

## Ba-rich adularia from the Ouachita Mountains, Arkansas: Implications for a postcollisional hydrothermal system

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### ABSTRACT

Jet-black Ba-rich adularia occurs as twinned, euhedral crystals within the Womble Shale (Lower Ordovician) on the shore of Lake Ouachita, Arkansas, in the area of the Benton uplift. The adularia crystals are localized along organic-rich seams in silty micrite, in intimate association with postfolding quartz veinlets. They display two distinct habits. Earlier adularia of the Felsöbanya habit are Ba zoned with typical core compositions near  $K_{(0.760)}Ba_{(0.180)}Al_{(1.161)}Si_{(2.849)}O_8$  and edges near  $K_{(0.935)}Ba_{(0.034)}Al_{(1.059)}Si_{(2.955)}O_8$ . Later, blocky adularia crystals are not Ba zoned and have compositions similar to those in the edges of crystals with the earlier habit. X-ray diffraction analysis indicates that both adularia habits are dominantly monoclinic with a low degree of triclinicity. K-Ar analysis yields a date of  $262 \pm 10$  Ma, consistent with a Permian age for adularia mineralization. Fluid-inclusion data suggest that adularia was deposited from a hydrothermal fluid with a salinity of 3 wt% NaCl equivalent at a maximum temperature of 300°C and a maximum pressure of 1.9 kbar. This pressure corresponds to a maximum lithostatic depth of 7.6 km, considerably less than that postulated for rocks overlying the Womble Shale (> 15 km). The age, composition, and depth of formation of the Ba-rich adularia place severe constraints on the postcollisional evolution of the Ouachita Mountains and may suggest a genetic tie to the formation of Mississippi Valley–type Pb-Zn-Ba deposits.

### INTRODUCTION

Jet-black, Ba-rich adularia occurs as twinned, euhedral crystals within thinly bedded micrite of the lowest member of the Womble Shale (Lower Ordovician), in outcrop on the shore of Lake Ouachita, Arkansas, in the area of the Benton uplift. The Womble Shale is a black, carbonaceous, graptolitic, illitic shale, intercalated with silty micrite, silty sandstone, and phosphatic conglomerate beds (Sterling et al., 1966). The adularia crystals appear to be localized along organic-rich seams in the micrite, frequently in intimate association with postfolding quartz veinlets. Adularia is frequently the only mineral that can be used to date events within the Ouachita Mountains. Thus, detailed geochemical studies were undertaken to determine the composition and age of the adularia, and their relationship to the structural evolution of the Ouachita Mountains.

### ADULARIA MINERALOGY AND CHEMISTRY

#### Petrography

Micrite samples from the Womble Shale were collected at the tip of a small peninsula [459850 m E, 3828460 m N, Universal Transverse Mercator (UTM) grid zone 15]

on the shore of Lake Ouachita, Arkansas. Examination of thin sections of micrite containing adularia crystals and quartz veinlets indicates synchronous deposition. Although the adularia crystals are generally larger (up to 2 mm diameter) than the quartz veinlets (less than 0.2 mm wide), they occur within the veinlets, cluster tightly against the veinlets, and float in the micrite matrix as much as 10 cm from the veinlets (Figs. 1a, 1b, 1c). Adularia occurrences distal to the quartz veinlets tend to be restricted to organic-rich seams and stylolites within the micrite. This suggests to us that movement of hydrothermal fluids occurred along stylolites during the adularia-forming event and that incorporation of the abundant associated organic matter may be responsible for the jet-black appearance of the adularia.

Previously reported adularia crystals from the same region are restricted to quartz veins. They occur especially at vein margins adjacent to shaly rocks or as cement or coats on shale fragments included in the quartz veins (Engel, 1951), or they line irregular vugs at the centers of larger quartz veins (Bass and Ferrara, 1969).

In thin section the adularia crystals display two distinctive cross sections (Fig. 1). The first is a diamond-shaped cross section (Felsöbanya habit of Kalb, 1924); many such crystals display sector zoning and locally complex extinction patterns (Figs. 1a, 1b). Many larger adu-

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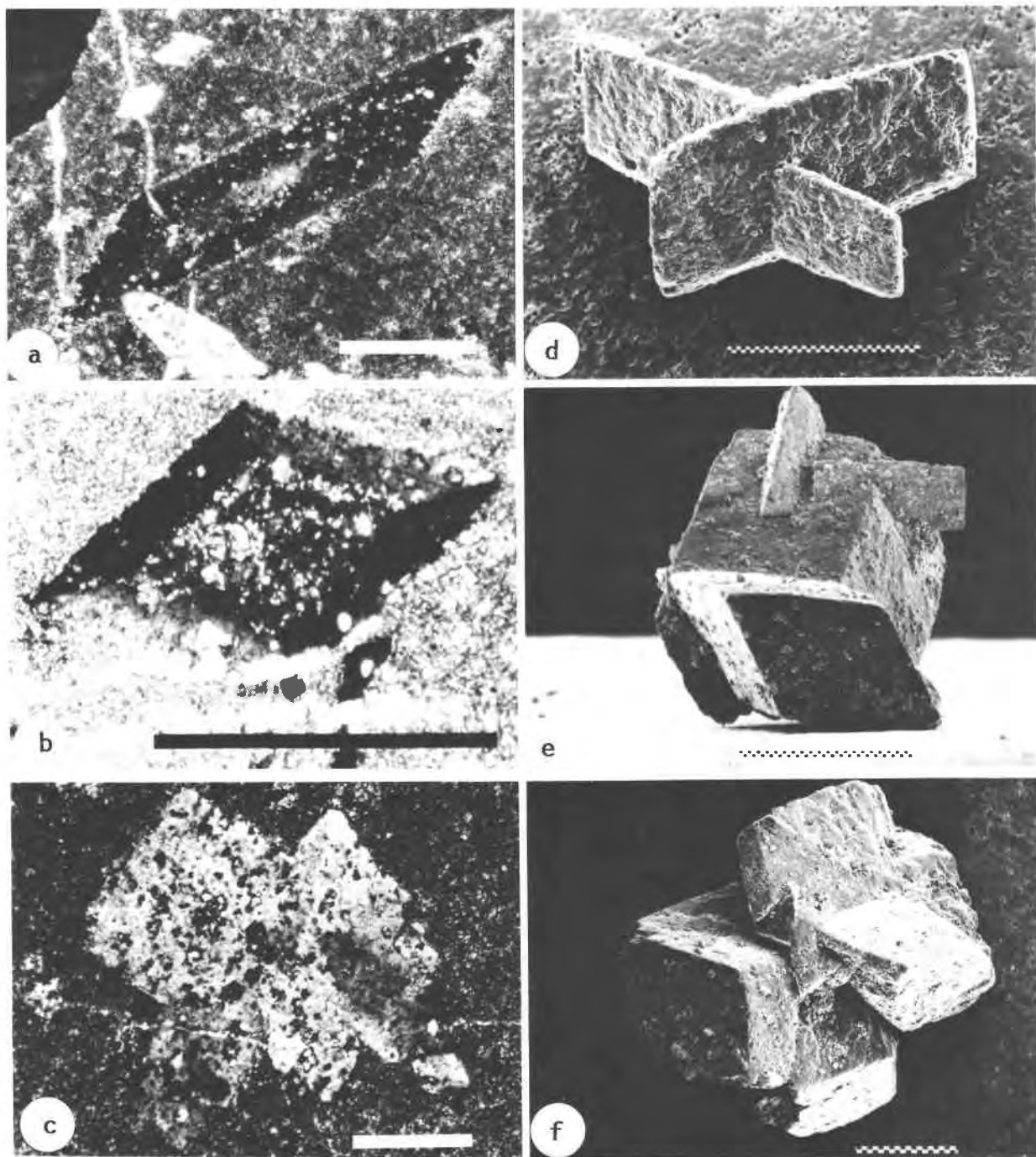


Fig. 1. (a) and (b) Photomicrographs of Ba-zoned Felsöbanya habit of adularia crystals, contained within micrite, displaying optical discontinuity between solid-inclusion-rich cores and inclusion-poor edges. Note sector zoning of diamond-shaped cross section. Cross-polarized transmitted light. (c) Larger, blocky habit of adularia in micrite. Cross-polarized transmitted light. (d) and (e) Scanning electron photomicrographs of the Ba-zoned Felsöbanya habit of adularia crystals displaying penetration twinning. (f) Larger, blocky habit of adularia displaying multiple penetration twinning in a cyclical fashion. All scale bars are 0.5 mm. Representative scanning electron photomicrographs (d), (e), and (f) are positioned opposite their thin-section counterparts (a), (b), and (c), respectively.

Table 1. Typical chemical compositions of zoned Ba-rich adularia crystals

wt %	Core	Edge
K <sub>2</sub> O	12.33	15.81
BaO	9.50	1.88
Al <sub>2</sub> O <sub>3</sub>	20.40	19.39
SiO <sub>2</sub>	58.99	63.78
Total	101.22	100.86
K	0.760	0.935
Ba	0.180	0.034
Al	1.161	1.059
Si	2.849	2.955
$x(R^{1+} + R^{2+})$	0.940	0.969

Atomic contents calculated on the basis of 8 oxygens

larial crystals of this type (Fig. 1b), viewed in the plane normal to the *c* axis, display cores with extinction parallel to (010) cleavage and edges with slightly inclined extinction (Chaisson, 1950). Optic axial planes have variable orientations, and values of  $2V$  (negative) are variable (from  $31^\circ$  to  $43^\circ$ ). Commonly the cores of these adularia crystals contain numerous solid inclusions (most less than  $10\ \mu\text{m}$  in diameter), whereas the edges tend to be free of inclusions (Figs. 1a, 1b). The solid inclusions are quartz, calcite, sodium feldspar, pyrite, iron oxide, and an unidentified Fe-Mg silicate (see next section).

The second distinctive cross section of adularia crystals in thin section exhibits larger, blocky, irregular outlines consisting of multiple crystals (Fig. 1c). They frequently display undulatory extinction and have variable values of  $2V$  (negative). Many of these crystals contain the same assortment of solid inclusions as found in the diamond-shaped crystal cross sections.

Cathodoluminescent analysis did not indicate the presence of detrital K-feldspar cores.

#### Scanning electron microscopy (SEM) and energy-dispersive spectrometry (EDS)

Samples of the Womble Shale micrite were dissolved in glacial acetic acid. Insoluble residues included black adularia crystals, one conodont element, fragments of thin-bedded shale, quartz veinlets, and abundant black organic matter. Representative samples of the two distinctive habits of adularia were examined with an Amray 1600T-KeveX 7000 SEM-EDS system. Individual crystals were photographed directly; others were mounted in epoxy and polished.

Representative scanning electron photomicrographs are positioned opposite their thin-section counterparts in Figure 1 (1d, 1e, 1f). Penetration twins of the long, narrow Felsöbanya habit are shown in Figures 1d and 1e; multiple cyclic penetration twins of the larger, blocky habit are shown in Figure 1f.

Elemental X-ray information on the polished crystals provided qualitative analyses of the adularia and helped to identify the solid inclusions (see Petrography section). The Felsöbanya habit revealed significant amounts of Ba

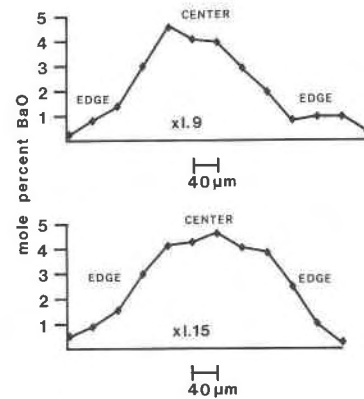


Fig. 2. Calibrated traverses of Ba-zoned adularia (crystals 9 and 15) showing systematic decreases of mole percent BaO from centers to edges. The interval between analyses is  $40\ \mu\text{m}$ .

in their inclusion-rich cores, whereas the more inclusion-free edges were found to be Ba poor. The larger, blocky habits were also found to be Ba poor, resembling the edges of the earlier habit. This suggests to us that the large, blocky crystals were likely formed later than the Ba-zoned, narrow crystals. Though the time frame over which the change from Ba-rich to Ba-poor crystallization took place cannot be directly determined, it is likely less than 100 000 yr. This is a generally accepted upper limit for small hydrothermal systems (Norton and Cathles, 1979; Cathles, 1981).

#### Electron-probe microanalysis

AN ARL EMX electron microprobe with four wavelength-dispersive spectrometers was used to determine the chemical compositions of individual adularia crystals in polished sections. An operating voltage of 15 kV and a beam current of 20 nA were used. Standards used were orthoclase for K, Al, and Si and barite for Ba. The data were reduced following the correction methods of Bence and Albee (1968) and Albee and Ray (1970). Results of analyses are shown in Table 1 (gross zoning) and Figure 2 (details).

Calibrated traverses were performed, normal to the *c* crystallographic axes of the long, narrow (Felsöbanya) habit of adularia crystals in the polished sections. Great care was taken to avoid solid inclusions. Results of the traverses indicate that Ba and Al substitute to a large degree for K and Si in the cores of crystals. This substitution decreases systematically outward from the crystal cores to edges (Fig. 2). The adularia analyses yield a typical core composition of  $\text{K}_{(0.760)}\text{Ba}_{(0.180)}\text{Al}_{(1.161)}\text{Si}_{(2.849)}\text{O}_8$  and a typical edge composition of  $\text{K}_{(0.935)}\text{Ba}_{(0.034)}\text{Al}_{(1.059)}\text{Si}_{(2.955)}\text{O}_8$ .

Similar analyses of adularia with the larger, blocky habit revealed no systematic Ba zonation and are nearly identical to those of the Ba-poor edges of the Ba-zoned elongate adularia crystals. This supports our qualitative observation based on SEM-EDS study that the larger blocky habit of adularia may be paragenetically later than the elongate habit.

Adularia typically has low contents of minor and trace elements:  $\text{Na}_2\text{O} < 1.5$ ,  $\text{Rb}_2\text{O} < 0.37$ ,  $\text{BaO} < 1.7$  (rarely,  $< 3.2$ ), and  $\text{SrO} < 0.25$  wt% (Weibel, 1957, 1961; Rybach and Nissen, 1967; Gubser and Laves, 1967; Smith, 1974b; Dimitriadis and Soldatos, 1978; Černý and Chapman, 1984). The adularia crystals examined here contain no detectable Na. However, they have large Ba contents, up to 9.5 wt% oxide (Fig. 2, Table 1).

The high contents of Ba suggest the hydrothermal leaching and remobilization of Ba from rocks at depth without reprecipitation of Ba in the form of crystallochemically more accommodating species (e.g., Ba phosphates, well-site, or barite).

### X-RAY DIFFRACTION STUDY

A study of the adularia structural state was performed using a Phillips X-ray diffractometer. X-ray scans were run at  $1^\circ/\text{min}$  between  $4^\circ$  and  $46^\circ$   $2\theta$  across powdered samples of adularia using  $\text{CuK}\alpha$  radiation. Further scans were run at  $1/4^\circ/\text{min}$  between  $20^\circ$  and  $36^\circ$   $2\theta$ , this being the critical range for determining feldspar structure (Steiner, 1970). The reflections were identified using the powder patterns of Borg and Smith (1969).

All the adularia crystals have (201) reflections at  $2\theta \approx 21^\circ$ . This suggests a very pure (low-Na) K-feldspar (Bowen and Tuttle, 1950). The (131) reflection at approximately  $2\theta = 29.6^\circ$ , in some samples (larger, blocky adularia crystals) has an adjacent, smaller (131) peak developed at a small  $\Delta 2\theta$  angle (less than  $0.15^\circ$ ) to the (131) peak, suggesting a small proportion of triclinic material (Smith, 1974a). The elongate Ba-zoned adularia crystals do not yield discernible (131) peaks, though their (131) peaks are of variable width. The  $\Delta 2\theta$  values for (040)–(200) at approximately  $2\theta = 27.5^\circ$  fit monoclinic adularia or monoclinic orthoclase (Borg and Smith, 1969). The adularia crystals examined plot within the orthoclase region of the *b-c* quadrilateral of Stewart and Wright (1974).

The adularia crystals are therefore dominantly monoclinic, though some may have a low degree of triclinicity. Afonina and Shmankin (1970) claimed that Ba substitution inhibits ordering in K-feldspar, on the basis of comparing weight percent Ba to the (131) triclinic index of specimens. It is therefore not surprising that the Ba-rich adularia crystals of our study are dominantly monoclinic.

### DATE OF MINERALIZATION

K-Ar data were obtained for Ba-rich adularia. Ar extraction was made using a conventional extraction system with an induction furnace. The Ar-isotope composition was determined using a 6-in.-radius, Nier-type mass spectrometer. A spike of  $^{38}\text{Ar}$  added before each analysis enabled calculation of the quantity of  $^{40}\text{Ar}$  released from the samples. K analyses were made using standard atomic absorption techniques. The results are presented in Table 2. The adularia grains yielded a date of  $262 \pm 10$  Ma, consistent with a Permian age of mineralization.

The adularia was chosen for dating in this study because it is the *only* phase present in the rock that can be dated

Table 2. K-Ar data of adularia

Sample Description	Radiogenic $^{40}\text{Ar}$ cc/g STP $\times 10^{-6}$	Atmospheric $^{40}\text{Ar}\%$	Date <sup>1</sup> m.y. $\pm 2\sigma$
Ba-rich adularia crystals from micrite	10.63 10.22	114.4	4.5 $262 \pm 10$

<sup>1</sup>  $K_{\lambda_B} = 4.962 \times 10^{-11} \text{y}^{-1}$ ,  $K_{\lambda_C} = 5.81 \times 10^{-11} \text{y}^{-1}$ ,  
 $^{40}\text{K}/\text{K} = 0.01167$  (Steiger and Jäger, 1977)

by K-Ar methods. K-Ar behavior of adularia is not well known, and it is not within the scope of our study to systematically investigate it through application of  $^{40}\text{Ar}/^{39}\text{Ar}$  age-spectrum dating. We do not intend for a single K-Ar date for an adularia to stand alone as an indicator of the age of formation of the hydrothermal quartz veins. We do argue that concordancy of this K-Ar date with Rb-Sr dates for presumably cogenetic adularias elsewhere in the Ouachita Mountains is an indicator that these dates are geologically meaningful.

We believe that the K-Ar date of  $262 \pm 10$  Ma obtained in our study represents the age of formation of the adularia and associated quartz veins. It seems unlikely to us that the adularia crystals would have experienced significant Ar loss due to either their structural state or the thermal history of the host rock. The adularia crystals are almost completely monoclinic; X-ray diffraction analysis suggests very low triclinicity. Previous studies (Halliday and Mitchell, 1976) have suggested that an inverse correlation exists between triclinicity of adularia and K-Ar age, which has been interpreted as representing Ar loss related to the structural state. Monoclinic adularia crystals (low-triclinicity crystals such as ours) are least likely to lose Ar unless they have experienced a significant high-temperature, postdepositional reheating (hydrothermal) event. Such a high-temperature event is unlikely: the adularia crystals show no evidence of significant recrystallization; a conodont geothermometer suggests a maximum rock temperature of approximately  $300^\circ\text{C}$ ; and fluid inclusions show no evidence of a postdepositional, high-temperature hydrothermal event. Therefore, we suggest that the K-Ar date of  $262 \pm 10$  Ma represents the age of formation of the adularia and associated quartz veins. This date is in agreement with Rb-Sr ages of adularias that are from elsewhere in the Ouachita Mountains but that are assumed to have had similar geologic histories (Bass and Ferrara, 1969; Denison et al., 1977).

The concordancy of K-Ar and Rb-Sr dates has been used as a test of the reliability of dates for minerals that are not routinely dated. For example, the reliability of glauconite dates, which may be subject to inaccuracies from sources similar to those that may affect adularia (i.e., the presence of a detrital component or Ar loss), is routinely tested in this manner (see, e.g., Grant et al., 1984). Bass and Ferrara (1969) obtained ages for cogenetic ad-

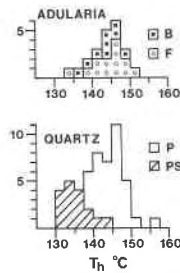


Fig. 3. Histograms of homogenization temperatures ( $T_h$ ) of fluid inclusions in adularia and quartz. Note the similarity of fluid-inclusion homogenization temperatures in both minerals. B = primary inclusions in the larger, blocky habit of adularia, F = primary inclusions in the Felsöbanya habit of adularia, P = primary inclusions in quartz, PS = pseudosecondary inclusions in quartz.

ularia in quartz veins in the Ouachita Mountains, Garland County, Arkansas. Their results by the K-Ar method were  $190 \pm 5$ ,  $205 \pm 6$ , and  $214 \pm 6$  Ma—apparent Triassic ages. They ascribed these ages to Ar loss from their adularia crystals of variable triclinicity. Rb-Sr data for the 205 Ma sample yielded an age between 279 and 287 Ma (Bass and Ferrara, 1969); ( $\lambda = 1.39 \times 10^{-11} \text{ yr}^{-1}$ ). This range of ages is 263 to 271 Ma if a 47-b.y. half-life of  $^{87}\text{Rb}$  is used (Denison et al., 1977). The difference in age (263 or 271 Ma) depends on the initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio chosen—0.704 for the older age or 0.709 for the younger age. Denison et al. (1977), from their recalculated ages, concluded that the age of quartz + adularia mineralization in the Ouachita Mountains was Permian, using any reasonable initial Sr ratio (0.700 to 0.709). A Permian age is in agreement with the K-Ar data of our study.

### FLUID-INCLUSION STUDY

Fluid inclusions (74 primary and pseudosecondary; Roedder, 1984) were examined in thin, doubly polished plates of adularia and associated quartz veins. Microthermometric measurements were made using a Fluid Inc. gas-flow fluid-inclusion stage. Replicate measurements of the homogenization temperatures of standard synthetic

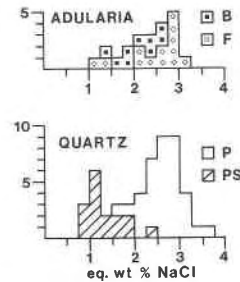


Fig. 4. Histograms of salinities of fluid inclusions in adularia and quartz (weight percent NaCl equivalent). Note the similarity of fluid-inclusion salinities in both minerals. Abbreviations as in Fig. 3.

fluid inclusions in quartz (Shelton and Orville, 1980) showed a reproducibility within  $\pm 0.2^\circ\text{C}$  at temperatures up to  $350^\circ\text{C}$ . Replicate measurements of the melting temperatures of pure-water synthetic fluid-inclusion standards and  $\text{CO}_2$ -rich inclusions from Camperio, Italy, showed a reproducibility within  $\pm 0.1^\circ\text{C}$ . The results of heating and freezing experiments on fluid inclusions are presented in Table 3 and Figures 3 and 4. The salinity data are based on freezing-point depression in the system  $\text{H}_2\text{O}$ -NaCl (Potter et al., 1978).

Adularia crystals were found generally to be ill-suited for fluid-inclusion study owing to their relative opacity, a result of significant inclusion of organic matter. Only 22 suitable fluid inclusions were found within 20 crystals studied. A larger number of suitable fluid inclusions (52) was found in associated quartz veins. Although the temperature and salinity data presented are dominantly from inclusions in quartz, the great similarities of data from quartz and adularia suggest that both phases are products of the same hydrothermal system.

All fluid inclusions observed in adularia and quartz are water-rich, low-salinity inclusions consisting of liquid and a small bubble that comprises approximately 10 to 15 vol% of each inclusion. The inclusions are nearly spherical and range in size from 10 to  $40 \mu\text{m}$ . No daughter minerals were observed. Crushing tests suggest that  $\text{CO}_2$  and other dissolved gases are not present in significant concentrations in the inclusion fluids. All of the inclusions homogenize to the liquid by vapor disappearance.

Primary fluid inclusions in adularia homogenize at temperatures between  $134$  and  $151^\circ\text{C}$  and have salinities between 1.1 and 3.4 wt% NaCl equivalent. No correlations exist between location within the Ba-zoned adularia crystals and either fluid-homogenization temperature or fluid salinity.

Primary and pseudosecondary fluid inclusions in quartz homogenize at temperatures between  $131$  and  $157^\circ\text{C}$  and have salinities between 0.9 and 3.7 wt% NaCl equivalent. The nearly identical ranges of homogenization temperature and salinity data from adularia and quartz suggest that both phases are likely products of the same hydrothermal system (Table 2, Figs. 3 and 4). Our fluid-inclusion studies revealed no evidence (i.e., presence of sec-

Table 3. Fluid-inclusion data of adularia and quartz

Samples	Inclusion Type		$T_h$ $^\circ\text{C}$	$\text{H}_2\text{O}$ $^\circ\text{C}$ $T_{\text{melt}}$	Salinity eq. wt % NaCl
	P	PS			
Felsöbanya habit adularia crystals	13	0	134 to 151	-0.6 to -1.8	1.1 to 3.2
larger, blocky adularia crystals	9	0	136 to 148	-0.7 to -2.0	1.3 to 3.4
vein-filling quartz	36	16	131 to 157	-0.4 to -2.2	0.9 to 3.7
	58	16			

P = primary fluid inclusions, PS = pseudosecondary inclusions.

ondary inclusions) of a postdepositional hydrothermal system.

It is not possible to use the fluid-inclusion data of this study to determine the formation temperature of the adularia and associated quartz veins because an independent estimate of pressure is not possible. It is possible, however, to estimate pressure (and by inference, depth) in the hydrothermal system by interpreting the fluid-inclusion homogenization temperatures and salinities within the context of another geothermometer—conodonts. A conodont from the adularia sample locality has a CAI (color alteration index) of 4 (R. L. Ethington, University of Missouri—Columbia, pers. comm.). A CAI of 4 indicates that the conodont sample has experienced a temperature between 190 and 300°C (Epstein et al., 1977). Which end of the temperature range the CAI datum indicates is dependent upon the length of time the sample remains at a given temperature. For durations of less than 100 000 yr (the maximum life of most small hydrothermal systems: Norton and Cathles, 1979; Cathles, 1981) a temperature between 250 and 300°C is indicated.

Assuming a maximum formation temperature of 300°C, and using an average homogenization temperature of 145°C and salinity of 2.8 wt% NaCl equivalent, the calculated maximum pressure on the hydrothermal system at the time of adularia and quartz formation was approximately 1.9 kbar (Potter, 1977; Haas, 1971; Lemmlin and Klevstov, 1961). This estimate of maximum pressure corresponds to a maximum lithostatic depth of approximately 7.6 km. For a formation temperature of 250°C, the calculated pressure is approximately 1.1 kbar, corresponding to a lithostatic depth of approximately 4.4 km. These depth estimates are considerably less than that postulated for rocks overlying the Womble Shale (greater than 15 km: Viele, 1974; Sharp, 1978). This suggests either (1) there was a significant hydrostatic component to the pressure due to an interconnected network of open fractures above the site of adularia deposition or (2) there was significant erosion in this portion of the Ouachita Mountains prior to Permian hydrothermal activity.

## DISCUSSION OF RESULTS AND THEIR IMPLICATIONS

The age, composition, temperature, and depth of formation of the Ba-rich adularia crystals place constraints on the postcollisional evolution of the Ouachita Mountains.

The date of  $262 \pm 10$  Ma is consistent with a Permian age for adularia and associated quartz deposition. This age is in agreement with several investigators who have suggested that the Ouachita orogeny extended into Permian time (Waterschoot van der Gracht, 1931; Bass and Ferrara, 1969; Denison et al., 1977; Desborough et al., 1985). Early Permian deformation is known in the Marathon region of Texas and in northeastern Mexico, and one might therefore infer that deformation and associated hydrothermal activity persisted into Permian time in the Ouachita Mountains where absence of Upper Pennsyl-

vanian and Permian rocks does not allow setting an upper stratigraphic limit on deformation.

Within the Arkoma basin, the youngest rocks exhibiting deformation are mid-Desmoinesian (Dane et al., 1938) although some workers (e.g., Melton, 1930) have suggested that joint patterns in the Permian strata of central and eastern Oklahoma were formed during the waning phases of the Ouachita orogeny. Uplift of the region of the Benton uplift, however, probably started somewhat earlier. Houseknecht (1981) reported the presence of fragments of slate, possibly from the Stanley or Jackfork Formations of Mississippian and Morrowan age, respectively, in the Desmoinesian Hartshorne Sandstone of the Arkoma basin. Moreover, conglomerates composed of chert pebbles have been reported in mid-Desmoinesian strata of the Ardmore basin of Oklahoma (Tomlinson and McBee, 1959). If the chert pebbles are from the Arkansas Novaculite or older siliceous formations, as seems most probable, some part of the lower Paleozoic rocks of the uplift was exposed to erosion before the Middle Pennsylvanian. The earliest hint of deformation of Ouachita rocks comes from a poorly understood series of radiometric dates of Devonian age obtained from exotic blocks in the Carboniferous strata of the Marathon region of western Texas and from micas from the lower Paleozoic strata of the Broken Bow uplift (Denison et al., 1977). Recent work (Underwood and Viele, 1985) suggests that the thrust sheets of the Ouachitas were pushed onto the southern margin of the North American craton by mid-Atokan time. Although the thickness of the Atokan strata across the Benton uplift is not known, it seems probable that uplift of this region may have started by Atokan time. The deformation front continued to migrate northward, finally involving rocks of mid-Desmoinesian or younger age in the northern part of the Arkoma basin.

A Permian hydrothermal event recorded in the adularia of our study may also coincide with a  $255$  to  $265 \pm 10$  Ma widespread thermal event in the southern Appalachians (Kulp and Eckelmann, 1961). The similarity of the ages of these events may suggest that crustal orogenic events proceed from north to south along the Appalachian foldbelt and then from east to west along the Ouachita foldbelt.

It is tempting to interpret the origin of the Ba-rich adularia within the context of the widespread occurrence of Pb-Zn-Ba mineralization of the midcontinent region. The date of  $262 \pm 10$  Ma (Permian) obtained for adularia of our study is in agreement with ages suggested for Mississippi Valley-type Pb-Zn-Ba deposits of the Viburnum trend, southeast Missouri. Wu and Beales (1981), on the basis of dating of mineralization-related magnetic material by paleomagnetic methods, suggested a Late Pennsylvanian–Early Permian age for the Pb-Zn-Ba mineralization.

Recently, Sharp (1978), Leach et al. (1984), and Rowan et al. (1984) have suggested that many Mississippi Valley-type Pb-Zn-Ba deposits in the central and eastern United States are related to rapid expulsion of fluids from peri-

cratonic-foreland basins during the Appalachian-Ouachita orogeny in late Paleozoic time. Their ideas are consistent with fluid-inclusion, geochemical, and geologic studies suggesting that the Ouachita-Arkoma basin may be the source of the ore-forming fluids responsible for the Pb-Zn-Ba deposits of the Ozark region (Leach, 1973). Thick Carboniferous flysch sediments accumulated in the Ouachita-Arkoma basin during the subduction phases of the Ouachita orogeny. During the collision phase, these sediments were folded and carried northward in complex thrust sheets that overrode coeval shelf sediments on the continental margin (Viele, 1974; Leach et al., 1984).

The crustal collision is thought to have resulted in the rapid migration of metal-bearing fluids onto the craton in response to sediment compaction and pressure from tectonic and burial metamorphic processes. Homogenization temperatures from fluid inclusions in dolomite from Missouri, Kansas, Arkansas, and Oklahoma provide evidence for a broad-scale Late Pennsylvanian–Early Permian heating of the Paleozoic section to temperatures of 90 to 160°C. Temperatures of 200 to 300°C have been documented for fluids expelled from the 12–18-km-thick Ouachita section. The observed temperatures may reflect the thermal gradient of a slowly cooling fluid moving northward out of a deep sedimentary basin such as the Ouachita-Arkoma basin (Rowan et al., 1984; Leach and Rowan, 1985). The maximum temperature (300°C) and maximum pressure (1.9 kbar) determined for the Ba-rich adularia crystals are consistent with this Permian hydrothermal event.

Occurrences of Pb and Zn in western Oklahoma and Texas flank the continuation of the Ouachita foldbelt into Mexico (Leach et al., 1984), where an Early Permian deformation is known. Bethke et al. (1984) have also suggested that uplift of the Pascola arch during the Ouachita orogeny may have permitted Illinois basin water to flow northward and deposit Pb-Zn-Ba ore in the Upper Mississippi Valley.

The Pb-Zn-Ba deposits of the folded Appalachians, located in shelf carbonates, have a similar relationship to deep foreland basins and orogeny related to crustal collision. Thus, the occurrence of Pb-Zn-Ba deposits also suggests that crustal orogenic events, proceeding from north to south along the Appalachian foldbelt and then from east to west along the Ouachita foldbelt, may have resulted in a major period of Pb-Zn-Ba metallogeny in North America (Leach et al., 1984).

In summary, the Permian Ba-Rich adularia crystals of our study reflect the presence of postcollisional hydrothermal activity in the Ouachita Mountains. The Ba-rich adularia crystals and associated quartz veins are likely the results of postfolding, Ouachita orogenic faulting that tapped a vast reservoir of hot, excess-pressured fluids (Sharp, 1978), which may have resulted in Pb-Zn-Ba mineralization in the northern Arkansas–southeastern Missouri area.

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