Oxygen isotope analysis of mineralized fault planes, Five Springs region, Bighorn Mountains, Wyoming

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INTRODUCTION

Laramide uplifts juxtapose old basement rock against sedimentary cover rocks across thrust faults with a significant vertical component. They are common throughout the Rocky Mountain foreland, and the structural evolution of many of the basement block uplifts has been extensively studied (Snoke, 1997; Narr, 1993; Spang and Evans, 1988). However, the detailed timing and uplift history, thermal evolution, and the role of fluids during faulting of these ranges remain to be determined. The Bighorn Mountains of northern central Wyoming form a Laramide basement-cored uplift, and offer an ideal location to investigate the details of fluid circulation along faults. The Five Springs fault zone (Figure 1), a structurally well-studied section along the northwest flank of the Bighorn Mountains (Wise and Obi, 1992), has mineralization along minor fault planes that indicates the presence of fluids related to faulting. In this study, using laser-based micro-analytical techniques, _^{18}O values of quartz, feldspar, and epidote grains were measured to investigate the fluids involved in the faulting. The temperatures calculated from _^{18}O fractionations are hotter than expected temperatures for Laramide faulting, prompting one to consider the possibility that mineralization along these fault planes pre-dated the Laramide, or that hot, mid-crustal fluids played a role in Laramide deformation.

GEOLOGIC SETTING AND BACKGROUND

In their structural review of the Five Springs area, Wise and Obi (1992) examined a section of pervasively faulted granite where continuous exposures of the fault system bounding the Bighorn uplift are exposed in new road-cuts along Wyoming Highway Alternate 14 (figure 1). They divided the structural profile into three differentially rotated basement blocks separated by shattered zones of poor exposure. Within each of these blocks, they characterized three populations of minor faults: (1) an early set characterized by polish or smearing of hematite, epidote and/or chlorite (Smeared HEC), (2) an intermediate set with similar mineralization, but no smear or polish (Unsmeared HEC), and (3) a young set of faults marked by gouge and pervasive shattering. In this study, the first two were combined, as they were indistinguishable along the study traverse.

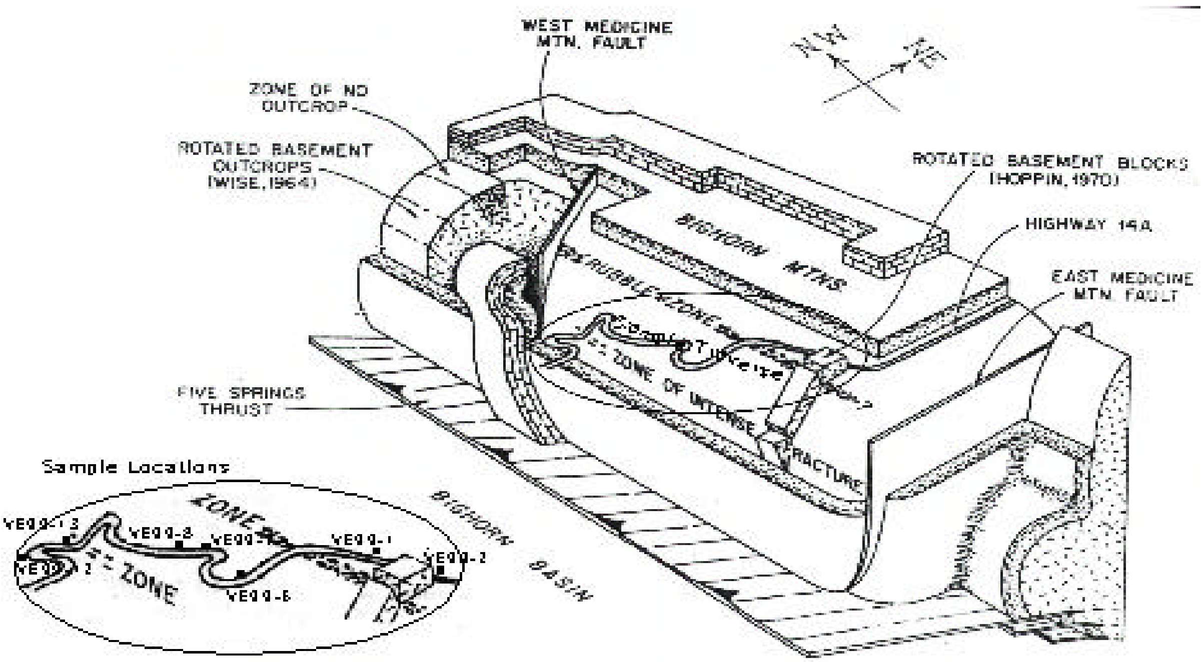

Figure 1. Diagram showing sample locations (after Wise and Obi, 1992).
Samples collected from all three rotated basement blocks in the hanging wall of the Five Springs thrust.

The mineral precipitation on the fault planes is a sign of fluid circulation during fault movement. Thus, oxygen isotope ratios from these minerals can be used to constrain the temperature and source of fluids. Oxygen isotope ratios have been successfully used to determine temperatures associated with detachment faulting in metamorphic core complexes (Morrison and Anderson, 1998), and to show interaction between rocks and meteoric ground water in various localities (Taylor, 1990; Perfit and Lawrence, 1979; Taylor, 1971; Taylor, 1968). These methods of oxygen isotope thermometry and the interpretations of the fluid source can be applied to the Five Springs fault zone to gain a greater understanding of the temperature and composition of fluids involved in faulting there.

METHODS

Study samples represent material from striated HEC mineralized faults and younger gouge and shatter faults (Table 1). Samples were collected from all three of the rotated blocks along the roadcuts of highway 14A. Each block is penetrated by shear fractures and striated minor fault planes. Smeared HEC samples were chosen based on abundance of fluid-derived minerals, such as epidote, whereas gouge and shatter fault samples were chosen for a relative abundance of quartz and feldspar, and the presence of epidote or sericitic alteration of plagioclase, as a sign of fluid alteration. In all cases, care was taken to sample as close to a particular fault plane as possible. In order to compare the _^{18}O fractionations of minerals in rock unaffected by fluid circulation to those from the fault zone, a sample of undeformed granite taken from several kilometers away from the faulted area was also chosen in addition to the samples collected from the Five Springs site.

Oxygen isotope analysis was performed at the California Institute of Technology in the lab of John Eiler. Samples were crushed, taking care that the crush contained material from within 5 cm of the fault plane. Large, inclusion-free mineral grains were selected for analysis. Although this technique caused fine-scale textural relations to be lost, several grains of each mineral were picked, and because fluid alteration is assumed to have pervaded a 5 cm zone around the fault surface, the values of _^{18}O should represent material affected by fault-related fluids.

RESULTS

Measured values of _^{18}O were tabulated (Table 1) and converted for temperature based on the calibration of Matthews (1994). Plagioclase and quartz _^{18}O values form a relatively tight cluster (Figure 2), their fractionation values (_ $_{qtz\text{-}fsp}$ = _$^{18}O_{qtz}$ – _$^{18}O_{fsp}$) ranging from approximately 1-2.5 per mil. Because equilibrium temperatures of oxygen isotope exchange are inversely related to fractionation, temperatures corresponding to these fractionations range from

Temperature Conversions								T ºC* (Qz-Ep)	T ºC* (Qz-Fsp)
Sample #	Location	Type of Fault	δ^{18}O Qtz	δ^{18}O Fsp	δ^{18}O Ep	$\Delta_{(Qtz-Fsp)}$	$\Delta_{(Qz-Ep)}$	Al/Fe $^{3+}$ = .284	An=0.0109
99PRBH22	Away from Fault	none	8.47	6.24		2.24			275
VE99-1	Top block	HEC	8.02	7.00		1.02			470
VE99-2	Top block	HEC	8.66	6.19	4.60	2.46	4.06	465	253
VE99-6	Middle Block	Gouge/Shatter	8.11	6.23		1.88			316
VE99-7	Middle Block	HEC	8.37	7.04	3.62	1.33	4.74	410	402
VE99-8	Middle Block	HEC	7.73	6.50		1.23			423
VE99-11	Bottom Block	HEC		6.83	3.60				
VE99-12	Bottom Block	HEC	8.49	7.34		1.15			440
VE99-13	Bottom Block	Gouge/Shatter	8.65	6.89		1.76			332

Table 1. Oxygen isotopic compositions of mineralized fault plane samples from the Five Springs and Shell Canyon regions. Analytical uncertainties are approximately ± .05‰.
*Calculated on the basis of Matthews (1994), using an Al/Fe3+ ratio of .284, and feldspar composition of An .0109. Al/Fe ratio and An composition determined by electron microprobe composition analysis at Amherst College by Peter Crowley

approximately 470 to 250 ^{o}C. For two samples, VE99-2 and VE99-7, the oxygen isotope ratiof epidote was also measured. The quartz-epidote fractionations of these samples yielded temperatures of 465 and 410 ^{o}C, respectively.

In order to calculate meaningful temperatures from fractionation values, oxygen isotope exchange between the two minerals must reach equilibrium. In this experiment, equilibrium can be inferred several ways. Quartz-feldspar fractionation values >2.5‰ or <1.0‰ indicate disequilibrium or partial exchange with an anomalously high or low _^{18}O fluid (Taylor 1990), due to the much faster $^{18}O/^{16}O$ exchange rate of feldspar relative to quartz. Taylor (1968) notes that "normal" igneous rocks (unaltered by foreign materials such as low _^{18}O meteoric water) all have _^{18}O values of quartz and feldspar between 5.5‰ and 10.0‰. The 99PRBH22 "control" sample shows a typical fresh magmatic intrusive partitioning signature, while the Five Springs samples reflect a small shift toward heavier oxygen. Since the measured oxygen isotope ratios from the Five Springs samples are still within the range of "normal" igneous values, and quartz-feldspar fractionations from Five Springs fall within the equilibrium range, oxygen isotope equilibration with a mid-crustal fluid can be assumed. Also, if quartz-epidote fractionations yield equilibrium temperatures roughly equivalent to those given by the quartz-feldspar fractionations, this provides strong evidence for equilibrium exchange. In sample VE99-7, the

_ $_{qtz-fsp}$ temperature calculated differs from the _ $_{qtz-ep}$ by only 8ºC. Sample VE99-2 is less well behaved, the two calculated temperatures differing by over 200º C. However, the epidote measured from sample VE99-2 contained abundant inclusions, and thus the calculated temperature may be an incorrect evaluation of equilibrium temperature.

With the exception of sample VE99-2, the samples from “smeared HEC” faults plot along a line with a slope of one, (i.e. a line of constant temperature) corresponding to the 425ºC isotherm (Figure 2). Due to inclusions in the feldspar and epidote grains, VE99-2 apparently reflects unreliable isotopic ratio values. The samples of gouge and shatter faults also plot along an isotherm, but of considerably lower temperature, closer to 325ºC. All these values are higher than the control sample from near the Five Springs region, sample 99PRBH22, which yielded a temperature of 275ºC.

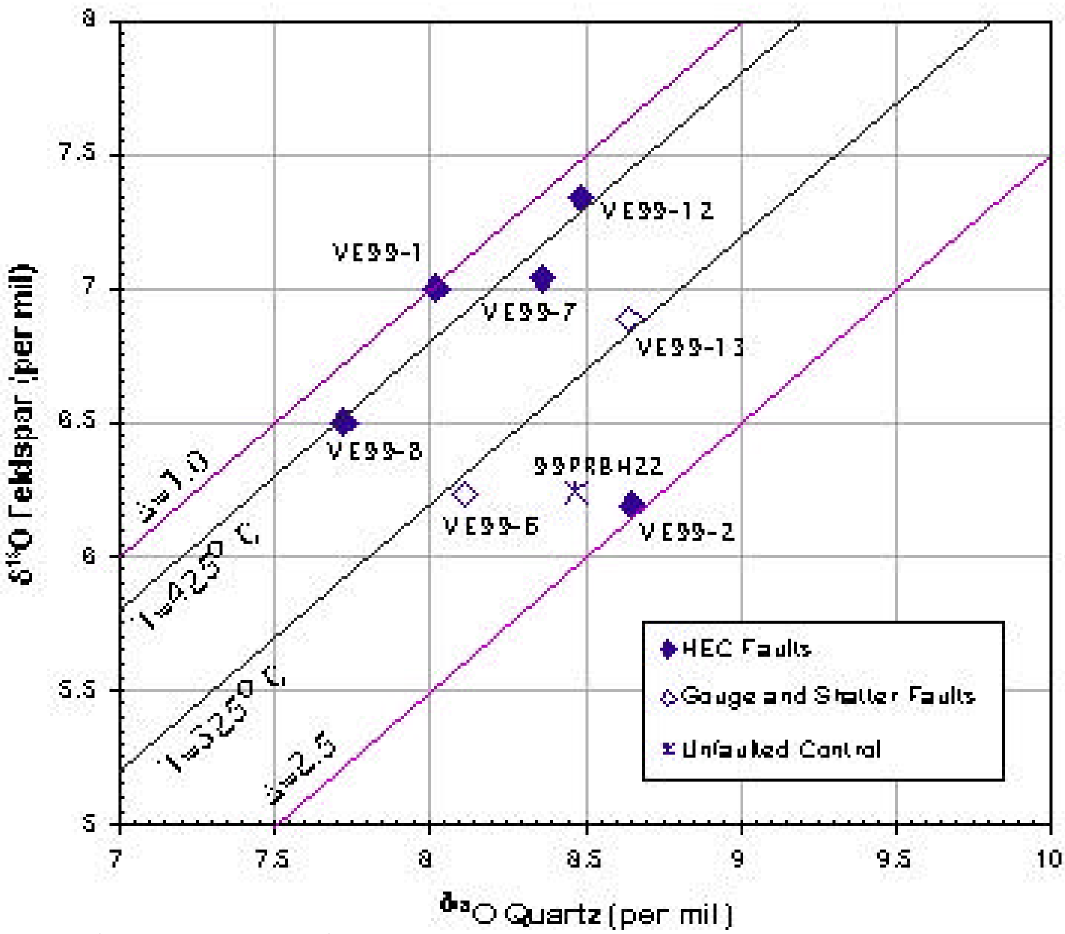

Figure 2. Quartz $\delta^{18}O$ values versus feldspar $\delta^{18}O$ values for coexisting pairs from fault plane samples. Temperatures corresponding to lines of constant $\Delta_{qtz-fsp}$ were calculated using Matthews (1994). The data are interpreted to indicate equilibration between quartz and feldspar during an early faulting event that involved fluids at ~425º followed by a second event with ~325ºC fluids.

DISCUSSION

Based on deformation textures, Wise and Obi (1992) interpreted three generations of faults in the Five Springs area: (smeared HEC, unsmeared HEC, and gouge/shatter faults). Our observations, as well as those of Wise and Obi (1992), clearly show that the gouge and shatter faults cross-cut the HEC faults, and are therefore younger. The oxygen isotope data support this interpretation in that the HEC faults exhibit oxygen isotope equilibration temperatures near 425^{o}C, whereas the gouge and shatter faults fall along a 325^{o}C isotherm. This is a logical difference, as higher temperatures are expected of fault zones enabling the smearing out of minerals, as compared to zones of cataclasis. Thus, combined with the isotope equilibration temperatures, a thermal progression can be interpreted. The older HEC mineralized faults slipped at higher temperatures, then, once initial uplift had been accomplished it was followed by lower-temperature, more brittle failure of the gouge and shatter faults.

The calculated equilibrium temperatures (Table 1) pose an interesting problem. Temperatures of Laramide thrusting have been calculated and assumed to be near 150^{o}C (Warnock and Van de Kamp, 1999; Mitra and Frost, 1981), whereas the values obtained in this study were substantially higher than this, ranging from ~315-470^{o}C. Several possibilities can explain this discrepancy. If one accepts that Laramide age of the faults and mineralization (as suggested by Wise and Obi, 1992; Hoppin 1970), faulting must have involved circulation of hot, deep, mid-crustal silica-equilibrated fluids. Although there is no evidence of magmatism associated with the Laramide uplift of the Bighorns between ~66-58 Ma (Gries, 1983), other ranges in Wyoming contain igneous rocks which may have formed contemporaneously. The igneous rocks of the Black Hills, Rattlesnake Hills, and the Absaroka volcanic province are remnants of magmatism in this area extending from ~62-38 Ma (Snoke, 1997). Thus, it is possible that early magmatic circulation caused a thermal anomaly, which produced extremely hot fluids to lubricate the Five Springs fault zone.

Another possibility to explain the temperature discrepancy is the timing of the mineralization. Similar mineralized faults, (chlorite, actinolite, epidote) in the Wind River Ranges have been assigned a late Precambrian age (Mitra and Frost, 1981). Mitra and Frost argued this age determination based on the temperature of mineralization (greenschist facies) which they said was too high to have occurred during the Laramide, and that mineralized faults were only observed to displace late Precambrian or older rocks. It’s feasible that the Five Springs HEC faults, and the mineralized Wind River faults are of late Precambrian age and represent segments of a regional system of basement structures reactivated during the Laramide orogeny. Mineralization at moderate temperatures would then have predated the Laramide structural event. However, the younger gouge and shatter faults, which are unquestionably of Laramide age (Mitra and Frost, 1981, Narr, 1990, Wise and Obi, 1992), also exhibit temperatures of oxygen isotope equilibration higher than proposed for Laramide conditions. Thus, instead of assigning a late Precambrian age to explain the elevated mineralization temperatures, factors causing high temperature fluid circulation during the Laramide should be examined.

CONCLUSION

The oxygen isotope ratios from the Five Springs region of the Bighorn Mountains indicate two phases of faulting in the region; an older, hotter episode producing fault planes coated with smeared out hematite, epidote, and chlorite, and a younger, cooler phase characterized by gouge and shatter faults. The _^{18}O ratios show low quartz-feldspar fractionations, corresponding to relatively high equilibrium temperatures. These temperatures, ranging from roughly 325-425^{o}C, are significantly hotter than proposed temperatures of

Laramide-age faulting elsewhere, usually thought to be around 150º. This study thus proposes that mineralization along fault planes during Laramide events took place as a result of circulation of hot, mid-crustal fluids. Where these fluids came from, and why they accompanied the Laramide orogeny in this area is a question that still needs to be addressed. Perhaps flat slab subduction caused partial melting, leading to fluid circulation in the continental interior. These and other questions need to be considered, through more detailed studies of this phenomena. One way further studies could address these issues is by looking at fluid inclusions in quartz, which provide reliable temperature indicators. If other Laramide ranges exhibit isotope data reflecting these high temperatures of faulting, perhaps more a more complete picture can be drawn of how these large basement blocks were fractured and uplifted millions of years ago.

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