571$ (Yamaguchi et al., 1964).

TABLE 4. Lattice Parameter Comparison among Akdalaite¹

	akd	toh	deh-akd	deh-toh	akd-tyt
c (Å)	8.86	8.761	9.04	9.024	12.87
a (Å)	5.58	5.575	5.55	5.544	14.97
c/a	1.588	1.571	1.629	1.628	0.860
Space group	$P6_3mc$	$P6_3mc$	$P6_3mc$	$P6_3mc$	$P6_12$ or $P6_1$

¹ Abbreviations: akd = from Kokchetav in the present study; toh = tohdite; deh-akd = dehydrated akdalaite from Kokchetav; deh-toh = dehydrated tohdite; and akd-tyt = data of the akdalaite type specimen reported in Shpanov et al., 1970.

Sources: akd and deh-akd: this study; toh: Yamaguchi et al. (1964); deh-toh: Okumiya and Yamaguchi (1971); and akd-tyt: Shpanov et al. (1970).

these two elements were not detected in other micrometer-size inclusions, especially staurolite, in garnet core. The akdalaite-rutile inclusion pockets are also present in both garnet core and rim. Akdalaite, as well as other Zn \pm Ga-bearing submicrometer-size mineral inclusions, therefore, are most likely hydration products resulting from fluid infiltration during exhumation. The infiltrated fluid might have been rich in Zn and Ga, although its origin is not yet certain. P-T conditions of this fluid infiltration process cannot be determined based on the available information. However, hohobomite has been suggested as a high-

pressure retrograde phase ($T = 700\text{--}800^\circ\text{C}$, $P = 8\text{--}19$ kbar) in kyanite eclogites, central Rhodope, northern Greece (Liaty and Seidel, 1996). It has also been reported in some granulite- or amphibolite-facies rocks (Petersen et al., 1989). Akdalaite would be stable under even lower P-T conditions, but its presence, under the catalyzing effects of Ti, Ca, Mg, and Cd (a group IIB element like Zn), at $T > 460^\circ\text{C}$ and $P > 0.3$ kbar within the stability field of corundum has been demonstrated by Yamaguchi et al. (1966). More detailed studies on the stability field of akdalaite are obviously needed.

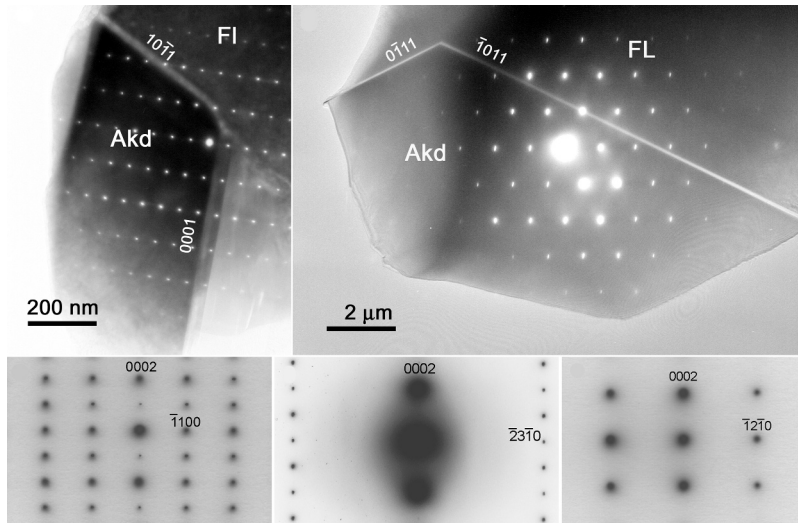


FIG. 5. TEM bright-field images with superimposed diffraction patterns of (A) $[1\bar{2}10]$ zone axis and (B) $[11\bar{2}3]$ zone axis showing akdalaite crystals (Akd) in fluorite (Fl) matrix from the type specimen. The akdalaite crystals were bounded by (0001) and $[1\bar{0}1]$ faces. The SAED patterns of (C) $[11\bar{2}0]$, (D) $[41\bar{5}0]$, and (E) $[10\bar{1}0]$ zone axes are identical to those shown in Figure 4.

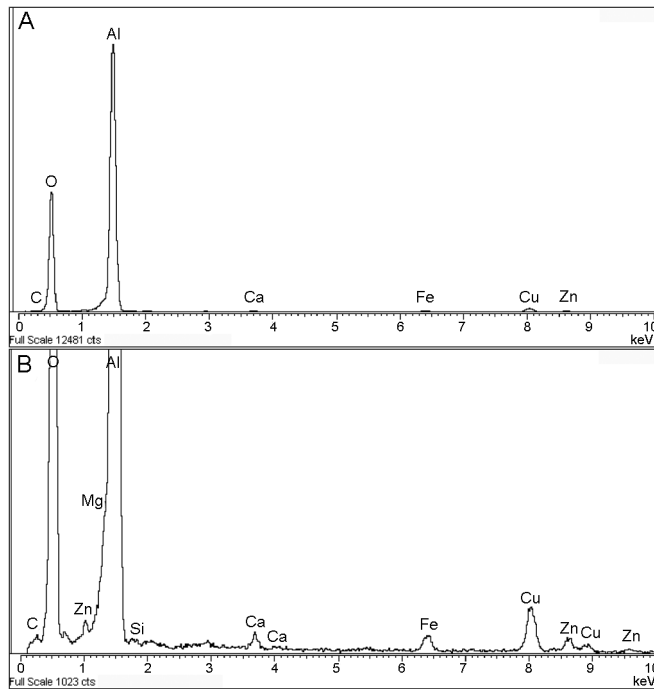


FIG. 6. AEM-EDX spectrum of akdalaite type specimen. A Whole spectrum. B. Spectrum with a different intensity scale to better show the weak X-ray peaks. The Cu peak was from the copper grid.

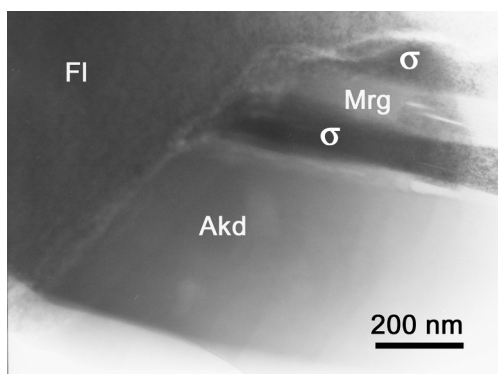


FIG. 7. Bright-field image showing fluorite (Fl), σ - Al_2O_3 (σ), and margarite (Mrg) associated with akdalaite (Akd).

Nomenclature of the $5\text{Al}_2\text{O}_3\cdot\text{H}_2\text{O}$ phase

Akdalaite was first named for an alumina hydrate phase, with a chemical composition $4\text{Al}_2\text{O}_3\cdot\text{H}_2\text{O}$, found in the Solnechnoye fluorite deposit of the USSR by Shpanov et al. (1970). The crystallographic parameters determined were: hexagonal system, space group $P6_32$ or $P6_3$, $a = 14.97 \text{ \AA}$, $c = 12.87 \text{ \AA}$. Despite the differences in reported chemical compositions and unit cell parameters (see Table 4), akdalaite was presumed to be the natural counterpart of tohdite by the CNMMN because of the similarities in optical and physical properties (Tilley and Eggleton, 1996).

In studying the Kulet whiteschist, we noticed an alumina hydrate phase as submicrometer-size inclusions in garnet with identical unit cell parameters as those of tohdite, but definitely different from those of akdalaite reported by Shpanov et al. (1970). A proposal was therefore submitted to CNMMN to name this natural phase tohdite, not only to honor the work of Yamaguchi et al. (1964) but also to forestall future confusion because the name “tohdite” has been used for the synthetic counterpart for decades in the scientific literature. The proposal was soon approved by CNMMN (IMA No. 2004-051), although it also raised the question as to whether tohdite and akdalaite are different minerals. Later, two small pieces of the akdalaite type specimen were kindly provided by Drs. I. Pekov and Ye. P. Shpanov. The AEM data clearly showed that the previously determined crystallographic data by Shpanov et al. (1970) had been in error. The correct crystallographic parameters are the same as those of tohdite. We informed CNMMN about these results in

TABLE 5. Observed (obs) and Refined (ref) d-spacings (\AA) of Akdalaite Type Specimen

hkl	d(obs) (\AA)	d(ref) (\AA) ¹
100	4.84	4.84
002	4.42	4.41
101	4.24	4.24
102	3.25	3.26
110	2.80	2.79
103	2.50	2.51
112	2.37	2.36
201	2.33	2.33
104	2.01	2.01

¹The refined hexagonal lattice parameters are: $a = 5.59(1) \text{ \AA}$; $c = 8.82(1) \text{ \AA}$; $c/a = 1.578$.

May 2005, inquiring whether the name “akdalaite” should be discredited when the results of tohdite are published. However, following the guidelines for new minerals, CNMMN decided to retain the name of akdalaite for the phase $5\text{Al}_2\text{O}_3\cdot\text{H}_2\text{O}$ and suggested that we publish the data as such. With the above background information, we hope scientists from different disciplines would notice that, based on the AEM data, it is now concluded that akdalaite is the natural counterpart of synthetic tohdite.

Conclusions

New crystallographic and compositional data for akdalaite, an alumina hydrate mineral from a new occurrence, are reported in this study. Akdalaite occurs as a submicrometer-size inclusion associated with rutile aggregates in garnet porphyroblasts of UHP whiteschists from the Kulet Kol region of the Kokchetav Massif, northern Kazakhstan. Submicrometer-size hohobomite, kyanite, Zn-bearing staurolite, Mg-chlorite, gahnite, hercynite, quartz, apatite, and zircon were also identified as submicrometer-size minerals in garnet. These inclusion phases were suggested to have formed through Ga/Zn-rich fluid infiltration during exhumation of the UHP terrane.

The akdalaite crystals, ~ 0.5 to $1 \mu\text{m}$ in size, are subhedral to euhedral, and are bounded by (0001), $\{1\bar{1}00\}$, $\{1\bar{1}01\}$ facets. EDX analyses show minor

amounts of Si, Ti, Cr, Fe, Mg, Zn, and Ga, in addition to the major component Al. Electron diffraction data yield the following crystal structural information: hexagonal system, space group $P6_3mc$, and $a = 5.58(1) \text{ \AA}$, $c = 8.86(2) \text{ \AA}$, $V = 238.91 \text{ \AA}^3$ with $Z = 1$, which are similar to those of synthetic tohdite.

The akdalaite type specimen from the VIMS museum in Moscow was also re-examined. The specimen consists of minor amounts of fluorite, topaz, $\sigma\text{-Al}_2\text{O}_3$, and margarite in addition to akdalaite. Akdalaite also contains chemical impurities such as Mg, Si, Ca, Fe, and Zn. The hexagonal unit-cell parameters of this akdalaite type specimen are $a = 5.59(1) \text{ \AA}$, $c = 8.82(1) \text{ \AA}$; these data are different from those reported by Shpanov et al. (1970) but are comparable to the akdalaite from Kazakhstan and to tohdite (Yamaguchi et al., 1964). It is therefore concluded that akdalaite is the natural counterpart of the synthetic tohdite reported in 1964.

Acknowledgments

We dedicate this paper to Prof. J. G. Liou, on this special occasion, in honor of his retirement. Prof. Liou initiated a U.S.-Taiwan cooperation project studying the Taiwan Mountain Belt during the late 1970s to early 1980s, stimulating local metamorphic petrological studies. From 1990 to the present, he has been coordinating international teams studying the HP/UHP terranes in China, Kazakhstan, as well as in other subduction/collision zones. He has been generous and kind in helping people to solve problems and many young scientists have benefited through working with him. His review comments/suggestions for this paper are greatly appreciated. We would also like to thank him, N. V. Sobolev, V. S. Shatsky, and A. A. Zayachkovsky for their help in field work in Kazakhstan in 2002; I. Pekov and Ye. P. Shpanov for providing the akdalaite type specimen from the museum in the All-Russian Institute of Mineral Resources in Moscow; and Jacob Chu for polishing the English of the manuscript. This study was supported by NSC grant (NSC 93-2116-M-259-001), Taiwan, ROC.

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APPENDIX I. X-Ray Powder Diffraction Data of Akdalaite¹ and their Correct Indexing

d (Å)	Fluorite ²	$\sigma\text{-Al}_2\text{O}_3$ ²	Margarite ²	Tohdite (akdalaite)	In-correct indexing ³
4.61		111			103
4.38				002	202
4.23				101	120
3.24				102	123, 114, 220
3.17	111				
2.781				110	400
2.530			200, 20 $\bar{2}$, 131		231
2.494				103	006
2.406				200	232
2.35				112	305
2.32				201	116
2.19				004	413
2.16			$\bar{1}35$, 221, 204, 042		135
2.11				202	234, 331, 240
2.07		400	135, $\bar{2}06$		332, 306
1.925	220				
1.905			206, 00 10, $\bar{1}37$		127
1.859				203	600
1.684				122	253
1.667		422	$\bar{1}39$, 240, $\bar{3}12$, 151		604
1.647				105	344
1.622				204	228
1.547				123	129, 260
1.511				302	238

¹Given by Shpanov et al., 1970.

²Fluorite (JCPDS #35-0816); $\sigma\text{-Al}_2\text{O}_3$ (JCPDS #47-1292); margarite (JCPDS #74-1190).

³Determined by Shpanov et al., 1970.