ADULARIA FROM HYDROTHERMAL VEIN DEPOSITS: EXTREMES IN STRUCTURAL STATE

PETR ČERNÝ AND RONALD CHAPMAN

Department of Geological Sciences, University of Manitoba, Winnipeg, Manitoba R3T 2N2

ABSTRACT

Specimens of adularia randomly selected from a variety of hydrothermal non-alpine veins indicate extensive variability in structural state. It ranges from close to maximum microcline in adularia from the Xihuashan wolframite deposit to extreme high sanidine in samples from the Michigan copper district. This range exceeds the diversity found in alpine adularia (low sanidine to orthoclase to intermediate microcline), but it matches the structural variability of adularia from granitic pegmatites. Highly ordered adularia from pegmatites and non-alpine veins is typically coarse grained, with predominant Fibbia–Zillertal morphology, conspicuously altered and overgrown by younger minerals. Crystallization at relatively high temperatures and extensive interaction with late fluids are responsible for this advanced ordering. In contrast, the end-member disorder is characteristic of fine–grained unaltered adularia, exclusively of the Felsöbanya–Maderaner habit and generally lacking overgrowths of late minerals. High nucleation and crystallization rates at low temperatures favor the metastable precipitation of totally disordered adularia, which must be subsequently shielded against order-promoting agents to preserve the original structural state.

Keywords: adularia, high sanidine, maximum microcline, chemical composition, unit-cell dimensions, infrared absorption spectroscopy.

SOMMAIRE

Des échantillons d'adulaire choisis au hasard d'une variété de veines hydrothermales d'affiliation autre qu'alpine définissent une grande variabilité en degré d'ordre. L'adulaire est proche du microcline ordonné dans le gîte de wolframite de Xihuashan, et du pôle de la sanidine désordonnée dans les échantillons des gisements de cuivre du Michigan. Cette diversité dépasse ce que l'on trouve dans l'adulaire des fentes alpines (sanidine ordonnée à orthoclase à microcline intermédiaire), mais elle ressemble à celle de l'adulaire des pegmatites granitiques. L'adulaire très bien ordonnée de pegmatites et de veines autres que les fentes alpines est typiquement à granulométrie grossière, à morphologie Fibbia–Zillertal dominante, relativement altérée et montrant des minéraux tardifs en surcroissance. Une cristallisation à température relativement élevée et une interaction poussée avec des fluides tardifs seraient à l'origine du degré d'ordre avancé. Par contre, un désordre complet caractérise l'adulaire fraîche à grains fins et à morphologie Felsöbanya–Maderaner, qui ne montre aucune surcroissance. Des taux élevés de nucléation et de croissance à basse température favoriseraient la formation métastable d'adulaire complètement désordonnée, qui aurait échapé par la suite aux effets des agents-promoteurs de la mise en ordre, pour préserver le degré d'ordre Al–Si original.

(Traduit par la Rédaction)

Mots-clés: adulaire, sanidine désordonnée, microcline ordonné, composition chimique, dimensions de la maille, spectroscopie par absorption dans l'infrarouge.

INTRODUCTION

The adularia variety of potassium feldspar is well known for the high variability and broad range of its structural state. However, most samples of adularia exhibit intermediate degrees of order, and structural states closely approaching maximum microcline or high sanidine have been considered very rare (Gubser & Laves 1967). Adularia-type representatives of the structural end-members have been documented only recently.

In the nineteen seventies, Černý (1972) and Lenton (1979) examined adularia from the Tanco and Buck Claim pegmatites in southeastern Manitoba. These samples were found to be monoclinic sanidine-type phases with unusual cell-dimensions that plot significantly beyond the high-sanidine corner of the $b-c$ quadrilateral of Stewart & Wright (1974). Additional occurrences of this type of feldspar were found during a systematic study of adularia from granitic pegmatites (Černý & Chapman 1983, 1984).

During the same period, Ferguson (1980, 1982) and Kroll & Ribbe (1983) were led by bonding considerations and other factors to the conclusion that the high-sanidine end-members of Stewart & Wright (1974), Smith (1974a) and Kroll *et al.* (unpublished; *cf.* Kroll & Ribbe 1983, p. 70-74) are not fully disordered. The "anomalous" cell-dimensions of adularia from three pegmatite localities examined by Černý, Lenton and Chapman turned out to be close to the new co-ordinates for the high sanidine end-member defined by the above authors. So far, these three localities of adularia have represented the only natural occurrences of K-feldspar closely corresponding to the extrapolated fully disordered sanidine. Some of these samples are currently under investigation (structure refinement by R.B. Ferguson, optical study by S.C. Su).

A homogeneous structural state closely approaching that of maximum microcline was also discovered during our study of adularia from granitic pegmatites. Three localities yielded samples with nearly total Al–Si order (Černý & Chapman 1984).

In the course of our work on the pegmatites, we have also examined several specimens of adularia from hydrothermal vein-type deposits and searched the literature for indications of further possible oc-

currences of extreme structural states in adularia. The results of this study are reported here.

EXPERIMENTAL METHODS

Electron-microprobe analyses were performed on a MAC–5 instrument, on polished sections of grains randomly selected from material separated for X-ray diffraction and infrared absorption. Energy-dispersion analysis for Si, Al, Na (albite standard) and K (orthoclase) was done at the accelerating voltage of 15 kV and specimen current of 0.005 mA. The wavelength-dispersion mode was used for Rb (K-feldspar), Cs (pollucite), Ca (titanite), Sr (SrTiO₃), Ba (benitoite) and Fe (pyrope). Accelerating voltage was 20 kV and specimen current 0.04 mA for all these elements except Rb and Sr, for which 25 kV was used. The data were reduced using a modified version of the EMPADR VII program of Rucklidge & Gasparrini (1969).

Optical properties were examined in oil-immersion mounts of crushed feldspar grains, and in thin sections on a universal stage. Infrared-absorption spectra were collected between 14.9 and 19.3 μm on pellets prepared from a mixture of 0.22 g KBr and 0.0006 g feldspar. The spectra were recorded on a Nicolet MX–1 Fourier transform IR spectrometer calibrated by laser interferometry and checked against an international polystyrene standard.

Unit-cell dimensions were determined by the least-square refinement (modified Appleman & Evans 1973) of powder data obtained on a Philips auto-mated X-ray powder diffractometer, system PW 1710. CaF₂ (a = 5.4636 ± 0.0002 Å) was added as an internal standard. For some specimens, unit-cell dimensions were also provided by Dr. H. Kroll, Westfälische Wilhelms-Universität, Münster, refined by the JAGO–KOR program from Au-calibrated powder data obtained in an AEG Guinier-Jagodzinski camera. The precision of these cell data is superior to that of the values derived from the Philips diffractograms, the standard errors being lower by 26 to 73%. However, the Guinier-Jagodzinski data are within <1.5σ of the Philips-derived cell-dimensions, indicating satisfactory accuracy of the latter.

Triclinicity (Δ) is used here as defined by Goldsmith & Laves (1954), equal to $12.5(d_{131} - d_{1\bar{3}1})$, with values ranging from 0 for monoclinic feldspar to 1 for maximum microcline.

Morphology of adularia is referred to using combined terminologies of Kalb (1924) and Nissen (1967). The Felsöbanya–Maderaner habit is dominated by {110} and {$\bar{1}$01}, whereas the Zillertal-Fibbia crystals also exhibit significant {010} and {001}, and elongation parallel to c and a, respectively (Fig. 1; cf. Smith 1974b, p. 255-258).

Further details on the experimental techniques are available in Černý & Chapman (1984).

THE XIHUASHAN TUNGSTEN DEPOSIT, PEOPLE'S REPUBLIC OF CHINA

Subvertical quartz veins in the gigantic tungsten deposit of Xihuashan, Jianxi Province, carry abundant wolframite, with lesser quantities of scheelite, sulfides of Mo, Bi, Cu, Fe, Pb and Zn, cassiterite and sparse beryl, helvite and monazite. Central parts of the quartz veins locally contain vugs lined with quartz crystals; these are occasionally covered with adularia, which is commonly slightly altered and overgrown by rare fluorite. The Felsöbanya-Maderaner crystal habit (Fig. 1) is well developed, and the crystals vary from 2 to 6 mm in size.

Two specimens of adularia from Xihuashan were examined, one white with faint yellowish pink tint (#51; Mineralogical Museum, Univ. Manitoba, M5946) and the other rusty brownish red (#52; M5945). Except for this difference in color and a slightly higher degree of clayey alteration in sample 52, the two specimens exhibit very similar properties.

Chemical analyses gave compositions close to pure KAlSi₃O₈ (Table 1). Optical properties are difficult to observe because of sericitization and turbidity, caused by pervasive clayey and hematitic alteration. Nevertheless, an irregular pattern of twinning can be distinguished on the (001) cleavage fragments, somewhat similar to that displayed by the Rubellite Dike adularia (Fig. 1c,d in Černý & Chapman 1984).
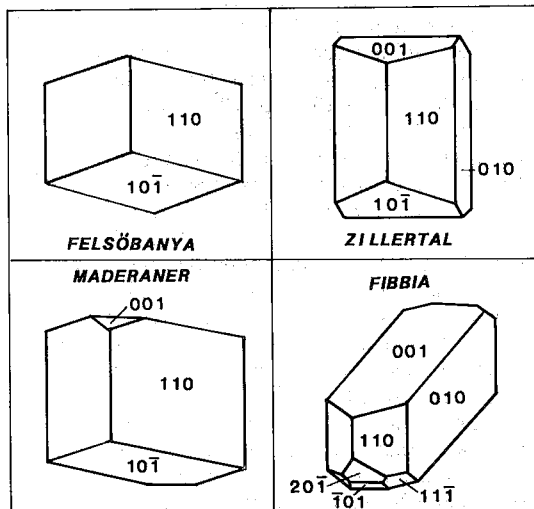

FIG. 1. The characteristic crystal habits and combinations of forms of the Felsöbanya and Zillertal types of adularia (Kalb 1924), and of the Maderaner and Fibbia types (Nissen 1967).

TABLE 1. CHEMICAL COMPOSITION

	Xihuashan pink	Xihuashan rusty	Mirošov	Hot Springs	Guanajuato	Alexander	Bodie*	St. Andreasberg	Phoenix Mine
SiO_2	65.3	65.2	64.2	64.2	64.9	65.3	65.82	64.9	65.1
Al_2O_3	18.4	18.3	18.1	18.4	18.2	18.2	17.65	18.6	18.5
Fe_2O_3	<0.1	<0.1	<0.1	<0.1	<0.1	0.5	n.d.	<0.1	<0.1
CaO	<0.1	<0.1	<0.1	<0.1	<0.1	0.4	0.03	0.3	<0.1
SrO	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.01	0.2	<0.1
BaO	<0.1	<0.1	0.4	<0.1	<0.1	<0.1	n.d.	0.6	<0.1
Na_2O	<0.1	<0.1	0.15	<0.1	<0.1	5.3	0.56	1.4	<0.1
K_2O	17.3	17.4	16.2	16.3	16.5	9.2	15.54	14.0	17.0
Rb_2O	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	0.09	<0.1	<0.1
Total	101.0	100.9	99.05	98.9	99.6	99.0	99.78**	100.0	100.6
Si	3.001	3.001	3.003	2.998	3.010	2.975	2.998	2.990	2.998
Al	0.995	0.991	0.997	1.012	0.996	0.994	0.999	1.010	1.003
Fe^{3+}	–	–	–	–	–	0.017	–	–	–
Ca	–	–	–	–	–	0.019	0.001	0.015	–
Sr	–	–	–	–	–	–	–	0.005	–
Ba	–	–	0.006	–	–	–	–	0.011	–
Na	–	–	0.013	–	–	0.480	0.052	0.125	–
K	1.012	1.025	0.967	0.973	0.973	0.540	0.952	0.823	0.998
Rb	–	–	–	–	–	0.003	0.003	–	–
$\Sigma(R^{1+}+R^{2+})$	1.012	1.025	0.986	0.973	0.973	1.042	1.008	0.979	0.998

n.d. – not determined; *XRF analysis from Chesterman et al. (1974a), adjusted for 3.4 wt.% quartz; **the total includes TiO_2 0.01, P_2O_5 0.006, and H_2O 0.06 wt.%.

The X-ray powder-diffraction pattern corresponds to a triclinic feldspar; the 131 and 1$\overline{3}$1 diffraction peaks are well defined and sharp but have distinctly broadened low-intensity shoulders (Fig. 2). Unit-cell dimensions indicate a near-maximum microcline (Table 2, Fig. 3), in accord with the characteristic infrared-absorption maxima (Table 3, Fig. 4).

ALPINE VEINS AT MIROŠOV, CZECHOSLOVAKIA

The alpine veins hosted by high-grade amphibolites at Mirošov, western Moravia in Czechoslovakia, are notorious for their diversity of mineral species and assemblages (Černý 1955). Adularia occurs sparsely in association with either quartz, albite, titanite and tourmaline, or with quartz, axinite, epidote and chlorite. A specimen of the latter assemblage from the first author's research collection was used in the present study. Flesh-colored translucent to opaque crystals of adularia, displaying the typical Felsöbanya–Maderaner habit, range from 1 to 3 mm in size on this sample.

Chemical analyses reveal slightly elevated contents of Na and Ba (Table 1). The optical structure is extremely complex, consisting of interior lamellae parallel to {100} and an outer envelope of four segments underlying the faces of {110}. The overall pattern closely resembles the optical behavior of adularia from Val Casatscha, Switzerland (Bambauer & Laves 1960) and Ouranoupolis, Greece (Dimitriadis & Soldatos 1978).

X-ray powder diffractograms show a predominant monoclinic phase but its sharp 131 reflection is flanked by low-intensity shoulders indicative of subordinate triclinic material with variable Δ (Fig. 2). Refinement of the monoclinic pattern led to anomalous unit-cell dimensions with a large standard deviation on b, plotting outside the Stewart & Wright (1974) b – c quadrilateral (as well as any successors to this diagram; Table 2, Fig. 3). The infrared-absorption spectrum shows the characteristic maxima at intermediate values (Table 3, Fig. 4).

THE HOT SPRINGS DEPOSITS OF ROCK CRYSTAL, ARKANSAS

Occurrences of adularia at Hot Springs, Garland County, Arkansas, have been known in the literature since the eighteen nineties. However, to the best of our knowledge, no modern crystallochemical data
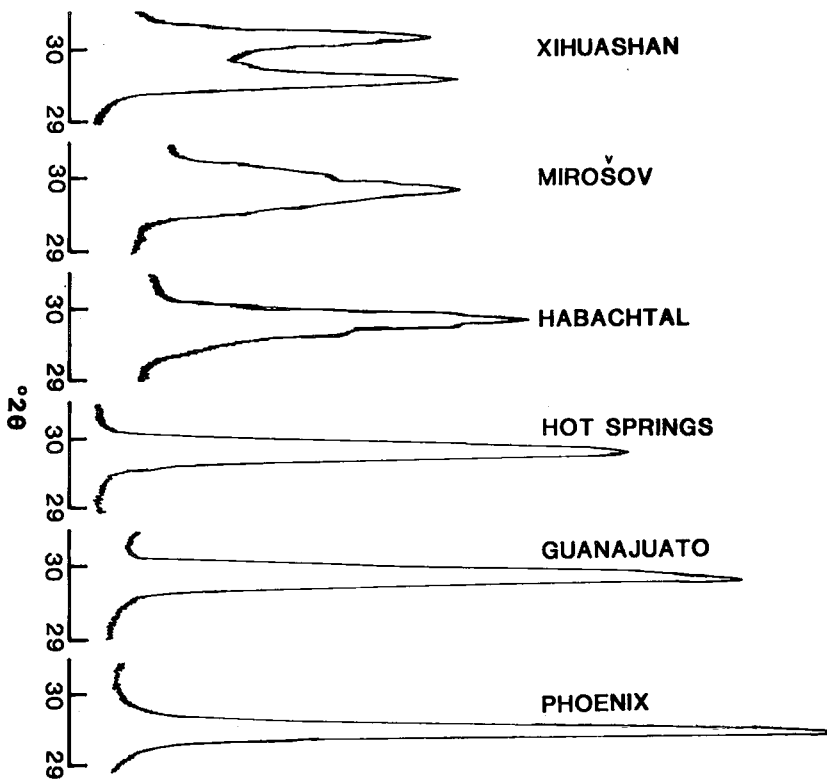
FIG. 2. The 131 and 131 + 1$\bar{3}$1 diffraction maxima of some of the adularia samples examined. The profile of the Habachtal specimen was provided by G. Grundmann (pers. comm. 1985).

are available for adularia from this region. In specimens used for K–Ar and Rb–Sr dating, Bass & Ferrara (1969) found the symmetry variable from monoclinic to triclinic. Engel (1951) provided a detailed insight into the host environment. Adularia occurs in quartz veins filling fissures in low-grade metasediments; it is located along the vein margins or with quartz crystals in open vugs. Associated minerals closely reflect the composition of the host rocks. On sample #122797 (Harvard Mineralogical Museum) examined in this study, milky white adularia forms sheafs of subparallel crystals of the Felsöbanya–Maderaner type, reaching 10 mm in length.

The chemically analyzed crystals proved to be very poor in elements other than K, Al and Si (Table 1); the slight deficiency in K may be due to a leaching effect suggested by the milky turbidity. Optical properties suggest a homogeneous monoclinic orientation throughout the crystals, except for sections parallel to {001} that display a fine lamellar texture parallel to {110} and rarely {010} [similar to the Xanthi adularia of Dimitriadis & Soldatos (1978)]. However, differences in extinction and birefringence among the lamellae are negligible.

X-ray powder diffractograms show a well-defined but distinctly broadened 131 peak, indicative of a substantial presence of material with very low triclinicity in addition to the truly monoclinic phase (Fig. 2). In this respect, the specimen is close to the most "cleanly" monoclinic adularia examined by Bass & Ferrara (1969). Unit-cell dimensions refined for monoclinic symmetry fall close to the values of ideal orthoclase of Ribbe (1983; Table 2, Fig. 3). The characteristic infrared-absorption peaks also plot in the orthoclase region (Table 3, Fig. 4).

THE GUANAJUATO EPITHERMAL DEPOSITS, MEXICO

The epithermal deposits at Guanajuato in Mexico carry mainly base-metal sulfides, and antimonides, tellurides and sulfides of Ag. Quartz and carbonates compose most of the gangue, with lesser amounts of adularia; fluorite, barite, milarite and zeolites are subordinate to rare. The adularia examined in the present study comes from a U.S. National Museum specimen of milarite (#120408). It forms subparallel aggregates of translucent to opaque and milky crystals, rarely grading into transparent domains at crystal terminations. The adularia
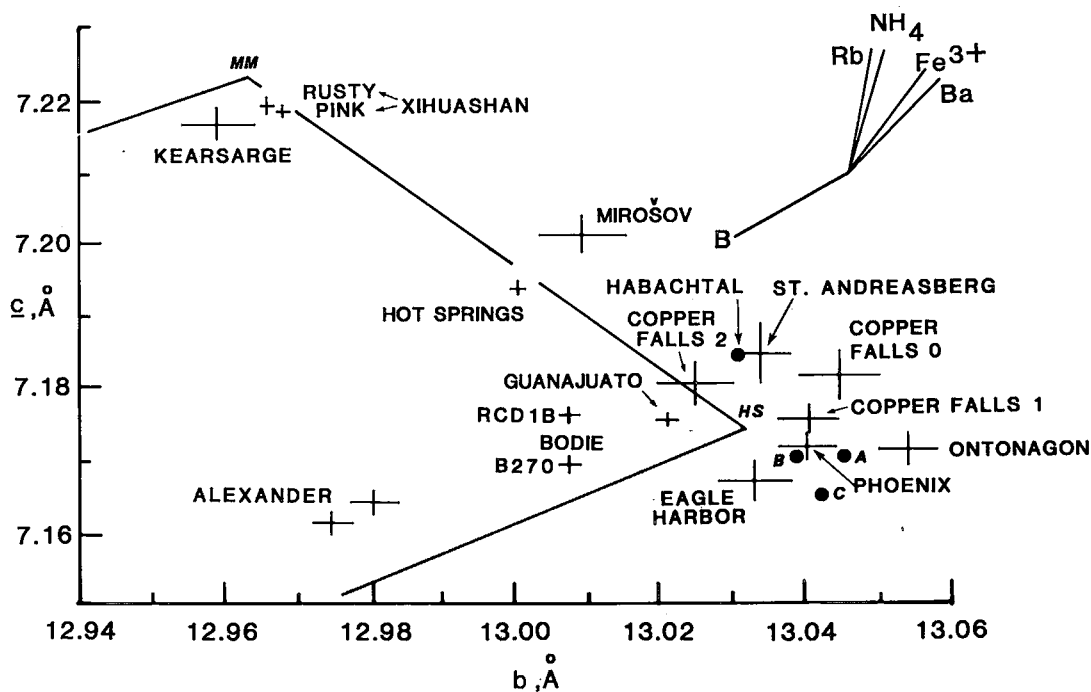
FIG. 3. The b and c cell dimensions of the adularia samples examined, in relation to the maximum microcline (MM) and high sanidine (HS) data preferred by Stewart & Wright (1974). The Habachtal specimen after G. Grundmann (pers. comm. 1985), the Kearsarge and Eagle Harbor data from Stewart & Wright (1974). Solid dots refer to the improved end-member data for high sanidine: A R.B. Ferguson (pers. comm. 1985), B Kroll & Ribbe (1983), C Kroll & Ribbe (pers. comm. 1983). Vectors indicate shifts in $b - c$ induced by substitution for K^+ or Al^{3+} in high sanidine.

is associated with quartz and milarite, and locally overgrown by calcite. Crystal terminations are rarely developed to a degree permitting identification of crystal faces; however, in most of these cases the Felsöbanya–Maderaner habit can be recognized.

The composition of this adularia is again very simple, marked by low contents of all nonessential elements (Table 1). Optical properties of the material used for X-ray powder diffraction in our laboratory are consistent with monoclinic symmetry [very small (–) 2V and the optic axial plane parallel to (010)]. Thin subsurface zones of the crystals show complex lamellar structure typical of adularia of intermediate and heterogeneous structural states (Bambauer & Laves 1960, Černý & Chapman 1984). However, this material is volumetrically insignificant.

An X-ray powder diffractogram recorded in our X-ray laboratory revealed the presence of a single monoclinic phase with a narrow 131 peak of high intensity (Fig. 2). Unit-cell refinement based on this diffractogram yielded data typical of high sanidine (Table 2, Fig. 3). However, a separate batch of adularia studied by Dr. H. Kroll gave a Guinier photograph with many reflections doubled, indicating the presence of two monoclinic phases.

The infrared-absorption maxima listed in Table 3 and plotted on Figure 4 also suggest a structural state different from that of high sanidine. The material used for the IR study could be similar to that examined by Dr. Kroll, the characteristic absorptions possibly representing an average of high sanidine and orthoclase-like components. Subsequent checks of optical properties in those parts of the hand specimen from which Dr. Kroll's material was separated revealed a complex lamellar and moiré texture suggestive of twinning or structural heterogeneity.

THE ALEXANDER TIN DEPOSIT, NEW MEXICO

Adularia occurs locally in the Black Range tin district, in the eastern part of the Datil–Mogollon volcanic field, Catron and Sierra Counties in southwestern New Mexico (Maxwell et al. in prep.). Oligocene rhyolite and associated pyroclastic rocks host cavity linings, veinlets and disseminated aggregates of cassiterite (predominantly wood tin) and hematite, commonly associated with a variety of silica polymorphs, silicate minerals and other oxide phases. Fluorite, durangite, jarosite and unidentified fluoroarsenates also are characteristic.
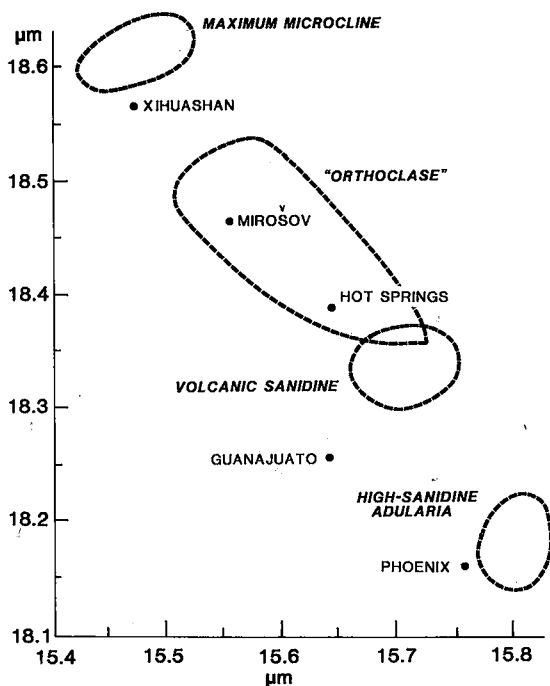
FIG. 4. The characteristic IR absorption maxima of the adularia samples examined. Fields populated by different types of K-feldspar compiled from Hafner & Laves (1957), Lehtinen (1974), Akizuki & Sunagawa (1978), Černý & Chapman (1984) and Černý (unpubl. data).

The examined specimen of adularia (provided by Dr. E.E. Foord, U.S. Geological Survey, Denver) comes from the Alexander deposit, hosted by a carapace breccia. Adularia is associated here with quartz, albite and hematite; it occurs apart from the mineralized veins that carry mainly crystalline Fe,Sb-rich cassiterite, hematite, cristobalite and REE-rich smectite (Maxwell et al. in prep.). Transparent to milky crystals of adularia locally reach 5 mm in size, and they display a transition from the Felsöbanya–Maderaner habit to the Zillertal–Fibbia morphology (Fig. 1). A faint bluish, moonstone-like schiller effect can be observed on some crystals.

Chemical analyses show a surprizingly high Na content, corresponding to about 45 mol.% Ab (Table 1). Nevertheless, the adularia is homogeneous at the scale of optical microscope and electron microprobe, with optical properties uniform throughout the crystals. Monoclinic optical orientation, moderate (-) 2V and optical plane normal to (010) are in evidence.

X-ray powder-diffraction patterns reveal the presence of subordinate albite. In view of the homogeneous optical behavior but an occasional moonstone schiller, this albite phase must belong to a cryptoperthitic exsolution of some of the substantial (and decidedly metastable) Ab content. Most of

the diffraction maxima of the K-phase are sharp and narrow (including the $\overline{2}01$ and 131 peaks), and the unit-cell data show moderate standard deviations (Table 2, Fig. 3). Nevertheless, the cell dimensions should be treated with caution, as they cannot be representative of the bulk composition shown by the electron-microprobe analysis, and the structure of the K-phase must be strained. It is noteworthy in this respect that the b-c plot suggests ~70 mol.% Ab_{ss} (according to Fig. 4a in Kroll & Ribbe 1983), whereas the bulk chemical composition shows only about 45%. A highly anomalous value of a is evidently indicated.

THE BODIE AU, AG DISTRICT, CALIFORNIA

Adularia is widespread in the Pliocene Au-, Ag-bearing veins and in their altered dacitic wallrocks in the Bodie mining district, Mono County, California (O'Neil et al. 1973, Chesterman et al. 1974a,b). Milky white, opaque to translucent crystals of adularia reach 5 mm in size in the fracture linings, and exhibit the Felsöbanya–Maderaner habit. They are locally associated with quartz and calcite.

Two specimens of adularia from the Bodie district were examined by Chesterman et al. (1974a,b): a coarse-grained adularia #B–270 from a vein at Bodie Bluff, and a fine-grained adularia #RC–D1B from vein material near Silver Hill. X-ray-fluorescence analysis of sample B–270 gave a Na-poor composition, which is in good agreement with the temperature of crystallization derived from isotopic and fluid-inclusion data (215–245°C; Chesterman et al. 1974a,b).

The Bodie adularia is optically homogeneous, with (-)2V averaging 64°, and the optic axial plane normal to (010). Both samples examined give a sanidine-type X-ray powder-diffraction pattern, and the unit-cell dimensions correspond to a highly disordered structural state (Table 2, Fig. 3). However, the unit-cell dimensions also suggest a higher proportion of the Ab component (~30 mol.%, from Fig. 4a in Kroll & Ribbe 1983) than that shown by chemical analysis (4.7 mol.%; Table 1). An anomalous a dimension is indicated, as in the case of the adularia from Alexander.

THE ST. ANDREASBERG MESOTHERMAL DEPOSITS, FEDERAL REPUBLIC OF GERMANY

Adularia was reported from this classic Ag-bearing district in the Harz Mountains by Schnorrer-Köhler (1983) as milky, occasionally pinkish crystals with the Felsöbanya–Maderaner habit, up to 5 mm in size. They are associated with water-clear tabular apophyllite and rarely chalcopyrite; all three minerals are deposited on calcite.

The chemical composition of the adularia crystals,

TABLE 2. UNIT CELL DIMENSIONS

	a(Å) a*(Å⁻¹)	b(Å) b*(Å⁻¹)	c(Å) c*(Å⁻¹)	α(Å) α*(°)	β(°) β*(°)	γ(°) γ*(°)	V(Å³)
Xihuashan, pink*	8.589(1) 0.12960(1)	12.968(1) 0.07716(1)	7.218(1) 0.15411(1)	90.541(6) 90.383(7)	115.979(6) 64.023(6)	87.977(7) 91.986(7)	722.3(2)
Xihuashan, rusty*	8.593(1) 0.12952(1)	12.966(1) 0.07717(1)	7.219(1) 0.15409(2)	90.478(12) 90.399(13)	115.972(8) 64.029(8)	88.090(11) 91.891(11)	722.7(3)
Mirosov	8.590(7) 0.12954(11)	13.010(6) 0.07686(4)	7.201(3) 0.15409(2)		116.02(3) 63.98(3)		723.3(6)
Hot Springs*	8.603(1) 0.12932(1)	13.009(1) 0.07686(1)	7.194(1) 0.15465(1)		115.990(6) 64.009(6)		723.7(2)
Guanajuato	8.594(2) 0.12954(3)	13.022(2) 0.07679(1)	7.176(1) 0.15514(3)		116.07(2) 63.93(2)		721.3(2)
Alexander 1	8.577(2) 0.12988(2)	12.981(3) 0.07703(2)	7.164(1) 0.15550(3)		116.14(2) 63.85(2)		716.0(2)
Alexander 2	8.576(2) 0.12984(3)	12.975(3) 0.07707(2)	7.162(1) 0.15548(3)		116.09(2) 63.94(2)		715.7(2)
Bodie B-270†	8.591(1)	13.008(1)	7.170(1)		116.05(1)		719.9(1)
Bodie RCD1B†	8.590(1)	13.008(2)	7.177(1)		116.06(2)		720.5(2)
St. Andreasberg	8.612(5) 0.12915(7)	13.035(3) 0.07672(2)	7.185(4) 0.15481(9)		115.97(5) 64.04(5)		725.1(5)
Copper Falls 0	8.609(4) 0.12932(5)	13.045(6) 0.07665(4)	7.183(5) 0.15501(8)		116.08(4) 63.95(4)		724.5(5)
Copper Falls 1	8.601(3) 0.12935(3)	13.041(4) 0.07668(3)	7.176(3) 0.15504(5)		115.99(2) 64.01(3)		723.5(3)
Copper Falls 2	8.619(3) 0.12907(5)	13.025(5) 0.07678(3)	7.181(4) 0.15491(6)		115.98(4) 64.02(4)		724.7(4)
Ontonagon	8.604(3) 0.12931(3)	13.054(4) 0.07660(2)	7.172(3) 0.15513(4)		115.99(3) 64.01(3)		724.0(3)
Phoenix Mine	8.597(2) 0.12935(4)	13.042(4) 0.07668(2)	7.172(2) 0.15505(5)		115.95(3) 64.06(3)		723.2(3)
Eagle Harbor**	8.588(4)	13.034(5)	7.167(3)		115.90(3)		721.7(4)
Kearsarge**	8.579(7)	12.959(5)	7.216(2)	90.53(6) 90.33	115.98(4)	88.13(5) 91.83	720.8(5)
Habachtal***	8.5898 0.12954	13.0321 0.07673	7.1844 0.15488	90.002 90.056	116.013 63.987	89.882 90.131	722.77
IDEAL HIGH SANIDINE							
Kroll & Ribbe (1983)		13.041	7.171				
Kroll & Ribbe (pers. comm. 1983)		13.044	7.165				
Ferguson (pers. comm. 1985)	8.602(5)	13.047(5)	7.161(5)		115.98(5)		723.5
IDEAL MAXIMUM MICROCLINE							
Kroll & Ribbe (1983)	8.592	12.962	7.222	90.62	115.95	87.67	722.6
Ferguson (pers. comm. 1985)	8.574(6)	12.963(3)	7.221(3)	90.64(4)	115.93(2)	87.68(5)	721.2(7)

*H. Kroll, pers.comm. 1984; **Stewart & Wright (1974); ***G. Grundmann (1979); †Chesterman et al. (1974a).

provided for the present study by Dr. G. Grundmann (Technische Universität, München), reveals moderate contents of Sr and Ba (Table 1). In the optical microscope, the St. Andreasberg adularia shows a complex lamellar structure, with small (−)2V and somewhat variable optical orientation. The optic axial plane is close to, but rarely parallel with, (010); a triclinic symmetry is suggested by the optical behavior.

X-ray powder diffractograms confirm Schnorrer-Köhler's (1983) identification of sanidine structural state. Unit-cell dimensions fall outside the high sanidine corner of the Stewart & Wright (1974) $b - c$ quadrilateral, but the value of c is much greater than expected for the totally disordered K-feldspar (Table 2, Fig. 3). A broadened base of the 131 peak also suggests a slightly ordered structural state and Δ values in part greater than 0.

TABLE 3. CHARACTERISTIC INFRARED ABSORPTIONS

Sample		A(μm)	B(μm)
Xihuashan,	pink	15.472	18.564
Xihuashan,	rusty	15.472	18.564
Mirošov		15.555	18.466
Hot Springs		15.643	18.388
Guanajuato		15.642	18.258
Phoenix		15.761	18.162

COPPER DEPOSITS OF THE UPPER MICHIGAN PENINSULA

Adularia is a fairly common gangue mineral in all types of the native copper deposits in Michigan (Cornwall 1951). No systematic study has been devoted to this feldspar, but Stewart & Wright (1974, Table II) listed unit-cell dimensions for two specimens. One of them corresponds to a near-maximum microcline (Kearsarge), the other is highly disordered sanidine (Eagle Harbor).

Specimens from Copper Falls (Harvard Mineralogical Museum #84720, 84721 and 84722, marked here as 0, 1 and 2, respectively), Superior mine at Ontonagon (#115103) and Phoenix mine (#88628) were examined in the present study. Pale rusty brownish adularia forms rich coatings on these specimens, deposited on milky quartz. Calcite locally fills interstices among the adularia crystals. Individual adularia crystals are 0.5–3 mm in size, lustrous and transparent with faint and patchy iron hydroxide stain, and they display the typical Felsöbanya-Maderaner habit.

Chemically, the Phoenix adularia is poor in nonessential elements (Table 1). Simple monoclinic optics reveal intermediate (–)2V in all four samples, with the optic axial plane parallel to (010).

X-ray powder diffractograms of all samples examined show clean monoclinic patterns, with sharp and narrow 131 peaks (Fig. 2). Refinement of unit-cell dimensions resulted in values that plot outside the high sanidine corner of the Stewart & Wright (1974) $b – c$ quadrilateral. Three data sets are close to the recently extrapolated end-member values of high sanidine; the cell dimensions of the Phoenix and Copper Falls 1 samples are identical within $\pm 2\sigma$ with b and c of the Eagle Harbor adularia of Stewart & Wright (1974; cf. Table 2, Fig. 3). Dr. Kroll has observed some doubling of several diffraction-maxima in Guinier photographs of the Phoenix adularia. However, infrared-absorption maxima also correspond to an extremely disordered sanidine (Table 3, Fig. 4).

DISCUSSION

The data of Gubser & Laves (1967) show that samples of adularia from the alpine veins of Switzerland predominantly have monoclinic (orthoclase-like) to triclinic (intermediate microcline) structural states. Out of the 105 specimens investigated only one has b^* and c^* inside the field of high sanidine, and only five show $\Delta > 0.6$. In contrast, our study of adularia from granitic pegmatites shows a relatively common occurrence of end-member maximum microcline and high sanidine states (Černý & Chapman 1984). Based as they are on only a few specimens, the present data suggest that adularia from hydrothermal veins of diverse but non-alpine affiliation also exhibits the extremes in terms of degree of Al–Si order.

The optical properties of the Xihuashan adularia indicate that under appropriate conditions, a metastable monoclinic adularia can be converted to nearly completely ordered microcline. Turbidity, deposition of late fluorite and incipient sericitization show that the adularia was subjected to extensive action of a fluid or gaseous phase.

The Mirošov feldspar is structurally similar to the orthoclase-like pegmatite adularia from granitic pegmatites that shows the presence of a subordinate triclinic phase of variable but low Δ (samples 5,8,9,25,27,28 of Černý & Chapman 1984). Large standard deviations in the cell dimensions (particularly b) derived from powder diffractograms are typical of these feldspars, and some of them plot beyond the maximum microcline – high sanidine join of Figure 3. The Mirošov specimen is the most "anomalous" one in this respect; the St. Andreasberg, Copper Falls 0 and Ontonagon specimens fall into the same category.

It is possible that both the large standard errors and "excessive" values of b and c result from shifts induced into the monoclinic diffraction-maxima by overlaps with the triclinic peak aggregates. Another explanation may be a low-triclinicity structural state simulating a monoclinic powder-diffraction pattern by overlap of very closely spaced triclinic peaks (e.g., $131 + 1\bar{3}1$ merging into a single quasi-131 diffraction maximum). These possibilities seem to be supported by the cell dimensions derived by Dr. P. Bernotat for a K-feldspar from Habachtal, Austria, which has the same type of 131 and $1\bar{3}1$ reflections (Fig. 2), and which also plots outside the $b – c$ quadrilateral (Fig. 3; Grundmann 1979). Negligible as its deviation from monoclinic symmetry is, this feldspar was best interpreted as triclinic (Table 2). Unfortunately, the standard errors of the cell dimensions are not available.

The monoclinic Hot Springs adularia is a borderline case between the ranges of low sanidine and orthoclase, as defined by Ribbe (1983). However, it is not perfectly homogeneous and cannot be taken as representative of the adularia population in the parent quartz veins. A wide variety of structural states is suggested by the published data, and a regional study of the compositional and structural variations should be rewarding for material from this locality.

The Guanajuato adularia consists largely of high sanidine, although its structure is far from its end-member state. As in the previous case, at least some structural diversity should be encountered in the extensive system of veins in the Guanajuato silver deposits.

The Alexander adularia is clearly metastable not only in terms of its structural state but also by its chemical composition. The Ab content of this feldspar is the highest ever encountered in adularia (cf. Gubser & Laves 1967, Nissen 1967, Černý & Chapman 1984), and it indicates disequilibrium precipitation. K-feldspar equilibrated with Cl- or F-based solutions at temperatures below ~350°C never contains more than 10 mol.% Ab, over a wide range of alkali ratios in the co-existing fluid [K/(K + Na) from 1.0 to ~0.2; Orville 1963, Fournier 1976, Barton & Frantz 1983]. A TEM study of the low-temperature cryptoperthitic exsolution in the Alexander adularia should prove interesting.

Finally, the Phoenix mine adularia is virtually identical (within the limits of experimental error) with the redefined high sanidine end-member. It is not known how widespread this extreme structural state may be in the Michigan copper deposits. However, the unit-cell dimensions of the Eagle Harbor, Copper Falls 1 and Ontonagon adularia plot close to the Phoenix data, and the Copper Falls 0 and 2 specimens also are highly disordered. Thus it appears possible that the structural state of high sanidine is characteristic of the late adularia in the Michigan copper district, even if the extreme disorder is not always in evidence.

GENETIC CONSIDERATIONS

Reviewing the pegmatite and non-alpine vein occurrences of adularia displaying the extremes in degree of Al–Si order, each group emerges as distinguished by specific features:

(i) Highly ordered adularia close to maximum microcline is typically coarse grained, predominantly of the Zillertal–Fibbia morphology, relatively extensively altered and overgrown by younger minerals; a massive granular type also occurs in pegmatites, showing a similar type of alteration.
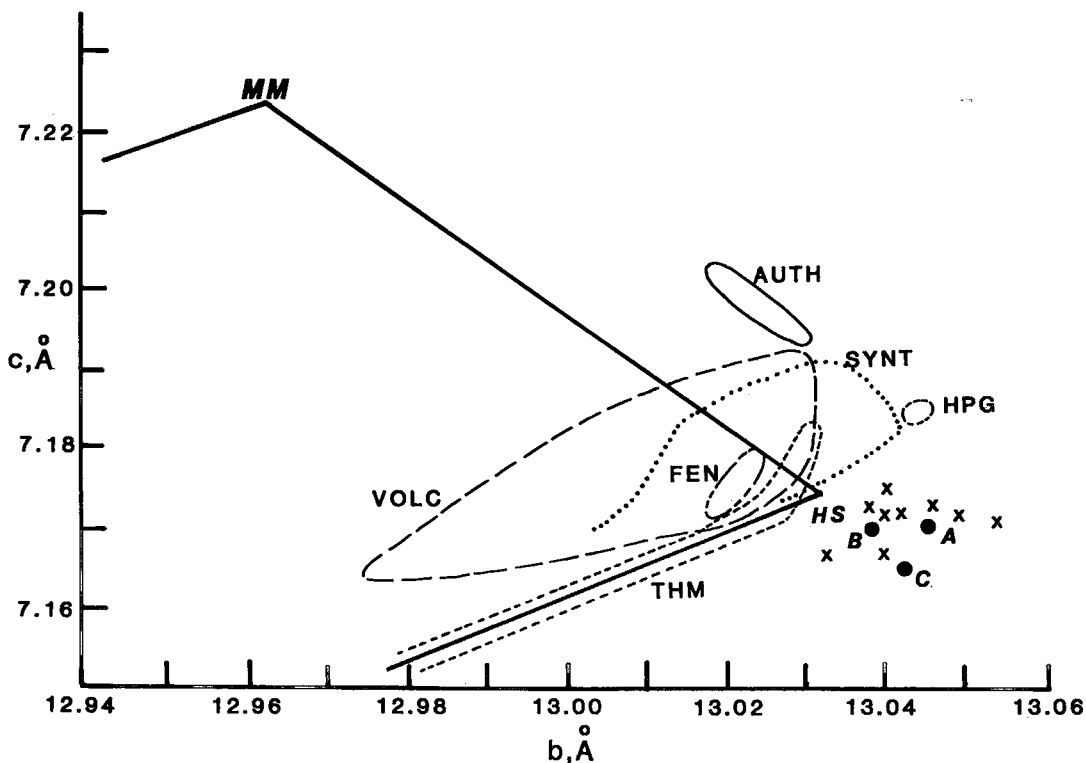

FIG. 5. The b and c cell dimensions of K-feldspar from different environments compared to the high sanidine corner (HS) of the Stewart & Wright (1974) quadrilateral: VOLC volcanic sanidine, THM thermal metamorphism of quartzo-feldspathic xenoliths in mafic lavas, HPG metamorphism of rocks in the high-pressure granulite facies, FEN fenitization in lower crust, AUTH authigenic precipitation in clastic sediments, SYNT synthetic phases (see last paragraph of the text for sources of data). X: high sanidine adularia from pegmatites and hydrothermal veins (Černý & Chapman 1984, this study). A,B,C: calculated high sanidine end-member as in Figure 3.

(ii) High sanidine adularia close to the theoretical totally disordered end-member shows exclusively the Felsöbanya–Maderaner crystal habit, very fine crystal-size or lamellar aggregation, no significant alteration of the transparent to water-clear crystals, and a general lack of subsequent mineral over-growths.

Exceptions to the above generalization do occur; *e.g.*, the Xihuashan maximum microcline adularia has the Felsöbanya–Maderaner morphology, and the high sanidine adularia from the High Grade Dike pegmatite is clouded by clayey alteration products (Černý & Chapman 1984). Nevertheless, in *all* cases examined, there is a good match between the given structural state and *most* of its characteristics listed above. These attributes should serve as fairly reliable guidelines in the search for other samples of adularia of extreme structural states.

It appears that the near-maximum microcline state is generated in monoclinic adularia subject to extensive action of late fluids. This may be particularly true of relatively high-temperature environments, suggested by the Zillertal–Fibbia habit of adularia (about 400°C; Nissen 1967). An alkaline environment should also promote ordering (Martin 1974).

In contrast, the metastable disorder of end-member high sanidine evidently occurs in adularia of low-temperature origin (Felsöbanya–Maderaner habit; ~250°C; Nissen 1967), precipitated at high rates of nucleation and crystal growth. An alkali-poor to peraluminous composition of the parent fluid would also be favorable (Martin 1974). The extremely disordered state is preserved by subsequent pressure or thermal quenching (or both), and by evacuation and sealing of the host cavities, shielding the feldspar against ordering-promoting agents (Foord & Martin 1979, Martin 1982).

Two generations of K-feldspar in the Michigan copper district are particularly illustrative of the above relationships. The triclinic K-feldspar from Kearsarge, which fills an amygdule in basalt (Stewart & Wright 1974, D.B. Stewart, pers. comm. 1985) is representative of the early generation of feldspar precipitated during the initial stages of ore deposition (Butler & Burbank 1929, Cornwall 1951). It acquired its near-maximum structural order, red staining and turbidity under the influence of mineralizing fluids depositing the ore minerals and late gangue assemblages. In contrast, the fine-grained monoclinic adularia is a very late (and occasionally the last) precipitate in the entire paragenesis. A general lack of subsequent action by fluids preserved its transparent to water-clear disposition, and the extremely disordered structural state imposed by fast nucleation and growth at low temperatures.

Considering the structural state of K-feldspar in diverse geological environments, a paradox becomes evident in the natural occurrences of the totally disordered K-feldspar. As indicated by the available data on volcanic sanidine, it is unlikely that the high sanidine end-member will be found among them (*cf.* data assembled by Wright & Stewart 1968, Smith 1974a,b, Stewart & Wright 1974, Lehtinen 1974, Stewart 1974, Kroll & Ribbe 1983). As noted by Stewart & Wright (1974), the high-temperature environment of volcanic sanidine always induces incipient ordering, short-lived as the thermal effect may be (Fig. 5; Černý 1985). Similarly, sanidine also shows some degree of Al–Si ordering in other high-energy environments, such as thermal metamorphism of quartzofeldspathic inclusions in mafic lavas (Grew 1979, Lehtinen & Sahama 1981), metamorphism of high-pressure granulite facies (Smyth & Hatton 1977), and fenitization at lower-crust levels (Morogan & Martin 1985). The only boron-free authigenic sanidine examined to date shows anomalous "excessive" *b* and *c* combinations (Woodard 1972, in Stewart & Wright 1974). A totally disordered sanidine has never been produced experimentally (Luth & Querol-Suné 1970, Fournier 1976, Openshaw *et al.* 1976, Kroll & Ribbe 1983, Kroll *et al.* 1986; *cf.* Fig. 5). Thus it seems likely that the ultimate in K-feldspar disorder occurs exclusively in metastable adularia, grown and preserved in the low-temperature stability field of maximum microcline.

REFERENCES

AKIZUKI, M. & SUNAGAWA, I. (1978): Study of the sector structure in adularia by means of optical microscopy, infra-red absorption, and electron microscopy. *Mineral. Mag.* **42,** 453-462.

APPLEMAN, D.E. & EVANS, H.T., JR. (1973): Job 9214: indexing and least-squares refinement of powder diffraction data. *U.S. Geol. Surv., Comp. Contr.* **20** (NTIS Document **PB2-16188**).

BAMBAUER, H.U. & LAVES, F. (1960): Zum Adular-problem. I. Adular vom Val Casatscha: mimetischer Lamellenbau, Variation von Optik und Gitterkonstanten und ihre genetische Deutung. *Schweiz. Mineral. Petrog. Mitt.* **40,** 177-205.

BARTON, M.D. & FRANTZ, J.D. (1983): Exchange equilibria of alkali feldspars with fluoride-bearing fluids. *Carnegie Inst. Wash. Year Book* **82,** 377-381.

BASS, M.N. & FERRARA, G. (1969): Age of adularia and metamorphism, Ouachita Mountains, Arkansas. *Amer. J. Sci.* **267,** 491-498.

BUTLER, B.S. & BURBANK, W.S. (1929): The copper deposits of Michigan. *U.S. Geol. Surv. Prof. Pap.* **144.**

ČERNÝ, P. (1955): Minerals from the amphibolite quarry at Mirošov (western Moravia). *Acta Musei Moraviae Brno* **40,** 93-107 (in Czech).

_____ (1972): The Tanco pegmatite at Bernic Lake, Manitoba. VIII. Secondary minerals from the spodumene-rich zones. *Can. Mineral.* **11,** 714-726.

_____ (1985): Extreme disorder in potassium feldspar: high-sanidine adularia. *Amer. Geophys. Union Trans.* **66,** 1117 (abstr.).

_____ & CHAPMAN, R. (1983): Crystal chemistry and paragenesis of adularia from granitic pegmatites. *Progr. Abstr. 3rd NATO Adv. Study Inst. Feldspars, Feldspathoids and their Paragenesis* (Rennes), 98.

_____ & _____ (1984): Paragenesis, chemistry and structural state of adularia from granitic pegmatites. *Bull. Minéral.* **107,** 369-384.

CHESTERMAN, C.W., SILBERMAN, M.L., KOSKI, R.A., FABBI, B.P. & O'NEIL, J.R. (1974a): Structure, optical properties, chemistry and paragenesis of hydrothermal K-feldspar at Bodie, Mono County, California. Unpubl. report, 18 p.

_____, _____, _____, & _____ (1974b): Hydrothermal potassium feldspar at Bodie, Mono County, California, and its use in determining the age and conditions of ore deposition. *Int. Mineral. Assoc., 9th Gen. Meet.,* 43 (abstr.).

CORNWALL, H.R. (1951): Differentiation in lavas of the Keweenawan series and the origin of the copper deposits of Michigan. *Geol. Soc. Amer. Bull.* **62,** 159-202.

DIMITRIADIS, S. & SOLDATOS, K. (1978): Optical and structural properties of adularia from Xanthi and Ouranoupolis, Greece, and their interpretation. *Neues Jahrb. Mineral. Abh.* **133,** 88-105.

ENGEL, A.E.J. (1951): Quartz crystal deposits of western Arkansas. *U.S. Geol. Surv. Bull.* **973-E,** 173-260.

FERGUSON, R.B. (1980): From unit cell parameters to Si/Al distribution in K-feldspars. *Can. Mineral.* **18,** 443-458.

_____ (1982): K-feldspar structural end-members ideal sanidine, ideal orthoclase and ideal maximum microcline. *Geol. Assoc. Can. – Mineral. Assoc. Can., Program Abstr.* **7,** 49.

FOORD, E.E. & MARTIN, R.F. (1979): Amazonite from the Pikes Peak batholith. *Mineral. Record* **10,** 373-384.

FOURNIER, R.O. (1976): Exchange of Na^+ and K^+ between water vapor and feldspar phases at high temperature and low vapor pressure. *Geochim. Cosmochim. Acta* **40,** 1553-1561.

GOLDSMITH, J.R. & LAVES, F. (1954): The microcline-sanidine stability relations. *Geochim. Cosmochim. Acta* **5,** 1-19.

GREW, E.S. (1979): Al-Si disorder of K-feldspar in crustal xenoliths at Kilbourne Hole, New Mexico. *Amer. Mineral.* **64,** 912-916.

GRUNDMANN, G. (1979): *Geologisch-petrologische Untersuchung der Smaragdführenden Gesteinsserien der Leckbachscharte, Habachtal (Land Salzburg, Österreich).* M.Sc. thesis, Technical University, Berlin.

GUBSER, R. & LAVES, F. (1967): On X-ray properties of "adularia", $(K,Na)AlSi_3O_8$. *Schweiz. Mineral. Petrog. Mitt.* **47,** 177-188.

HAFNER, S. & LAVES, F. (1957): Ordnung/Unordnung und Ultrarotabsorption. II. Variation der Lage und Intensität einiger Absorptionen von Feldspäten. Zur Struktur von Orthoklas und Adular. *Z. Krist.* **109,** 204-225.

KALB, G. (1924): Die Kristalltracht des Kali-feldspates in minerogenetischer Betrachtung. *Centralbl. Mineral. A,* **1924,** 449-460.

KROLL, H. & RIBBE, P.H. (1983): Lattice parameters, composition and Al,Si order in alkali feldspars. *In* Feldspar Mineralogy, 2nd edition (P.H. Ribbe, ed.) *Mineral. Soc. Amer., Rev. Mineral.* **2,** 57-99.

_____, SCHMIEMANN, I. & VON CÖLLN, G. (1986): Feldspar solid solutions. *Amer. Mineral.* **71**, 1-16.

LEHTINEN, M. (1974): Degree of Al/Si order in potassium feldspars. A combination of X-ray and infrared data. *Contr. Mineral. Petrology* **47**, 223-230.

_____ & SAHAMA, T.G. (1981): A note on the feldspars in the granite xenoliths of the Nyiragongo magma. *Bull. Volc.* **44**, 451-454.

LENTON, P.G. (1979): *Mineralogy and Petrology of the Buck Claim Lithium Pegmatite, Bernic Lake, Southeastern Manitoba.* M.Sc. thesis, Univ. of Manitoba, Winnipeg, Manitoba.

LUTH, W.C. & QUEROL-SUÑE, F. (1970): An alkali feldspar series. *Contr. Mineral. Petrology* **25**, 25-40.

MARTIN, R.F. (1974): Controls of ordering and subsolidus phase relations in the alkali feldspars. *In* The Feldspars (W.S. MacKenzie & Zussman, eds.). Proc. NATO Adv. Study Inst., Manchester Univ. Press, Manchester, England.

_____ (1982): Quartz and the feldspars. *In* Granitic Pegmatites in Science and Industry (P. Černý, ed.). *Mineral. Assoc. Can., Short Course Handbook* **8**, 41-62.

MOROGAN, V. & MARTIN, R.F. (1985): Mineralogy and partial melting of fenitized crustal xenoliths in the Oldoinyo Lengai carbonatitic volcano, Tanzania. *Amer. Mineral.* **70**, 1114-1126.

NISSEN, H.-U. (1967): Domänengefüge, Natriumgehalt, Natriumentmischung und Gitterkonstanten von Alkalifeldspaten (Mikroklin, Orthoklas, Adular) der Schweizeralpen. *Schweiz. Mineral. Petrog. Mitt.* **47**, 1140-1145.

O'NEIL, J.R., SILBERMAN, M.L., FABBI, B.P. & CHESTERMAN, C.W. (1973): Stable isotope and chemical relations during mineralization in the Bodie mining district, Mono County, California. *Econ. Geol.* **68**, 765-784.

OPENSHAW, R.E., HEMINGWAY, B.S., ROBIE, R.A., WALDBAUM, D.R. & KRUPKA, K.M. (1976): The heat capacities at low temperatures and entropies at 298.15 K of low albite, analbite, microcline and high sanidine. *J. Res. U.S. Geol. Surv.* **4**, 195-204.

ORVILLE, P.M. (1963): Alkali ion exchange between vapor and feldspar phases. *Amer. J. Sci.* **261**, 201-237.

RIBBE, P.H. (1983): Chemistry, structure and nomenclature of feldspars. *In* Feldspar Mineralogy, 2nd edition (P.H. Ribbe, ed.). *Mineral. Soc. Amer., Rev. Mineral.* **2**, 1-19.

RUCKLIDGE, J. & GASPARRINI, E. (1969): Specifications of a computer program for processing electron microprobe analytical data (EMPADR VII). *Dep. Geol., Univ. Toronto, Toronto, Ontario.*

SCHNORRER-KÖHLER, G. (1983): Das Silbererzrevier St. Andreasberg, Harz. II. Die Minerale des Gangdreiecks. *Aufschluss* **34**, 189-203.

SMITH, J.V. (1974a): *Feldspar Minerals. 1. Crystal Structure and Physical Properties.* Springer-Verlag, New York.

_____ (1974b): *Feldspar Minerals. 2. Chemical and Textural Properties.* Springer-Verlag, New York.

SMYTH, J.R. & HATTON, C.J. (1977): A coesite–sanidine grospydite from the Roberts Victor kimberlite. *Earth Planet. Sci. Lett.* **34**, 284-290.

STEWART, D.B. (1974): Optic axial angle and extinction angles of alkali feldspars related by cell parameters to Al/Si order and composition. *In* The Feldspars (W.S. MacKenzie & J. Zussman, eds.). Proc. NATO Adv. Study Inst., Manchester Univ. Press, Manchester, England.

_____ & WRIGHT, T.L. (1974): Al/Si order and symmetry of natural alkali feldspars, and the relationship of strained cell parameters to bulk composition. *Soc. franç. Minéral. Crist. Bull.* **97**, 356-377.

WOODARD, H.H. (1972): Syngenetic sanidine beds from Middle Ordovician Saint Peter sandstone, Wisconsin. *J. Geol.* **80**, 323-332.

WRIGHT, T.L. & STEWART, D.B. (1968): X-ray and optical study of alkali feldspar. I. Determination of composition and structural state from refined unit cell parameters and 2V. *Amer. Mineral.* **53**, 38-87.