Chemical U-Th-Pb Monazite Dating of Deformations versus Pluton Emplacement and the Proterozoic History of the Arkansas River Region, Colorado, USA

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Abstract: Five lengthy periods involving multiple phases of cordierite and andalusite growth were revealed by detailed studies of foliation inflection/intersection axes (FIA) preserved in porphyroblasts in schists from the Arkansas River region in Colorado, USA. The regionally consistent character of the succession of five different FIA trends enabled the relative timing of each FIA with respect to the next to be determined. The FIA succession from first to last is: FIA 1 trending W-E, FIA 2 trending SSW-NNE, FIA 3 trending NNW-SSE, FIA 4 trending NW-SE and FIA 5 trending SW-NE. For four of the FIA sets, samples were found containing monazite grains preserved as inclusions. These were dated on an electron microprobe. The ages obtained concur exactly with the FIA succession, with FIA 1 at 1506±15 Ma, FIA 2 at 1467±23 Ma, FIA 3 at 1425±18 Ma, FIA 4 not dated and FIA 5 at 1366±20 Ma. These ages are directly reflected in a succession of plutons in the surrounding region dated by other isotopic approaches, suggesting that deformation, metamorphism and pluton emplacement occurred together episodically, but effectively continuously, for some 140 Ma.

Key words: monazite dating, Arkansas River region, foliation inflection/intersection axes

1 Introduction

The Proterozoic metasedimentary rocks of the northern Wet Mountains of Southern Colorado, USA (Fig. 1), exposed to either side of the Arkansas River to the east of Texas Creek (Fig. 2), contain numerous andalusite, cordierite and plagioclase porphyroblasts. The rocks were deformed and metamorphosed approximately 1700 and 1400 Ma, being intruded by plutons at 1474, 1442 and 1371 to 1362 Ma (Bickford et al., 1989; Cullers et al., 1992; Graubard, 1990; Siddoway et al., 2000, Wobus et al., 2001). They lie on the boundary between the older Yavapai terrane to the north and the younger Mazatzal terrane to the south. Karlstrom et al. (1987) considered that Mazatzal continental rocks formed independently and were juxtaposed with, or deposited onto, Yavapai island-arc rocks late in the tectonic history.

Structural (Hickey and Bell, 2001) and microstructural work (Bell and Hickey, 1997; Bell et al., 1998, 2004) using newly developed quantitative methods, such as the measurement of foliation inflection/intersection axes (FIA) preserved within porphyroblasts, has revealed much more extensive histories of deformation and metamorphism than previously recognized. These methods have resulted in the recognition of successions of multiple phases of porphyroblast growth and foliation development, and provide a powerful means for establishing relative timing. Significantly, FIA successions allow datable monazite grains of many different generations to be quantitatively distinguished.

Recently, the EMPA U-Th-Pb monazite dating method, which has been widely used to date tectonothermal events, has been used to determine the time of development of periods of deformation and metamorphism preserved in porphyroblasts (Bell and Welch, 2002; Williams and Jercinovic, 2002; Sanislav, 2009). *In situ* dating, with a spatial resolution of 3 microns, is possible using the electron microprobe and is performed directly on thin sections in which small monazite grains averaging 12 microns in size can be readily identified in backscatter mode (Bell and Welch, 2002). EMPA U-Th-Pb monazite dating is becoming an efficient tool for dating

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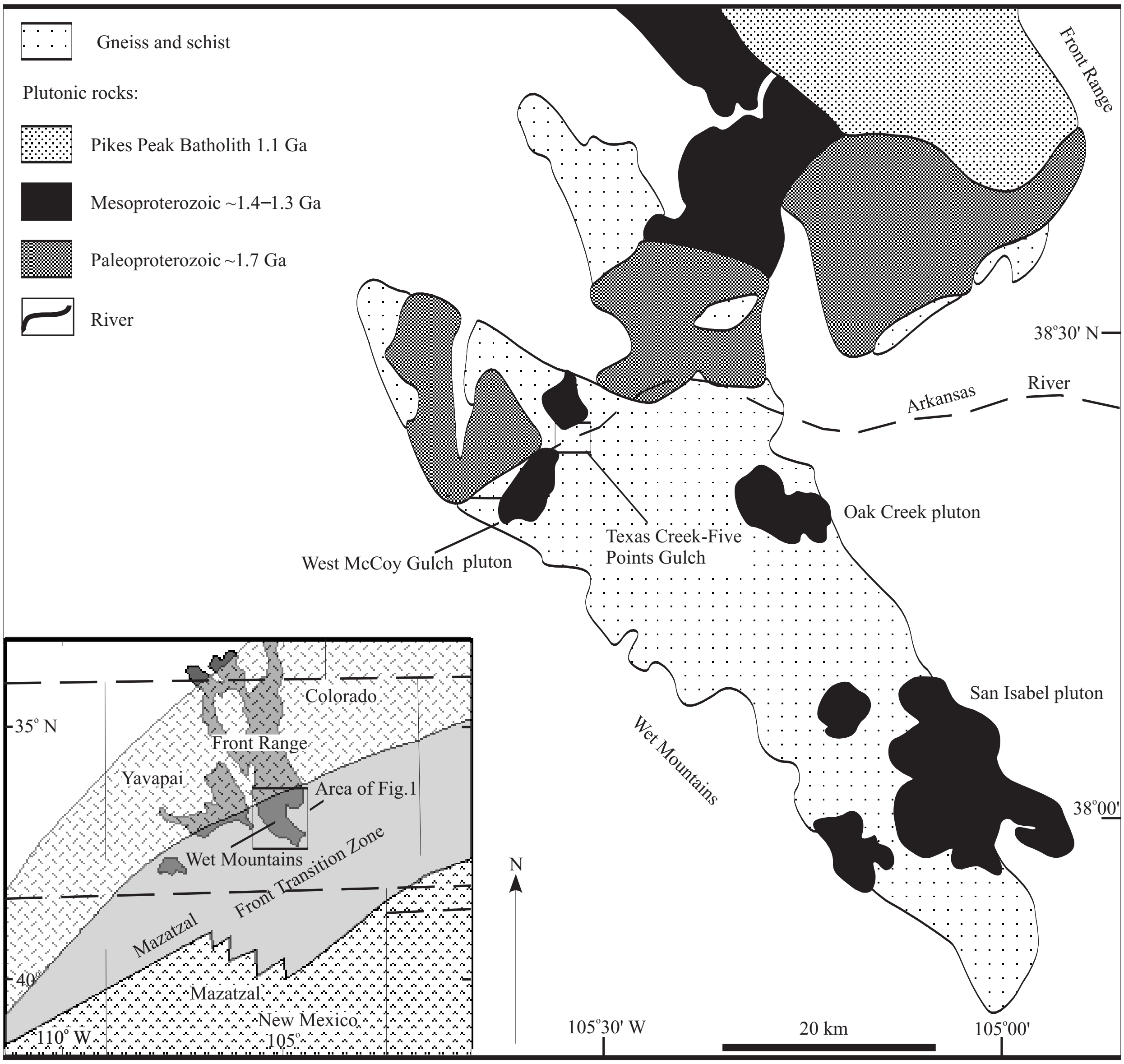

Fig. 1. Location of the Texas Creek–Five Point Gulch area described herein within a regional geological map of the Arkansas River region and relative to Colorado and New Mexico (modified from Siddoway et al., 2000). The inset map shows Proterozoic rocks and Proterozoic crustal province boundaries and/or transition zones after Jones and Connelly (2006).

metamorphism and deformation, and has received considerable attention since a paper was published by Williams et al. (1999). This article reports new EMPA U-Th-Pb monazite dating results from the Arkansas River region Precambrian metamorphic complex and discusses their geological significance in terms of the deformation history obtained using FIA (e.g. Bell and Welch, 2002).

2 Geological Setting

The Arkansas River Canyon lies on the boundary between the older Yavapai terrane (1.8–1.7 Ga; Karlstrom and Humphreys, 1998) to the north and the younger Mazatzal terrane (1.7–1.6 Ga; Karlstrom and Humphreys, 1998) to the south, which is a critical area for the development of continental crust in southwestern USA. The Texas Creek–Five Points Gulch area that bounds the Arkansas River (Fig. 1) provides access to the most detailed history of tectonometamorphic events because the metamorphic rocks were not migmatized. This means that the numerous cordierite and fewer andalusite porphyroblasts with well-developed inclusion trails present in these rocks (Givot, 1998; Siddoway et al., 2000; Stevens and Wilson, 1998) can be used to access the history of development of this region in great detail (Fig. 2). Three deformations and two periods of metamorphism have been recognized in the Wet Mountains by Siddoway et al. (2000) who reported $^{40}Ar/^{39}Ar$ hornblende ages of 1369±4 to

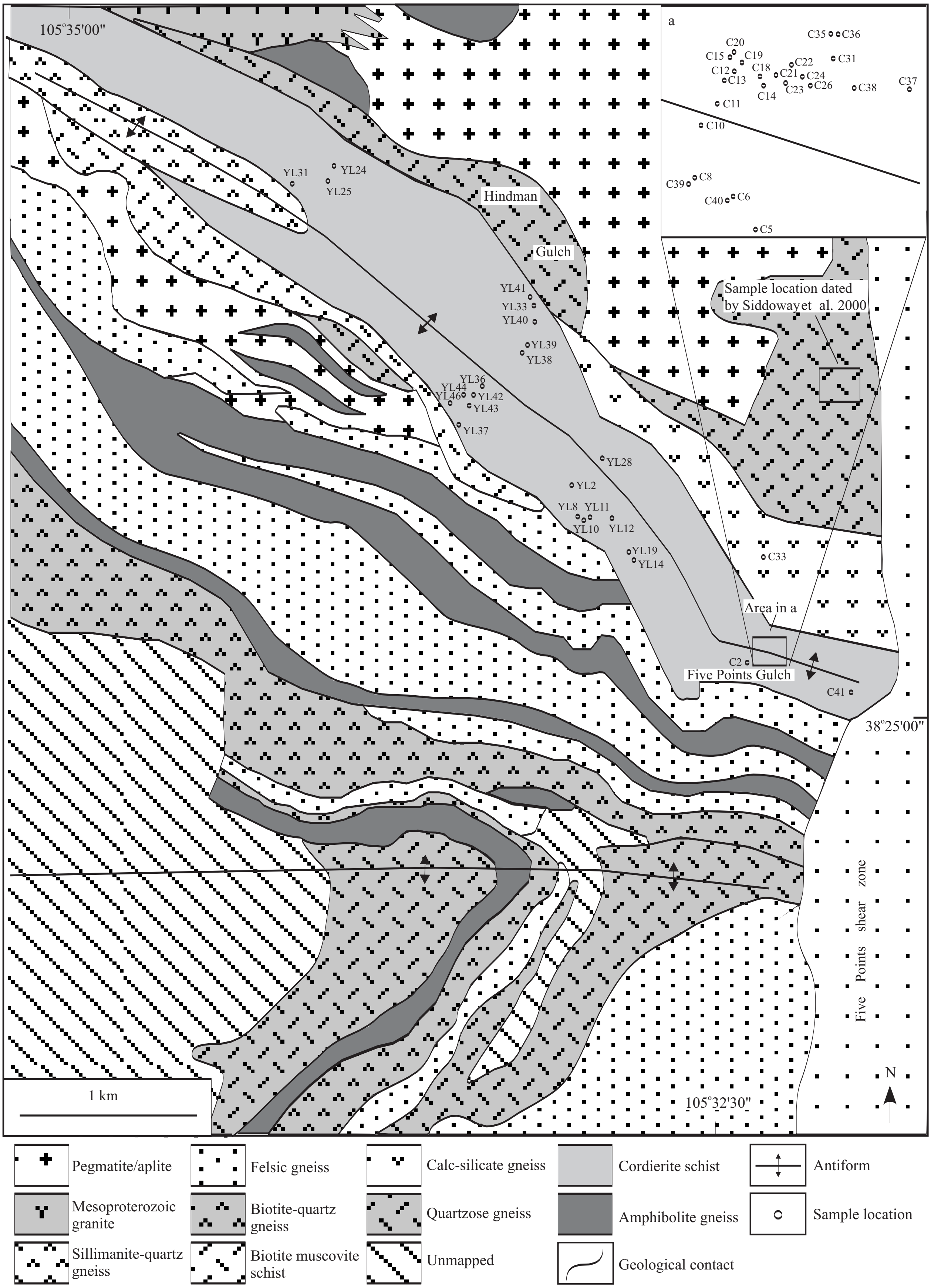

Fig. 2. Geological map of the Texas Creek–Five Point Gulch area (after Siddoway et al., 2000 and Gartner et al., 2001) showing sample locations.

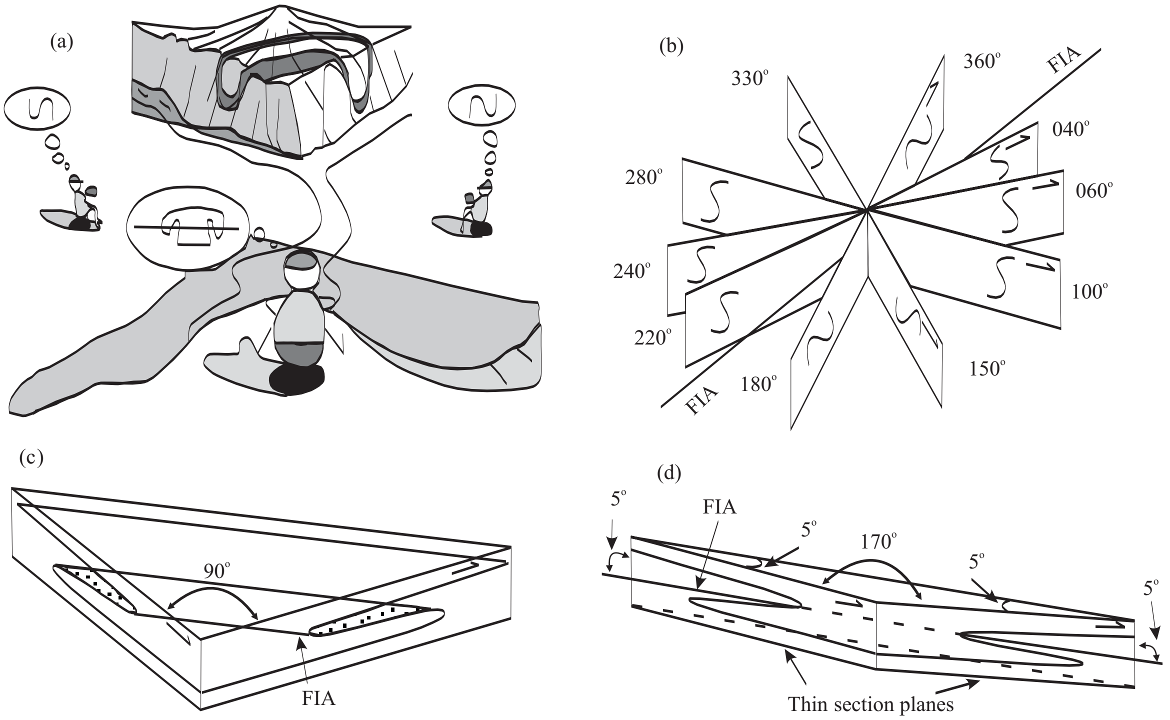

Fig. 3. Sketch illustrating the principle behind FIA measurement (after Bell et al., 2004).
(a) The geologists to either side see the opposite asymmetry for the same fold in a cliff face. They have no idea of its trend in 3-D. The geologist in the centre sees the fold on both cliff faces and knows it must trend from one to the other. (b) Asymmetry on a series of differently striking vertical sections. The asymmetry flips across the compass when viewed in the same direction. (c) Asymmetry of a sigmoid axis in two sections cut 90° apart. (d) Sigmoid axis of (c) in two sections cut 10° apart lying on either side of the axis. The switch in asymmetry between them defines the location of the axis within a 10° range.

1342±6 Ma near Five Points Gulch (Fig. 2). Plutons in the surrounding region have the following ages: 1474±7 Ma for the West McCoy Gulch pluton to the SW (Fig. 1), 1442±7 Ma for the Oak Creek pluton to the SE (Fig. 1; Bickford et al., 1989), 1442±2 Ma for the Mount Evans batholith ~50 km to the N of Fig. 1 in the Front Range (Graubard, 1990) and 1362–1371 Ma for the San Isabel batholith to the SE in the Wet Mountains (Fig. 1; Cullers et al., 1992).

3 FIA Data and Interpretation of the FIA Succession

The measurement of FIA allows different generations of the same mineral phase to be distinguished because of changes in FIA trend from the core to rim, or core to median to rim, of porphyroblasts in some samples (e.g. Bell et al., 1998). If these changes are systematic across a region they can be used to correlate different periods of growth of the same or different mineral phases, from location to location across folds, faults and region to region (Bell et al., 2004). The asymmetry approach provides a method for measuring the FIA trend preserved by inclusion trails in porphyroblasts. This method distinguishes successions of porphyroblast growth and foliation development through changes in the FIA trend with time. It constrains the timing of successive periods of porphyroblast growth to a specific period of tectonism defined by the FIA trend. FIA in cordierite, andalusite and plagioclase were measured using the asymmetry method developed by Hayward (1990) and Bell et al. (1995, 1998). This is shown in Fig. 3 and consists of initially cutting six vertical thin sections 30° apart around the compass and then two more 10° apart where the inclusion trail asymmetry flips. A total of 63 FIA were measured in porphyroblasts in 49 oriented samples located, as shown in Fig. 2. Single FIA were recorded in 36 samples. An additional 27 FIA were measured from 13 samples that contain multi-FIA porphyroblasts. The FIA obtained from each sample where measurement was possible are shown in Table 1 and Fig. 4.

The five distinct trends in FIA visible in Fig. 4 moving clockwise around the compass from N–S are SSW–NNE, SW–NE, W–E, NW–SE and NNW–SSE. A consistent pattern in the relative timing of these FIA trends was determined using changes in FIA trend from the core to median to rim of porphyroblasts from sample to sample. The following relationships were observed (Table 1):

(1) W–E trending FIA in porphyroblast cores are succeeded by SSW–NNE and SW-NE trending FIA in their rims in samples YL 39 and C 11.

(2) SSW–NNE trending FIA in porphyroblast cores are

succeeded by NNW–SSE trending FIA in the rim in sample YL 43.

(3) NNW–SSE trending FIA in cores are succeeded by NW–SE and SW–NE trending FIA in the rims in samples C 36 and YL 2.

(4) NW–SE trending FIA in porphyroblast cores are succeeded by SW–NE trending FIA in their rims in sample YL36.

These relationships (Fig. 4) show that W–E and SSW–NNE trending FIA dominate the cores and rims of the earliest porphyroblasts with FIA 1 (W–E) trends varying between 70° and 110° and FIA 2 (SSW–NNE) trends ranging from 20° to 40°. They were followed by NNW–SSE trending FIA 3 ranging from 160° to 180°N and NW–SE trending FIA 4 varying between 120° and 140°. SW–NE trending FIA 5 is the youngest FIA set, ranging from 50° to 60°. This interpretation can be confirmed using the samples (C 39, YL12, YL 19 and YL 38 in Table 1) containing pseudo-FIA (p-FIA; Bell et al. 1995, 1998).

Table 1 Foliation inflection/intersection axes (FIA) trend and its location within the porphyroblast determined for each sample from Arkansas River region, Colorado, USA.(unit: °)

Sample	Single FIA	Actual FIA	Pseudo FIA	Core FIA	Median FIA	Rim FIA
C2	120					
C5	130					
C6	125					
C8	120					
C10	120					
C11				100		50
C12	55					
C13	55					
C14		50	70			
C15	165					
C18	55					
C19	135					
C20		165	75			
C21	120					
C22	130					
C23	50					
C24	90					
C26	85					
C31	85					
C33	90					
C35	90					
C36				165		135
C37	25					
C38	65					
C39		160	20			
C40		85	105			
C41	135					
YL2				165		60
YL8	130					
YL10	20					
YL11	165					
YL12		175	75			
YL14	165					
YL19		165	25			
YL24	25					
YL25	45					
YL28	105					
YL31	25					
YL33	85					
YL36				130		50
YL37	90					
YL38				110	90	40
YL39				105		25
YL40	165					
YL41	30					
YL42	30					
YL43				30		165
YL44	25					
YL46	175					

4 Samples and Dating Method

Although 10 polished thin sections (two per FIA set) were used to find monazite grains included in porphyroblasts, only five samples contained grains that were large enough to date (Table 2, Fig. 2). These grains occur in samples containing FIA sets 1, 2, 3 and 5. The samples selected for polished thin section preparation to date FIA set 4 contained monazite inclusions that were too small to date.

Sample C20 contains cordierite porphyroblasts that overgrew a differentiated crenulation cleavage. The crenulated cleavage defines a pseudo FIA belonging to FIA set 1. The differentiated crenulation cleavage defines a FIA belonging to FIA set 3. All dated monazite grains were located in the crenulated cleavage that defines FIA set 1. C40 contains cordierite porphyroblasts, which have inclusion trails defining FIA set 1. YL 42, YL14 and C23 contain cordierite porphyroblasts, which have inclusion trails defining FIA sets 2, 3 and 5, respectively. Figure 5 shows a monazite that was dated in sample C23 and the spot size resulting from beam damage of the locations dated.

Suzuki and Adachi (1991) proposed the principles of EMPA U-Th-Pb dating of monazite and zircon and Montel et al. (1996) systematically summarized these for monazite. This method has been discussed in many articles published worldwide (Bell and Welch, 2002; Williams et al., 2002; Liu et al., 2004; Zhang et al., 2006; Sanislav, 2009).

U-Th-Pb dating of monazite was conducted in the Advanced Analytical Centre of James Cook University on a JX8200 manufactured by JEOL (Tokyo, Japan). The detailed methods, steps, and age calculation approaches have been documented by Cihan et al. (2006) and Sanislav (2009). Measurements were taken at an accelerating voltage of 15 kV, probe current of 200 nA and spot size at 1–2 microns. Interference corrections for Th and Y on Pb and Th on U were applied as described in Pyle et al. (2002). The ages were calculated using the average weight method and compiled with Isoplot v. 3.00 (Ludwig, 2003). The

Table 2 Electron microprobe analytical results of monazites from Arkansas River region, Colorado, USA

Sample no.	PbO (wt%)	UO_2 (wt%)	ThO_2 (wt%)	Y_2O_3 (wt%)	Age (Ma)	Age error (Ma)	Sample no.	PbO (wt%)	UO_2 (wt%)	ThO_2 (wt%)	Y_2O_3 (wt%)	Age (Ma)	Age error (Ma)
c40-07-003	0.315438	0.252319	3.86	1.87	1518	88	yl14-30-003	0.310091	0.206608	4.31	1.52	1414	83
c40-07-005	0.321694	0.228872	4.01	1.71	1526	88	yl14-30-008	0.410342	0.260198	5.52	1.79	1461	69
c40-07-007	0.31546	0.20584	3.95	1.64	1542	90	yl14-35-001	0.308478	0.262612	4.19	1.64	1387	81
c40-07-101	0.622014	0.404134	8.09	2.44	1497	51	yl14-35-003	0.373583	0.251648	5.19	1.74	1412	71
c40-07-102	0.485288	0.374295	6.01	2.31	1514	61	yl14-35-004	0.280502	0.297087	3.42	1.71	1440	92
c40-07-301	0.254065	0.355037	2.63	1.91	1495	102	yl14-36-003	0.358397	0.32015	4.71	1.83	1410	74
c40-07-302	0.278154	0.320225	3.06	1.98	1516	98	yl14-37-003	0.37799	0.4384	4.61	1.78	1410	70
c40-08-001	0.366037	0.297942	4.74	1.99	1450	73	yl42-20-004	0.293763	0.08441	4.29	1.57	1469	89
c40-08-002	0.365516	0.286384	4.47	1.91	1524	79	yl42-20-006	0.39698	0.083831	5.88	1.67	1475	69
c40-08-102	0.251904	0.237376	3	1.76	1502	105	yl42-20-007	0.228145	0.051996	3.43	1.36	1450	108
c40-50-001	0.366127	0.290988	4.54	1.93	1505	77	yl42-20-009	0.26977	0.057946	3.95	1.49	1489	96
c40-50-003	0.380095	0.311705	4.77	1.94	1483	73	yl42-20-010	0.27322	0.072557	3.95	1.82	1489	96
c40-50-004	0.348641	0.243649	4.42	1.87	1511	81	yl42-20-011	0.194091	0.052672	2.89	1.4	1449	123
c40-50-101	0.346737	0.261668	4.37	1.75	1499	80	yl42-20-012	0.272472	0.070347	4.07	1.73	1448	93
c40-10-002	0.455292	0.326953	5.85	2.17	1489	64	yl42-21-004	0.336268	0.396089	3.73	1.95	1499	82
c40-03-001	0.400135	0.274239	5.18	1.9	1491	71	yl42-21-005	0.217657	0.23731	2.52	1.67	1484	117
c40-03-002	0.445133	0.307131	5.7	1.94	1502	66	yl42-04-001	0.322172	0.05748	4.87	1.66	1458	80
c40-03-003	0.479083	0.295138	6.2	1.87	1514	63	yl42-04-002	0.356611	0.081968	5.24	1.51	1480	76
c40-03-005	0.418372	0.287107	5.35	1.91	1505	69	yl42-05-001	0.226286	0.029368	3.43	1.157	1470	107
c40-52-001	0.42077	0.343203	5.1	1.93	1524	70	yl42-05-002	0.372868	0.08222	5.7	1.88	1430	70
c40-52-002	0.395257	0.303244	4.9	1.99	1514	73	yl42-05-003	0.358294	0.076061	5.35	1.84	1464	74
c40-52-003	0.348468	0.288473	4.28	1.8	1505	80	c23-06-001	0.261457	0.183972	3.78	1.37	1359	92
c20-03-001	0.25327	0.17299	3.2	1.45	1520	107	c23-06-002	0.243671	0.216464	3.59	1.48	1292	90
c20-03-101	0.334009	0.241173	4.05	1.49	1556	87	c23-06-003	0.292481	0.269489	4.01	1.71	1357	83
c20-03-102	0.318865	0.21985	4.09	1.36	1500	87	c23-06-004	0.281305	0.252441	3.85	1.75	1366	87
yl14-12-001	0.281294	0.230849	3.78	1.53	1407	89	c23-07-001	0.450508	0.238455	6.61	1.68	1390	60
yl14-12-002	0.287808	0.196455	3.97	1.59	1418	89	c23-07-002	0.409643	0.263719	6.04	1.73	1353	62
yl14-12-003	0.357366	0.261428	4.8	1.86	1434	75	c23-07-003	0.337863	0.205796	4.93	1.58	1374	75
yl14-12-004	0.38079	0.156744	5.54	1.46	1435	71	c23-07-004	0.307208	0.230875	4.26	1.71	1392	82
yl14-12-005	0.446925	0.232308	6.34	1.62	1433	63	c23-07-006	0.316431	0.208453	4.5	1.56	1390	80
yl14-12-006	0.29515	0.238975	4.03	1.63	1392	85	c23-07-007	0.278178	0.18143	4.08	1.41	1357	87
yl14-11-002	0.285981	0.219951	3.95	1.54	1391	87	c23-07-009	0.296738	0.18447	4.26	1.42	1390	85
yl14-11-003	0.330064	0.242098	4.49	1.73	1418	79	c23-30-001	0.194641	0.200554	2.58	1.4	1363	117
yl14-11-004	0.430002	0.27421	5.83	2.01	1451	66	c23-30-002	0.266859	0.291029	3.35	1.63	1401	93
yl14-11-005	0.380695	0.291562	5.02	1.91	1444	72	c23-30-007	0.331033	0.266541	4.69	1.67	1354	74
yl14-33-002	0.346503	0.1993	4.8	1.57	1445	78	c23-30-010	0.269862	0.198793	3.83	1.56	1370	90
yl14-33-003	0.286276	0.200767	3.86	1.49	1438	90	c23-30-012	0.430517	0.731425	4.77	1.68	1349	59

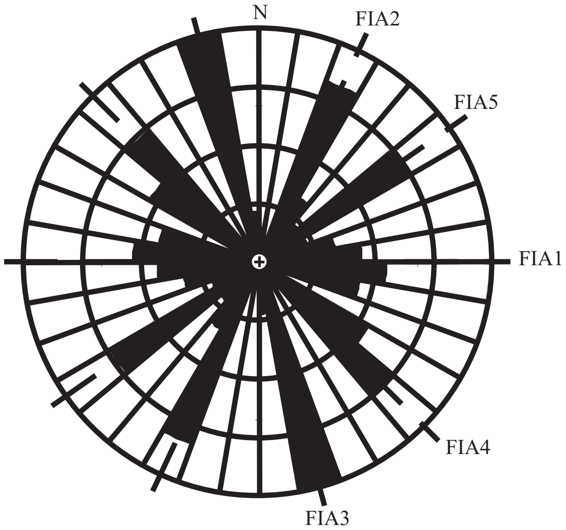

Fig. 4. All the FIA data from Table 1 plotted on a rose diagram. Five distinct peaks in the distribution of these FIA are apparent and suggest five distinct sets of FIA trend have been preserved by the porphyroblasts that grew in this region.

concentration errors were then propagated through the age equation (Lisowiec, 2006). Once single point dates and errors were determined at a 2σ level, data was grouped separately by grain and textural setting. Age groups between grains in similar textural settings (i.e. FIA set) were formed, and dates from the individual analyses comprising these groups were weighted and averaged to reduce errors on the age of the geological event recorded in a single FIA set.

5 Interpretation of Results

FIA form perpendicular to the direction of horizontal bulk shortening and are produced by a succession of multiple deformations that are preserved as a succession of subvertical and subhorizontal foliations in porphyroblasts (Bell and Welch, 2002). The five FIA obtained reveal four changes in the direction of bulk shortening accompanied orogenesis. These changes should occur in the same order as the succession of FIA trends derived from the changes in FIA orientations from the core to the rim of porphyroblasts described earlier. This can be tested by selecting samples containing one of the FIA sets for dating using monazite preserved as inclusions within them. The ages obtained should become progressively younger in accord with the FIA succession. Seventy four monazite spots in total on several monazite grains in porphyroblasts from five

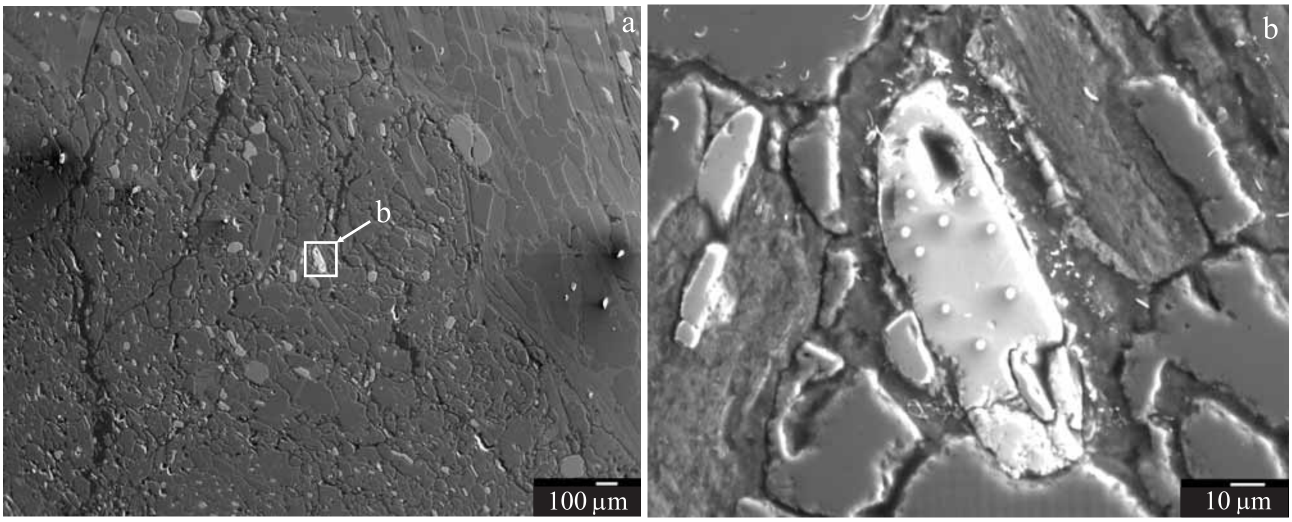

Fig. 5. Location of monazite in porphyroblast (a) and the spot dated in monazite (b) in sample C23.

samples were analyzed. For each analytical spot chemical ages were calculated (Table 2). Monazite grains in porphyroblasts from the same FIA set were grouped and a single weighted average age was calculated (Fig. 6). For FIA set 1, monazite grains in samples C20 and C40 were analyzed. The weighted average age calculated for this FIA is 1506±15 Ma (Fig. 6a, e). For FIA sets 2, 3 and 5, monazite grains in samples Yl42, YL14 and C23 gave weighted ages of 1467±23, 1425±18 and 1366±20 Ma, respectively (Fig. 6b, f; c, g; d, h). Bulk shortening was directed N–S around 1506±15 Ma when the W–E trending FIA set 1 developed. It was directed WNW–ESE at approximately 1467±23 Ma when the SSW–NNE trending FIA set 2 developed. It was directed WSW–ENE at approximately 1425±18 Ma when the NNW–SSE trending FIA set 3 developed. The age of FIA 4 was not determined. However, bulk shortening was directed NW–SE at approximately 1366±20 Ma when the SW–NE trending FIA set 5 developed.

6 Discussion

The direct match of the succession in ages with the FIA succession strongly confirms the success of the FIA approach to resolving the history of deformation of a complex group of rocks. It also confirms that FIA can be used to access to role of changes in deformation partitioning with time through the foliations preserved within porphyroblasts across a large region, as well as from outcrop to outcrop (e.g. Bell and Mares, 1989; Bell et al., 2004). Significantly, the monazite electronic microprobe ages obtained suggest that each FIA can be correlated to a specific period of regional tectonic development associated with pluton emplacement. These plutons were dated during previous geochronological work in and around the Arkansas River using a variety of techniques and methods (e.g. U-Pb chemical extraction; Graubard, 1990; $^{40}Ar/^{39}Ar$ isotopic dating; Siddoway et al. 2000). The ages produced are remarkably similar to those obtained by this study and this strongly suggests that plutons were emplaced throughout the succession of FIA that developed. The combination of cordierite and andalusite porphyroblasts suggests that the low pressures reached during FIA 1 were maintained for approximately 140 million years. The 1474±7 Ma age of West McCoy Gulch pluton to the SW (Fig. 1; Bickford et al., 1989) is very similar to that associated with the 1467±23 Ma development of FIA 2. The 1442±7 Ma age of the Oak Creek pluton to the SE (Fig. 1; Bickford et al., 1989) and the 1442±2 Ma age of the Mount Evans batholith to the N in the Front Range (Graubard, 1990) is very similar to the 1425±18 Ma age of FIA 3. The 1362–1371 Ma age of the San Isabel batholith to the SE in the Wet Mountains (Fig. 1; Cullers et al., 1992) and the $^{40}Ar/^{39}Ar$ hornblende ages of 1369±4 to 1342±6 Ma near Five Points Gulch reported by Siddoway et al. (2000) are very similar to the 1366±20 Ma age of FIA 5. Therefore, orogenesis throughout this region was accompanied by episodic, but continuous granite emplacement. This concurs with very recent work by Sanislav (2009), who found that metamorphism in Maine began before pluton arrival and continued for some 70 million years with some evidence for granite development still occurring in the very last stages. Similar lengthy histories of metamorphism have been recognized by Shah (this volume) in rocks approximately 200 km to the north.

7 Conclusions

The succession of porphyroblast growth revealed by changes in FIA trend in cordierite and andalusite

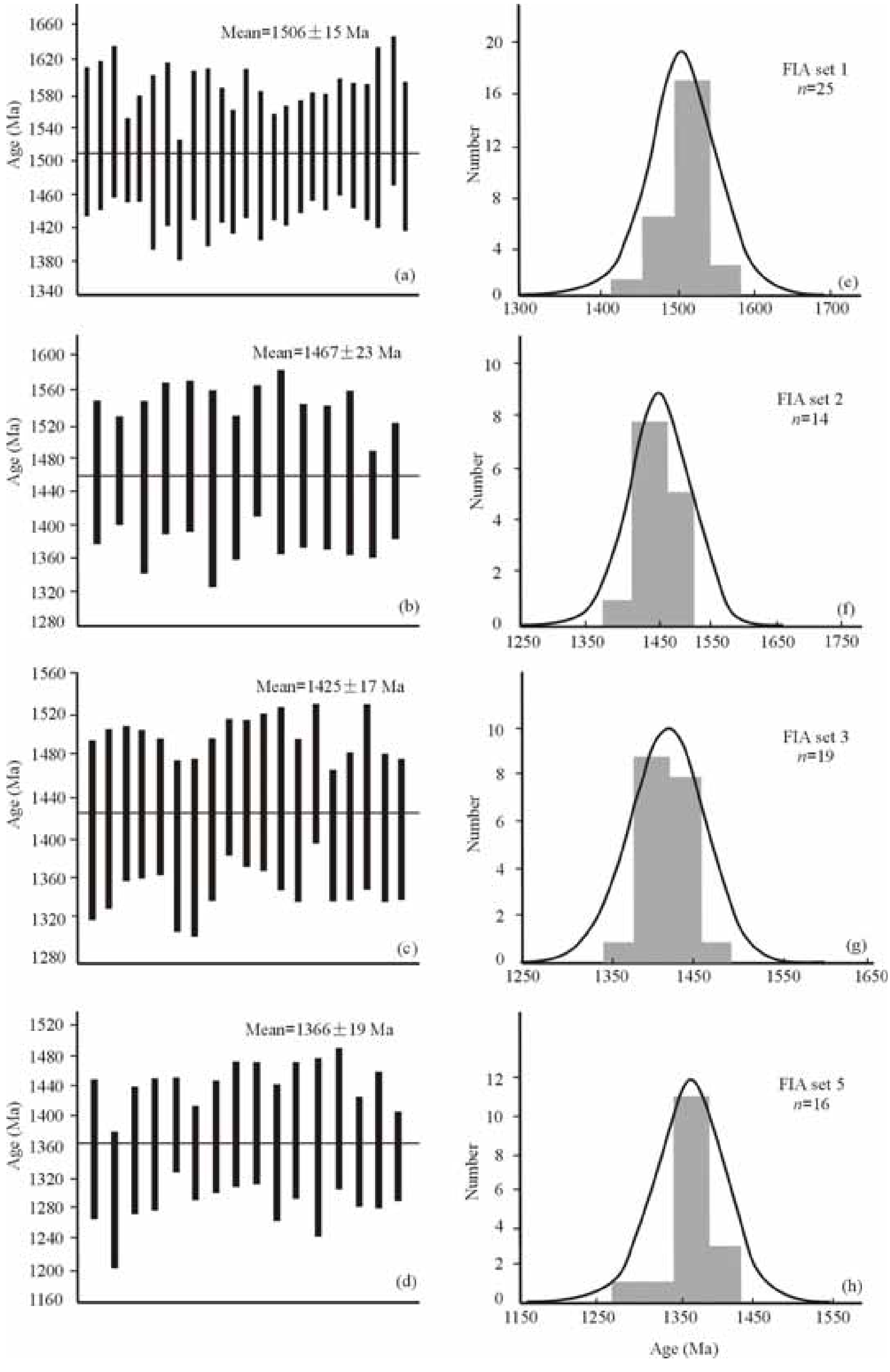

Fig. 6. Probability diagrams and monazite ages for FIA set 1 (a, e), FIA set 2 (b, f), FIA set 3 (c, g) and FIA set 5 (d, h).

porphyroblasts is confirmed by the succession in ages of monazite grains preserved as inclusions that help define these FIA trends. Multiple phases of cordierite and andalusite growth took place episodically in this region for a period of time lasting more than 100 million years. Pluton emplacement in the region accompanied porphyroblast growth, but was not directly spatially coupled to it. Rather, the region heated up and remained at a similar structural level due to the development of succession of subhorizontal and subvertical events for a very lengthy period of time as deformation after deformation took place (Bell and Hickey, 1998). The exact location of pluton development appears to have been controlled by features other than heat, suggesting that further work might define some large-scale structural control.

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OBITUARY

Yang Zunyi, 1908–2009

Dr Yang Zunyi, a member of the Communist Party of China and activist of the Central Committee of the Jiu San Society, a prominent geologist and educator, and academician of China Academy of Sciences, died of illness in Beijing at 12.38 am, 17 September 2009. He was 101.

Dr Yang, a professor of China University of Geosciences, was the founder of Chinese paleontology and stratigraphy, and was one of the pioneers of China's undertaking in stratigraphy and paleontology and geological education. Dr Yang graduated from Tshinghua University and then went to Yale University, from which he graduated with PhD degree. In 1952, he was one of the people responsible for preparing the construction of Beijing College of Geology. He taught there for the rest of his life.

Dr Yang engaged in geological education and research for more than 70 years, with a deep love of our country, sense of innovation, devotion of spirit and willingness to help others. He fostered many talents for China. He also served as a member of the editorial committee of *Acta Geologica Sinica* (English edition) for many years. He made a distinguished contribution to China's geological education and research, and won widespread approbation and respect in geological communities due to his profound knowledge, innovative mind, noble morality and excellent personality.

The passing away of Dr Yang Zunyi is a huge loss to the cause of Chinese geology, education, science and technology, as well as to China University of Geosciences and *Acta Geologica Sinica* (English edition). His noble sentiment and moral demeanor is the treasure he left to us.

Eternal glory to Dr Yang Zunyi!
23 September 2009