Oxygen isotope trends of granitic magmatism in the Great Basin: Location of the Precambrian craton boundary as reflected in zircons

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ABSTRACT

The $\delta^{18}O$ values of magmas in the Great Basin help to decipher the tectonic assembly of North America and to determine the magmatic source and potentially the composition of the crust at depth. Igneous zircons from Precambrian, Jurassic, Cretaceous, and Tertiary intrusive bodies of the northern Great Basin best preserve the record of magmatic oxygen isotope ratios. The variation of $\delta^{18}O$ values in zircon with age reconciles previous differences in interpretation based on $\delta^{18}O_{WR}$ and radiogenic isotope data. The new $\delta^{18}O_{Zrc}$ data support the results of previous radiogenic isotope studies documenting the increased availability of crustal and sedimentary components to magmas in the Cretaceous during the Sevier orogeny and a return to a larger proportion of mantle-derived components in the Tertiary during Basin and Range extension.

In the Great Basin, $\delta^{18}O_{Zrc}$ values also vary systematically with crustal structure as determined by radiogenic isotope systematics. Plutons emplaced east of the $^{87}Sr/^{86}Sr_i$ = 0.706 isopleth have higher $\delta^{18}O_{Zrc}$ values than plutons intruded west of the 0.706 line. However, analyses of $\delta^{18}O$ values in quartz do not show the bimodal distinction across the 0.706 line owing to subsolidus alteration. On the basis of $\delta^{18}O_{Zrc}$, plutons intruding the Walker Lane belt are indistinguishable from other plutons emplaced west of the 0.706 line despite significant tectonic displacement and rotation of the belt.

The difference in $\delta^{18}O$ values across the 0.706 line reflects the involvement of high-$\delta^{18}O$ Precambrian and Paleozoic sedimentary rocks of the continental margin and Precambrian craton in magmas intruded east of the 0.706 line, whereas magmas west of the 0.706 line are dominated by lower-$\delta^{18}O$ rocks derived from juvenile volcanic arcs. Crustal boundaries and discontinuities in the Great Basin determined by radiogenic isotope systems agree with discontinuities observed in $\delta^{18}O_{Zrc}$ values; this agreement indicates that the 0.706 line marks a geochronologic and compositional discontinuity in the basement rocks.

Keywords: Great Basin, oxygen isotopes, zircon, terrane boundaries.

INTRODUCTION

The Great Basin of northern Nevada and Utah has undergone extensive tectonic activity since the middle Paleozoic. Abundant magmatism throughout the Great Basin's history documents the variability in thickness and age of the continental crust through which plutons have ascended. The location of the western edge of Precambrian crystalline basement has been the topic of many isotopic studies, yet there is still disagreement as to the placement of this crustal boundary (Kistler and Peterman, 1973, 1978; Zartman, 1974; Lee et al., 1981; Farmer and DePaolo, 1983; Solomon and Taylor, 1989; Barton, 1990; Elison et al., 1990; Wright and Wooden, 1991; Elison, 1995). The $^{87}Sr/^{86}Sr_i$ = 0.706 isopleth (where $^{87}Sr/^{86}Sr_i$ is the initial Sr isotope ratio of the plutonic rocks) defined by Kistler and Peterman (1973, 1978), commonly known as the 0.706 line, has been interpreted to mark the transition from continentally derived rocks on the east to volcanic-arc–derived rocks on the west (Kistler and Peterman, 1973, 1978; Farmer and DePaolo, 1983; Elison et al., 1990). Kistler and Peterman (1973) interpreted the 0.706 line as the western edge of the Precambrian crystalline basement (Fig. 1A). Further work by Farmer and DePaolo (1983), however, has defined the edge of the crystalline basement farther to the east at the $\varepsilon_{Nd} = -7$ line, which coincides with the $^{87}Sr/^{86}Sr_i$ = 0.708 (Fig. 1A). The zone between the western edge of the crystalline basement ($^{87}Sr/^{86}Sr_i$ = 0.708) and the western edge of the continentally derived sedimentary rocks ($^{87}Sr/^{86}Sr_i$ = 0.706) is a transition zone containing continentally derived sedimentary rocks, the thickness of which generally increases westward to the 0.706 line; west of that line, the thickness of arc-derived rocks increases (Fig. 2).

Solomon and Taylor (1989) interpreted whole-rock (WR) $\delta^{18}O$ values of felsic igneous rocks to place the craton edge even farther east, along their eastern zone/central zone boundary in Utah (Fig. 1B). The $\delta^{18}O_{WR}$ values range from 7‰ to 9‰ in their eastern zone and 9‰ to 13‰ in the central zone (Sol-

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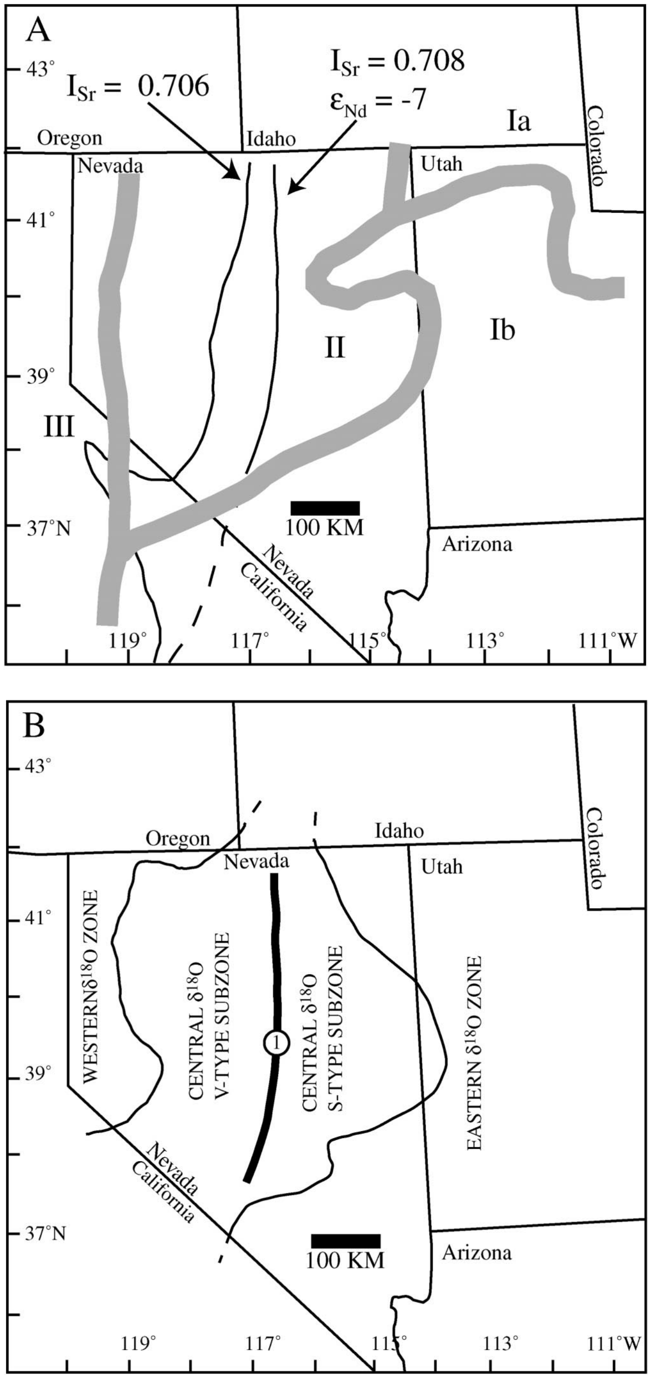

Figure 1. Simplified map of isotopic discontinuities in the western United States. (A) The $^{87}Sr/^{86}Sr_i$ (I_{Sr}) = 0.706 and 0.708 lines of Kistler and Peterman (1973) as labeled. The $\varepsilon_{Nd} = -7$ of Farmer and DePaolo (1983) is coincident with the 0.708 line. The thick, gray lines denote the boundaries of the Pb isotope zones Ia, Ib, II, and III of Zartman (1974). The area between the 0.706 and 0.708 lines is the transition zone between continentally derived rocks and arc-derived rocks. (B) The boundaries of the oxygen isotope zones defined by Solomon and Taylor (1989) on the basis of whole-rock analyses. The line labeled 1 is the $\varepsilon_{Nd} = -7$ line from A. The $\delta^{18}O_{WR}$ values of the western zone range from 6‰ to 8.5‰, those of the central zone range from 9‰ to 13‰, and those of the eastern zone range from 7‰ to 9‰. Modified from Farmer and DePaolo (1983) and Solomon (1989).

omon and Taylor, 1989). The presence of high $\delta^{18}O_{WR}$ values in eastern Nevada and western Utah is interpreted as requiring a primarily sedimentary magma source; therefore Solomon and Taylor (1989) suggested that the Precambrian craton basement is located significantly farther east than radiogenic studies indicate. The $\delta^{18}O_{WR}$ data indicate unaltered accreted volcanic-arc rocks at depth in the crust in the western zone ($\delta^{18}O_{WR}$ = 6‰ to 8.5‰) (Fig. 1B). Additional isotopic and stratigraphic studies (i.e., Barton, 1990; Elison et al., 1990) have agreed more with the Farmer and DePaolo (1983) and Kistler and Peterman (1973) crustal boundaries than with the stable isotope boundaries of Solomon and Taylor (1989).

This study investigates oxygen isotope ratios of magmatic zircons across the northern Great Basin to address the tectonic evolution of the crust in the region as reflected in igneous rocks and the disagreement between crustal boundaries delineated by previous stable and radiogenic isotope studies. Zircon oxygen isotope analyses have successfully been used to determine crustal structure and magmatic evolution in numerous studies of igneous and metamorphic rocks from a variety of geologic settings (King et al., 1998, 2002; Bindeman and Valley, 2000, 2003; Peck et al., 2000, 2001; King and Valley, 2001; Valley et al., 2002, Valley, 2003).

Zircon is a common trace mineral in granitic magmas and can preserve oxygen isotope ratios representative of magmatic conditions even after geologic events that alter oxygen isotope ratios of many other rock-forming minerals (see Valley, 2003). Such geologic events include hydrothermal alteration (Valley and Graham, 1996; King et al., 1997, 2000; Monani and Valley, 2001) and high-grade regional metamorphism (Valley et al., 1994; Peck et al., 2000, 2003). Even if rocks are relatively unaltered and undeformed, exchange of oxygen isotopes can still occur in a rock by volume diffusion between minerals during cooling (Eiler et al., 1992). Slow diffusion rates of oxygen through the zircon lattice and high closure temperature relative to most other minerals makes zircon an ideal mineral to preserve magmatic $\delta^{18}O$ values (Dodson, 1973; Watson and Cherniak, 1997; Peck et al., 2003; Valley, 2003). Plutons in regional studies such as this, can be subject to variable cooling rates, alteration, and tectonic histories. As a result, correlations based on quartz and whole-rock stable isotope analyses may not accurately represent the magmatic values that are evident with analyses of $\delta^{18}O$ in zircon.

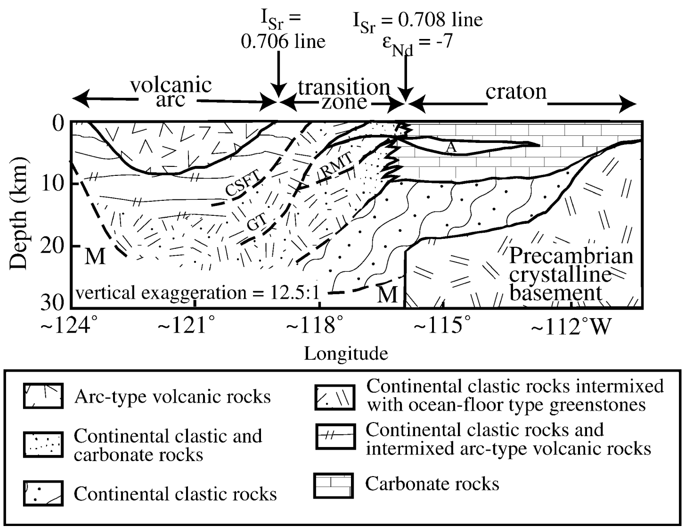

Figure 2. Simplified, interpretive cross section of the Great Basin, western United States, before the Jurassic. RMT—Roberts Mountains Thrust; GT—Golconda Thrust; CSFT—Calaveras-Shoofly Thrust; A—Antler flysch; M—mantle. The edge of the Precambrian crystalline basement is located at the $\varepsilon_{Nd} = -7$ line of Farmer and DePaolo (1983). The western edge of the transition zone is located approximately at the 0.706 line of Kistler and Peterman (1978). Figure of modified from Farmer and DePaolo (1983).

REGIONAL GEOLOGY

The Great Basin preserves a full record of pre-Cenozoic tectonic activity along the continental margin of North America. Shelf sedimentation was continuous from the Precambrian through the Triassic; the thickness of sedimentary rocks exceeds 15 km in eastern Nevada and thins eastward toward the craton (Gans and Miller, 1983; Miller et al., 1988). Passive-margin sedimentation along the western edge of the North American continent was disrupted by two collisional events prior to the Mesozoic. During the Late Devonian to Early Mississippian, the Antler orogeny thrust lower Paleozoic sedimentary rocks eastward along the Roberts Mountains Thrust (Figs. 2 and 3) (Speed et al., 1988; Dilek and Moores, 1999). The second collisional event was the Sonoma orogeny during the Permian–Triassic when the Golconda allochthon was thrust along the Golconda Thrust over the Roberts Mountains allochthon.

During the Middle to Late Triassic, active-margin tectonic activity began again along the western edge of the North American continent, as indicated by the igneous rocks in the Great Basin, perhaps due to a subduction zone dipping eastward at the western margin of the continent (Saleeby et al., 1992). The western Great Basin was subjected to crustal shortening during the Jurassic (between 200 and 150 Ma) (Wyld and Wright [2001] and the references therein). A second middle Mesozoic compressional event occurred primarily in the eastern and central Great Basin with the onset of contractional deformation associated with the Sevier orogeny. This orogeny is marked by ~50% crustal thickening and eastward thrusting along the Sevier Thrust belt (Fig. 3) from the late Early Cretaceous to the early Tertiary; the maximum intensity occurred at ca. 100–90 Ma (Armstrong, 1968; Stewart, 1980; Allmendinger and Jordan, 1981; Allmendinger, 1992; Wyld and Wright, 2001). After crustal thickening during the Sevier orogeny, extension began during the Oligocene and continued through the Miocene (Wernicke, 1992) along low-angle detachment faults throughout much of the Great Basin. Extension averaged 40% across the region but is highly variable, reaching ~250% in the eastern Great Basin (Gans and Miller, 1983; Coney and Harms, 1984; Miller et al., 1988). This extension was oriented east-west with little or no rotation.

The Walker Lane belt of the western Great Basin (Fig. 3) has undergone more complex tectonic activity than the simple east-west contraction and extension that affected the majority of the Great Basin. The Walker Lane belt is a northwest-trending zone ~700 km long and 100–300 km wide in western Nevada and eastern California (Fig. 3). The belt contains complex dextral strike-slip faults along which Mesozoic and Cenozoic offset has occurred (Stewart, 1988; Schweickert and Lahren, 1990; Wyld and Wright, 2001).The Walker Lane belt currently accommodates 1.1 ± 0.1 cm/yr of right-lateral slip between the stable craton to the east and the Sierra Nevada to the west (Argus and Gordon, 1991).

Magmatism in the Great Basin has occurred primarily during three intervals, not including the subduction-related magmatism in the Triassic on the far western edge of the Great Basin. The first pulse of igneous activity was during the Middle Jurassic–Early Cretaceous (ca. 170–100 Ma) preceding the Sevier orogeny (Wright and Wooden, 1991). Late Cretaceous (ca. 83–75 Ma) magmatism occurred during the Sevier orogeny. This period of magmatism abruptly shifted to the east with changes in the angle of subduction at the onset of the Laramide orogeny (Barton, 1990). Another magmatic pulse during the Cenozoic (ca. 39–20 Ma) was concurrent with the onset of Basin and Range extension.

PREVIOUS ISOTOPE STUDIES

Previous regional isotope studies focused on correlations between geographic location and isotopic composition. Zartman (1974) analyzed Pb isotopes in Mesozoic and Cenozoic igneous rocks in the Great Basin and defined three isotope provinces from east to west: (Ia) contains Pb derived from Archean basement rocks; (Ib) contains Pb isotope ratios indicative of Proterozoic basement rocks; (II) contains Pb isotope ratios indicative of sedimentary rocks derived from the Precambrian craton; (III) contains Pb derived from younger arc-derived igneous and sedimentary rocks (Fig. 1A). Kistler and Peterman (1973, 1978) identified a boundary between different crustal domains based on the $^{87}Sr/^{86}Sr_i$ (i.e., the 0.706 line) (Fig. 1A) in central Nevada, which they interpreted as the western edge of the Precambrian continental crust.

Farmer and DePaolo (1983) coupled Nd and Sr isotopes to map the crustal structure of the Great Basin. A Nd isotope discontinuity ($\varepsilon_{Nd} = -7$) (Fig. 1A), interpreted as the edge of the Precambrian crystalline basement, lies along the Sr isotope discontinuity shown by the initial $^{87}Sr/^{86}Sr = 0.708$ isopleth, slightly east of the originally suggested boundary delineated by initial $^{87}Sr/^{86}Sr = 0.706$ (Kistler and Peterman, 1973, 1978). The Nd isotope discontinuity coincides roughly with the Roberts Mountains Thrust (Fig. 3). The edge of the Precambrian crystalline basement occurs ~200 km west of a Sr isotope discontinuity that is interpreted as the boundary between Rb-depleted lower crust to the east and undepleted lower crust to the west (Farmer and

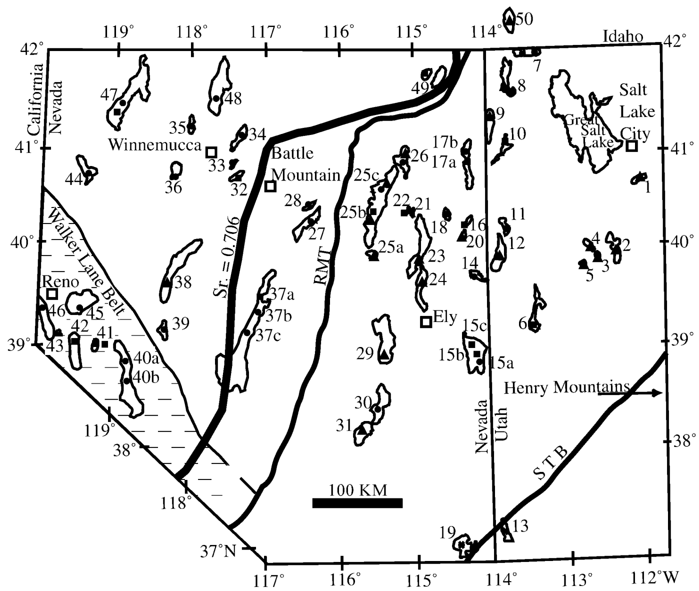

Figure 3. Simplified map of the northern Great Basin, western United States, showing the outlines of mountain ranges sampled in this study. Sample locations and map numbers correspond to sample descriptions in Table DR1 (see footnote 1 in text). The 0.706 line is from Kistler and Peterman (1978); the Walker Lane belt is from Stewart (1988). RMT—Roberts Mountains thrust; STB—Sevier Thrust belt. Solid symbols for ages of igneous rocks sampled: triangles—Tertiary; circles—Cretaceous; squares—Jurassic; stars—Precambrian. Open squares—city and town locations.

DePaolo, 1983). The zone between the 0.708 and 0.706 lines was interpreted by Farmer and DePaolo (1983) as a transition zone across which the thickness of continentally derived sediment increases westward. The western edge of the transition zone, which correlates with the 0.706 line, was interpreted by Farmer and DePaolo (1983) to indicate the increase of volcanic-arc–related rocks in the crust. Stratigraphic and structural analyses of sedimentary rocks of the Great Basin also place the transition from continentally derived sedimentary rocks to volcanic-arc–derived sedimentary rocks at the 0.706 line (Elison et al., 1990).

Solomon and Taylor (1989) measured the $\delta^{18}O_{WR}$ values of plutons in the Great Basin, and from these data they defined three crustal zones that reflect magma sources (Fig. 1B). They proposed on the basis of the whole-rock $\delta^{18}O$ values that the western zone ($\delta^{18}O_{WR}$ = 6‰ to 8.5‰) had an upper-mantle magma source and the eastern zone ($\delta^{18}O_{WR}$ = 7‰ to 9‰) had a magma source from Precambrian continental crust. The central zone is transitional and divided into two subzones: the western part had a magma source influenced by volcanogenic accreted terranes (V-type), and the eastern part had $\delta^{18}O$ values indicative of a Precambrian metasedimentary magma source (i.e., S-type) (Solomon and Taylor, 1989). Both the V-type and S-type central zones have $\delta^{18}O_{WR}$ values from 9‰ to 13‰, and the division between the subzones is based on the location of the 0.706 line. There is very little variation in the $\delta^{18}O_{WR}$ values of plutons on either side of the 0.706 line within the central zone.

Crustal zones defined previously on the basis of oxygen isotope ratios do not correspond with crustal structure interpreted from radiogenic isotope data. The central zone of Solomon and Taylor (1989)—the transition zone between continentally derived magmas and arc-derived magmas—is significantly wider than the radiogenic transition zone between the 0.708 and 0.706 lines (Farmer and DePaolo, 1983). The division of subzones in the central zone is based on Sr isotope data modified by the interpretation that the $\delta^{18}O$ component was derived from volcanic-arc–related rocks at depth for the V-type central zone and from continentally derived sedimentary rocks at depth for the S-type central zone. On the basis of high-$\delta^{18}O_{WR}$ plutons in eastern Nevada and western Utah, Solomon and Taylor (1989) also placed the western edge of the craton farther east than the $\varepsilon_{Nd} = -7$ discontinuity and closer to the Sr discontinuity indicating the western edge of the Rb-depleted lower crust.

Additional isotopic studies have focused more closely on crustal evolution in the Great Basin with respect to age rather than geographic distribution. Barton (1990) documented an increase of crustal input into granitic magmas during the Cretaceous as represented by increased $^{87}Sr/^{86}Sr_i$ ratios, increased $\delta^{18}O$ values, a transition from metaluminous to peraluminous magmatism, and decreased ε_{Nd}. Wright and Wooden (1991) further documented radiogenic isotope trends with age by analyzing Jurassic, Cretaceous, and Cenozoic plutons. Jurassic plutons are dominated by a subcontinental lithospheric mantle component with the addition of a minor crustal component that has primitive Nd and Sr isotope compositions but a high $\delta^{18}O_{WR}$ value (Wright and Wooden, 1991). Cretaceous magmatism in the Great Basin is the result of crustal thickening, and plutons of this age have evolved Sr and Nd isotope ratios that reflect a significant crustal component. Cenozoic magmatism is a mixture of mantle and crustal reservoirs with a significantly increased mantle component compared to Cretaceous plutonism.

SAMPLE LOCATIONS

Granitic rocks throughout northern Utah and Nevada were sampled for this study (see Fig. 3 and Table DR1).[1] In addition, one sample was collected from the Albion Mountains in southern Idaho. The goals of sampling were maximum geographic distribution and variety of age. The general sample locations within mountain ranges with respect to the 0.706 line are shown in Figure 3, and latitude/longitude, rock name, age, isotope data, and geochemistry for the intrusions are given in Table DR1 (see footnote 1). References for the radiogenic isotope data and geochemistry of intrusive samples in this study are shown in Table DR2 (see footnote 1). We analyzed quartz from 124 samples from 47 intrusive bodies and zircon from 139 samples from 42 intrusive bodies. We analyzed quartz and zircon from the same intrusion in a few cases (n = 11) but were not able to analyze any pairs from the same sample because zircon separates came from earlier studies.

Samples from localities 1 through 31 along with 37a, 37b, and 37c (Fig. 3) are located east of the 0.706 line as defined by Kistler and Peterman (1973). Sample localities 32–36 and

[1]GSA Data Repository item 2004046, Data tables with sample location, isotope and geochemical data, age, and references for previously published data included in this study, is available on the Web at http://www.geosociety.org/pubs/ft2004.htm. Requests may also be sent to editing@geosociety.org.

38, 39, 44, 47, 48, and 49 (Fig. 3) are located west of the 0.706 line. Sample localities 40–43, 45, and 46 are located within the Walker Lane belt as delineated by Stewart (1988). The data for samples HIL-1, HIL-10, LC-2, LC-5, LC-9, LC-15, LC-33, LC-34, and NP-1 are from King et al. (2001). Precambrian gneisses are from two different basement provinces. All samples of Precambrian quartz (sample localities 7 and 8) are from the northern Great Basin, and the Precambrian zircon samples (sample localities 13 and 19) are from basement rocks exposed in the southern Great Basin belonging to the Yavapai province. The southern Great Basin zircon samples are the only samples of this study belonging to that southern province.

TABLE 1. SUMMARY OF OXYGEN ISOTOPE RATIOS FOR PLUTONS OF THE GREAT BASIN

	East of the 0.706 line	West of the 0.706 line	Walker Lane belt
Quartz			
Precambrian gneisses	8.55‰ ± 0.41‰ (n = 7)		
Jurassic	10.80‰ ± 0.87‰ (n = 29)	10.22‰ ± 0.76‰ (n = 6)	9.77‰ ± 0.69‰ (n = 4)
Cretaceous	11.54‰ ± 1.19‰ (n = 13)	10.31‰ ± 0.98‰ (n = 17)	9.53‰ ± 0.59‰ (n = 10)
Tertiary	8.76‰ ± 3.19‰ (n = 35)	5.68‰ (n = 1)	
Zircon			
Precambrian gneisses	6.22‰ ± 0.75‰ (n = 12)		
Precambrian pegmatites	7.25‰ ± 1.38‰ (n = 7)		
Jurassic	7.71‰ ± 0.71‰ (n = 24)	5.76‰ ± 0.34‰ (n = 7)	5.48‰ ± 0.27‰/ (n = 4)
Cretaceous	8.24‰ ± 0.85‰ (n = 24)	6.22‰ ± 0.78‰ (n = 12)	5.99‰ ± 0.30‰ (n = 11)
Tertiary	6.41‰ ± 0.90‰ (n = 32)	5.68‰ ± 0.46‰ (n = 9)	

Note: See Table DR1 (see footnote 1 in text) for data.

ANALYTICAL METHODS

Mineral separates were prepared at the University of Wisconsin (by King), Stanford University (by Stockli), and Rice University and Stanford University (by Wright and J.H. Dilles). Zircons were separated from 15 to 20 kg samples by using standard crushing, hydraulic, magnetic, and heavy-liquid techniques. The least magnetic fraction of zircon available was analyzed to limit complications related to alteration that are typically associated with magnetic zircons (Krogh, 1982; Valley et al., 1994).

Mineral separates (quartz, titanite, garnet, and biotite) were obtained from ~0.5 kg samples that were crushed and sieved. All minerals were handpicked under a binocular microscope. Quartz was cleaned in 29*M* hydrofluoric, 12*M* hydrochloric, or 8*M* fluoroboric acid at room temperature to confirm purity prior to final selection.

Oxygen isotope ratios of 1–2 mg mineral separates were analyzed at the University of Wisconsin by laser fluorination (BrF_5) and gas-source mass spectrometry (Valley et al., 1995). The oxygen isotope data are reported in the standard δ notation in per mil (‰) relative to Vienna standard mean ocean water (V-SMOW). Zircon grains were analyzed after powdering in a boron carbide mortar and pestle to avoid any possible grain-size effects during analyses and to maximize the efficiency of fluorination. Quartz grains were analyzed by using rapid heating and a defocused laser beam (Spicuzza et al., 1998).

The UWG-2 garnet standard analyzed on 27 days concurrently with the mineral separates yielded an analytical precision of 0.06‰ (1 standard deviation, n = 91). On several days, daily averages of UWG-2 differed (±0.02‰ to 0.26‰) from the accepted value of 5.80‰ (relative to 9.59‰ for NBS-28). Analyses of unknown samples from these days have been corrected by this small amount as recommended by Valley et al. (1995). The average correction was 0.08‰. The average reproducibility of duplicated zircon and quartz analyses is ±0.05‰ (n = 111) and ±0.16‰ (n = 112), respectively. NBS-28 quartz, analyzed concurrently with quartz samples, yielded a $\delta^{18}O$ value of 9.55‰ ± 0.04‰ (n = 4).

RESULTS

Oxygen isotope ratios of analyzed zircon, quartz, titanite, garnet, and biotite are reported in Table DR1 (see footnote 1). The average $\delta^{18}O$ values for quartz and zircon by age and location are summarized in Table 1. Histograms of quartz analyses are plotted in Figure 4. Histograms of zircon analyses are plotted in Figure 5. The only samples not plotted in Figures 4 and 5 are 99GB–100, 99GB–113, 99GB–114, and 99GB–115 because of poor constraint on the age of the intrusions.

When classified by age, analyses of $\delta^{18}O_{Qtz}$ show significant variation from the Precambrian through the Tertiary. Precambrian $\delta^{18}O_{Qtz}$ values are >2‰ lower than Jurassic $\delta^{18}O_{Qtz}$ values (Figs. 4C, 4D). Cretaceous $\delta^{18}O_{Qtz}$ values have an average near the Jurassic average with no clear distinction between plutons emplaced east or west of the 0.706 line. Tertiary $\delta^{18}O_{Qtz}$ values are significantly lower and more variable than those of Cretaceous samples (Figs. 4A, 4B). The average $\delta^{18}O$ values of quartz from Tertiary plutons reported in Table 1 includes the anomalous Warm Springs granite of the Egan Range (map no. 24, see Fig. 3) with $\delta^{18}O_{Qtz}$ = −7.63‰ ± 0.16‰. The $\delta^{18}O_{Qtz}$ of this sample is not representative of magmatic values. Zircons from this mountain range, however, have $\delta^{18}O$ values typical for Tertiary intrusions in the region (6.78‰), and previous studies have suggested the modification of $\delta^{18}O$ values during Tertiary deformation (Lee et al., 1986). Excluding the anomalous Warm Springs granite, $\delta^{18}O_{Qtz}$ of Tertiary plutons east of the 0.706 line have an average value of 9.24‰ ± 1.45‰ (n = 34).

The $\delta^{18}O_{Zrc}$ values for Precambrian gneisses in the Great Basin are the lowest of all suites analyzed, but almost all are higher than those $\delta^{18}O_{Zrc}$ values from rocks in equilibrium with primitive-mantle–derived magmas ($\delta^{18}O$ = 5.3‰ ± 0.3‰) (Valley et al., 1998) (Fig. 5D). Jurassic $\delta^{18}O_{Zrc}$ values are nearly 1.5‰ higher than Precambrian gneisses. Jurassic plutons emplaced in the Walker Lane belt and west of the 0.706 line have distinctly lower $\delta^{18}O$ values than plutons intruded east of the 0.706 line (Fig. 5C). The $\delta^{18}O_{Zrc}$ values of Cretaceous plutons are similar to Jurassic $\delta^{18}O_{Zrc}$ values, but the highest measured $\delta^{18}O_{Zrc}$ values in the Great Basin are from Cretaceous rocks. The $\delta^{18}O_{Zrc}$ values for Cretaceous plutons are bimodal; plutons emplaced east of the 0.706 line have distinctly higher $\delta^{18}O_{Zrc}$ than those emplaced west of the 0.706 line or in the Walker Lane belt. Tertiary plutons have a significantly lower average $\delta^{18}O_{Zrc}$ value than Cretaceous plutons (Figs. 5A, 5B). The Tertiary sample west of the 0.706 line with the highest $\delta^{18}O_{Zrc}$ value is from the Job Canyon Pass Tuff of the Stillwater Range ($\delta^{18}O$ = 6.55, map loc. 38, see Fig. 3).

Trends observed with $\delta^{18}O_{Zrc}$ roughly correlate with trends in molar $Al_2O_3/(CaO + Na_2O + K_2O)$ (A/CNK; Fig. 6). Overall, increasing $\delta^{18}O_{Zrc}$ coincides with increasing molar A/CNK, indicating a larger proportion of high-$\delta^{18}O$ peraluminous crustal rocks incorporated into these magmas. Cretaceous plutons, intruded into the thickened crust of the Sevier orogen, are typically peraluminous with high $\delta^{18}O_{Zrc}$ values. Tertiary plutons generated during Basin and Range extension tend to be metaluminous, although some samples are peraluminous, and again are notable in the typically low $\delta^{18}O_{Zrc}$ values compared to plutons of other ages.

Four plutons were analyzed for variations

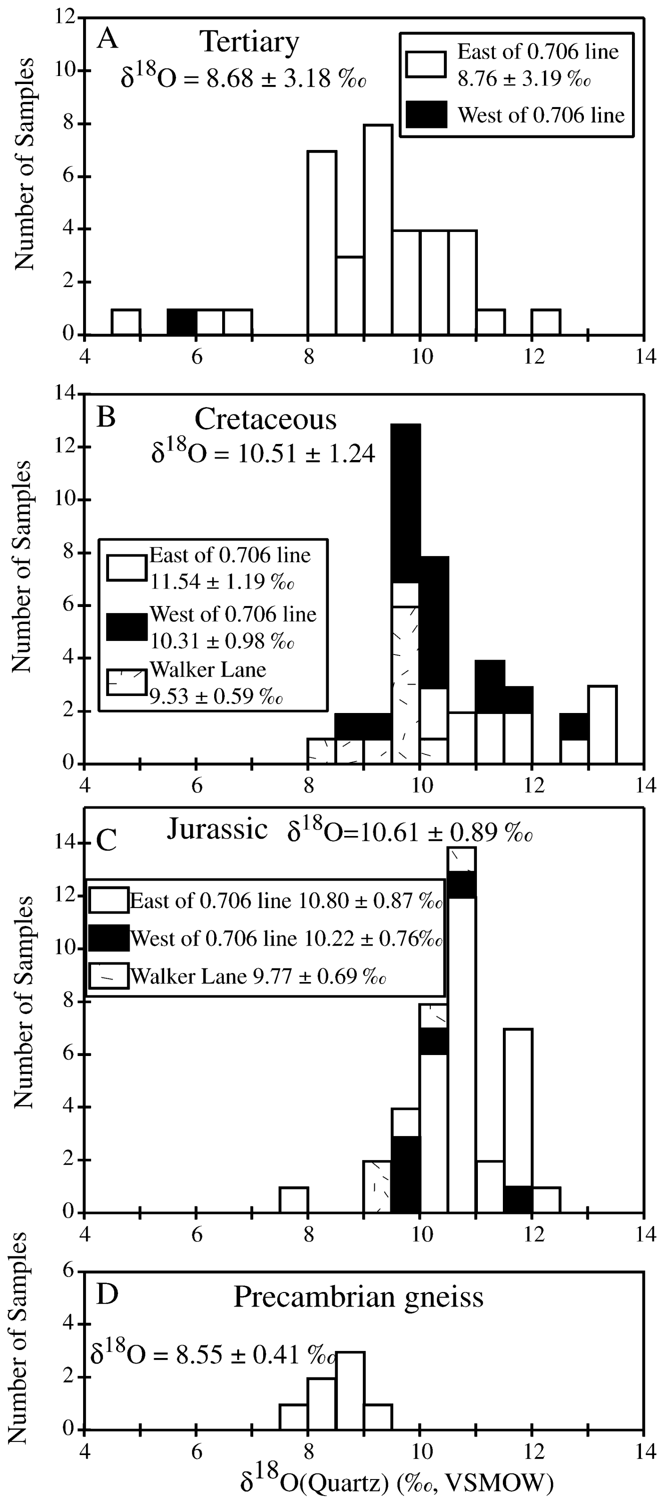

Figure 4. Histogram of average $\delta^{18}O$ values for quartz from granitic rocks of the Great Basin. Note there is no significant difference in $\delta^{18}O$ values between Cretaceous quartz from plutons intruding east or west of the 0.706 line. Cretaceous and Tertiary values are not markedly different. Alteration of quartz after crystallization may have changed magmatic $\delta^{18}O$ values and obscured information about the composition of the magmatic source or crust at depth.

in magmatic $\delta^{18}O$ values vs. elevation (Little Cottonwood stock, map loc. 1, 1801 m relief; Austin pluton, map loc. 37a, 400 m relief; IXL Canyon pluton, map loc. 38, 644 m relief; Bald Mountain, map loc. 40a, 1435 m relief). There is no consistent increase or decrease of $\delta^{18}O_{Zrc}$ with increased elevation. The respective magma chambers were homogeneous in magmatic $\delta^{18}O$ values on the basis of the zircon analyses of this study.

DISCUSSION

Alteration of Quartz and Whole-rock Oxygen Isotope Ratios

The refractory nature, high closure temperature, and slow rates of oxygen diffusion through the crystal lattice allow zircon to be highly retentive of primary magmatic oxygen isotope ratios (see Valley, 2003). Hydrothermal alteration and recrystallization during tectonic activity are two potential processes to alter $\delta^{18}O$ values in less refractory minerals such as quartz and feldspar, which is subsequently reflected in whole-rock values (Valley and Graham, 1996; King et al., 1997, 2000; Monani and Valley, 2001). The quartz and whole-rock $\delta^{18}O$ values of some plutons in this study may have been altered by hydrothermal and tectonic activity (i.e., rocks in the Egan Range and the Stillwater Range). A third process that can change the $\delta^{18}O_{Qtz}$ relative to $\delta^{18}O_{Zrc}$ is assimilation during crystallization. The assimilation of country rock has been documented to change the $\delta^{18}O_{magma}$ value that then changes the oxygen isotope fractionation between early- and late-crystallizing minerals (King and Valley, 2001; Lackey et al., 2002). Zircon, a mineral that crystallizes relatively early in the crystallization sequence of a granitic magma, can more accurately represent the original magmatic oxygen isotope ratios than minerals that crystallize later from a magma with a slightly altered $\delta^{18}O$.

A fourth process that can elevate the quartz and whole-rock $\delta^{18}O$ values relative to refractory minerals, such as zircon, is diffusional exchange of oxygen during cooling. If plutons are intruded at depth in the crust and allowed to cool slowly, minerals that crystallize early and have high closure temperatures to diffusion (i.e., zircon, garnet, titanite) (Dodson, 1973; Coghlan, 1990; Valley et al., 1994; Morishita et al., 1996; Watson and Cherniak, 1997; King et al., 2001; Peck et al., 2003) will preserve $\delta^{18}O$ values more representative of magmas compared to minerals that crystallize later and have low closure temperatures. The fast grain boundary model predicts the ex-

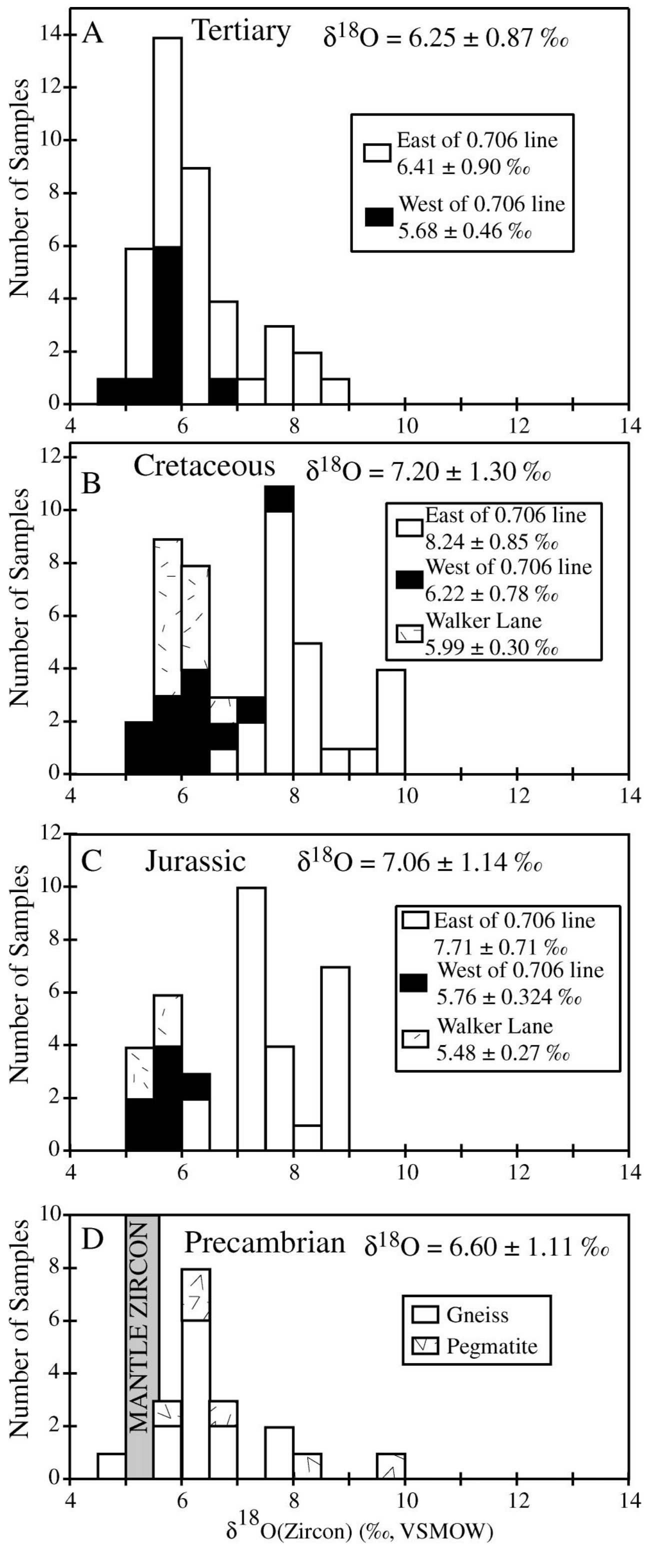

Figure 5. Histogram of average $\delta^{18}O$ values for zircon from granitic rocks of the Great Basin, western United States. Precambrian zircons from basement gneisses show a significant spread in values, typical of Proterozoic crust rather than Archean crust (Peck et al., 2000). In contrast to quartz, Jurassic and Cretaceous zircons show distinct populations east and west of the 0.706 line. Plutons intruding the Walker Lane belt are similar to those emplaced west of the 0.706 line. The bimodal $\delta^{18}O$ values of Jurassic and Cretaceous zircon are not apparent in quartz $\delta^{18}O$ analyses. There is a significant drop of average $\delta^{18}O$ values in Tertiary plutons east of the 0.706 line relative to older plutons in the same area, indicating a relative increase of mantle components in the magma source to the east during the Tertiary. Figure 5D shows the range of $\delta^{18}O_{Zrc}$ values from rocks in equilibrium with primitive-mantle–derived magmas (Valley et al., 1998).

change of oxygen isotopes between minerals in a rock during the cooling history (Eiler et al., 1992, 1994). During cooling, minerals that have not reached their blocking temperature will continue to exchange oxygen. Quartz and feldspar are major constituents of granitic rocks and also possess low closure temperatures. During the cooling history of a granitic magma, quartz and feldspar will exchange oxygen isotopes with other minerals in the rock and preferentially take up ^{18}O, resulting in a higher $\delta^{18}O$.

The majority of plutons in the Great Basin are likely affected by variable cooling histories, particularly as tectonic activity has changed crustal thickness significantly, that can lead to larger Qtz-Zrc fractionations than those representative of high-temperature magmatic values. This study shows that broad trends of $\delta^{18}O$ values and age are apparent with quartz analyses, but not for the finer-scale study of crustal structure. Quartz and feldspar may be modified by only a small amount from primary magmatic values, but the difference is enough that subtle distinctions are obscured by this diffusional resetting (King et al., 1998).

If cooling is closed system, the whole rock will still preserve the magmatic $\delta^{18}O$ value, but open-system cooling with even minor exchange with country rock or fluids will cause modification of the whole-rock $\delta^{18}O$ value. If the country rock is sedimentary with a typically high $\delta^{18}O$ value, the whole-rock will likely rise because of exchange. Evidence for the minor modification of whole-rock $\delta^{18}O$ values in the Great Basin is apparent when analyzed $\delta^{18}O_{WR}$ values are compared with calculated $\delta^{18}O_{WR}$ values based on $\delta^{18}O_{Zrc}$ and SiO_2 content (Valley et al., 1994) (Table DR1 [see footnote 1]). For the six plutons with $\delta^{18}O_{Zrc}$, $\delta^{18}O_{WR}$, and SiO_2 data available, the calculated $\delta^{18}O_{WR}$ values range from 1.5‰ lower than the analyzed $\delta^{18}O_{WR}$ values to

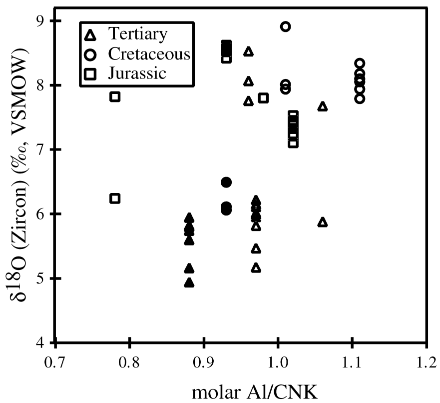

Figure 6. Plot of $\delta^{18}O$ values for zircon vs. molar Al/CNK [= Al_2O_3/(CaO + Na_2O + K_2O)] for plutons of various ages within the Great Basin. Filled symbols are samples located west of the I_{Sr} = 0.706 line. Tables DR1 and DR2 (see footnote 1 in text) present data and references. Plutons located west of the 0.706 line typically have lower molar Al/CNK ratios and lower $\delta^{18}O_{Zrc}$ values. Cretaceous plutons have the clearest trend of $\delta^{18}O_{Zrc}$ values that increase with molar Al/CNK ratios, whereas the $\delta^{18}O_{Zrc}$ values of Tertiary plutons appear relatively insensitive to molar Al/CNK ratios.

0.5‰ higher. The majority of the samples have lower calculated values than actual values, typically ~1.0‰ lower. Such modifications of actual whole-rock $\delta^{18}O$ values are substantial enough to obscure the small differences between magmatic sources.

Isotopic Trends of $\delta^{18}O_{Zrc}$ with Longitude

The zircon oxygen isotope data of this study identify a major crustal boundary that is broadly coincident with the 0.706 line and marks the boundary between lower-$\delta^{18}O$ plutons on the west and high-$\delta^{18}O$ plutons on the east. Farmer and DePaolo (1983) interpreted the 0.706 line as the transition from primarily continental sedimentary rocks to volcanic-arc–dominated rocks. The location of the zircon-based oxygen isotope discontinuity differs from that identified by using whole-rock data (Solomon and Taylor, 1989). Whole-rock data indicate high-$\delta^{18}O$ plutons farther west than the 0.706 line. Previous models of crustal structure incorporating oxygen and radiogenic isotope data proposed a zone of high-$\delta^{18}O$ arc-derived rocks west of the 0.708 line extending nearly to the western border of Nevada. The data of this study are in better accord with radiogenic isotopes, do not require such a broad region of high-$\delta^{18}O$ rocks from volcanic arcs, and indicate that the only major source of high-$\delta^{18}O$ sedimentary rocks assimilated into magmas of the Great Basin is continental rocks east of the 0.706 line.

Approaching the 0.706 line from the east, the inferred thickness of Precambrian basement decreases while the thickness of the craton-derived sedimentary rock section increases (Fig. 2). Elison et al. (1990) identified Paleozoic sedimentary rocks of the continental shelf to the east of the 0.706 line and on this basis suggested the crystalline basement lies farther east than the 0.706 line.

The increased thickness of craton-derived sedimentary rocks is evident in the increased $\delta^{18}O_{Zrc}$ as the 0.706 line is approached from the east (Fig. 7). In the Jurassic, Cretaceous, and Tertiary plutonic suites, the highest $\delta^{18}O_{Zrc}$ values are nearest the 0.706 line and on the eastern side of the boundary. Jurassic plutonic rocks indicate a steady increase in $\delta^{18}O_{Zrc}$ values as the 0.706 line is approached from the east. The Cretaceous suite is unique because it displays high average $\delta^{18}O_{Zrc}$ values east of the 0.706 line (the highest in the region), and the range of $\delta^{18}O_{Zrc}$ values increases as the 0.706 line is approached from the east. This increased presence of slightly lower $\delta^{18}O_{Zrc}$ values near the 0.706 line suggests the influence of low-$\delta^{18}O$ volcanic-arc rocks during this time period as the proportion of arc-derived rocks began to increase from east to west (Fig. 2).

Igneous rocks intruding the Great Basin west of the 0.706 line all have significantly lower $\delta^{18}O_{Zrc}$ values than those east of the 0.706 line, indicative of either less evolved crustal material involved in magma genesis or a lower proportion of evolved crustal material in magmas. The Jurassic and Cretaceous suites show bimodal $\delta^{18}O_{Zrc}$ distributions east and west of the 0.706 line (Fig. 5). This bimodality is not apparent in the $\delta^{18}O_{Qtz}$ distributions (Fig. 4). The difference between the quartz and zircon distributions could be the result of subsolidus alteration of quartz $\delta^{18}O$ values due to, for example, the diffusional exchange of oxygen during cooling. Despite the more complex tectonic history of the Walker Lane belt, these plutons appear to have a magma source similar to that of other plutons west of the 0.706 line. Jurassic and Cretaceous plutons emplaced in the Walker Lane belt all have low $\delta^{18}O_{Zrc}$ values and are indistinguishable from Great Basin plutons located west of the 0.706 line. The lower $\delta^{18}O_{Zrc}$ values of granitic rocks west of the 0.706 line suggest a less evolved, juvenile arc magma source.

Previous oxygen isotope studies suggested a crustal structure for the western United States that differed from structure delineated by the radiogenic isotope data. On the basis of whole-rock powder analyses, there is no correspondence between the 0.706 line and any discontinuity in the oxygen isotope data (Solomon and Taylor, 1989). The whole-rock data, if magmatic, would suggest that the high-$\delta^{18}O$ zone west of the 0.706 line is due to magmas generated from an altered volcanic component to explain the high $\delta^{18}O$ values but low $^{87}Sr/^{86}Sr$ ratios (Solomon and Taylor, 1989). The western edge of the Precambrian crystalline basement also was interpreted as being farther east on the basis of stable isotope analyses compared to radiogenic isotopes. The results of this study, however, indicate that the structure of the crust inferred from radiogenic isotopes is compatible with stable isotope analyses of $\delta^{18}O_{Zrc}$.

The $\delta^{18}O_{Zrc}$ data also indicate a $\delta^{18}O$ discontinuity approximately coincident with the 0.706 line in central Nevada that is not apparent with $\delta^{18}O_{Qtz}$. This $\delta^{18}O_{Zrc}$ discontinuity lies considerably east of Solomon and Taylor's boundary between the central and western zone. Approaching the 0.706 line from the east, $\delta^{18}O_{Zrc}$ values for Jurassic and Tertiary plutons increase, which suggests a coincident and gradual increase of high-$\delta^{18}O$ sedimentary rock in the crust as the crystalline basement terminates or thins. West of the 0.706 line, the $\delta^{18}O_{Zrc}$ values dramatically decrease regardless of the age of granitic rocks (Fig. 7). In contrast to zircon, the $\delta^{18}O_{Qtz}$ values of plutons west of the 0.706 line are difficult to distinguish from those east of the 0.706 line. The western edge of the central high-$\delta^{18}O$ zone of Solomon and Taylor (1989) is at long. ~119°W, west of the decrease in $\delta^{18}O_{Zrc}$ values. The eastern part of the central high-$\delta^{18}O$ zone of Solomon and Taylor (1989) includes a part of western Utah. The $\delta^{18}O_{WR}$ values of plutons decrease dramatically east of the eastern zone boundary. Zircons from Tertiary and Jurassic plutons maintain a fairly constant range of $\delta^{18}O$ values (5‰–7‰ and 6‰–8‰, respectively) across the eastern to central zone boundary, which is approximately equivalent to long. 114°W. The $\delta^{18}O_{Zrc}$ data of this study narrow the high-$\delta^{18}O$ zone of the northern Great Basin to lie just between the 0.706 and 0.708 lines, and the $\delta^{18}O$ values increase gradually as the 0.706 line is approached from the east.

Isotopic Trends with Age

Oxygen isotope results from this study document the changing sources of magmas and the availability of sedimentary rocks in the crust in the Great Basin from the Precambrian

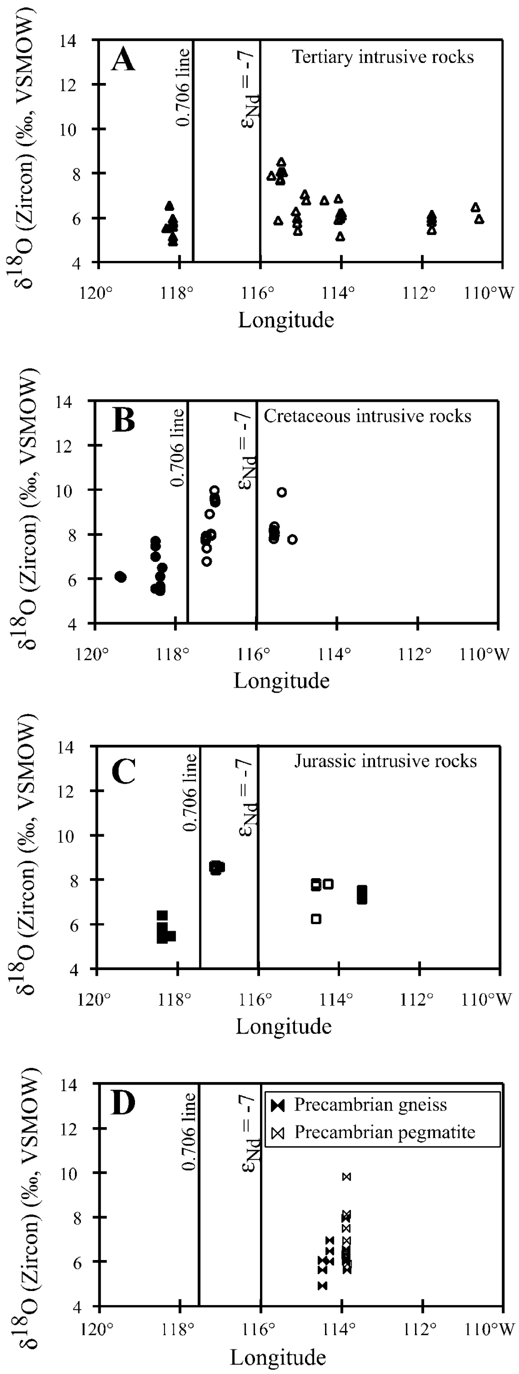

Figure 7. Plot of $\delta^{18}O$ values for zircon vs. longitude for plutons of various ages within the Great Basin, western United States. Jurassic plutons show an increase in $\delta^{18}O$ values as the 0.706 line is approached from the east. Cretaceous plutons become more variable as the 0.706 line is approached from the east. Jurassic, Cretaceous, and Tertiary plutons have a significant drop in $\delta^{18}O$ values west of the 0.706 line.

to the Tertiary (Fig. 8). The thickness of the crust in the Great Basin has changed as a result of tectonic activity. After the Antler and Sonoma orogenies, crustal thickening occurred during the Sevier orogeny; then thinning due to Basin and Range extension occurred since ca. 40 Ma. The variable crustal thickness not only affects the geotherm but also the amount of crust available for interaction with melts and the amount of sedimentary rocks available for contamination of and assimilation into magmas. These variations in crustal thickness are reflected in the stable isotope geochemistry of plutons intruding the region.

Zircons from Precambrian rocks within the southern Great Basin have $\delta^{18}O$ values that are similar to those of other Precambrian terranes in North America (King et al., 1998; Peck et al., 2000). The $\delta^{18}O_{Zrc}$ values of Proterozoic rocks in the Great Basin are similar to calc-alkaline orthogneisses of early Grenville crust (6.9‰ ± 1.5‰) (Peck et al., 2000).

Wright and Wooden (1991) proposed that the source for Jurassic magmatism in the Great Basin was primarily subcontinental lithospheric mantle. These plutons have a limited range of Sr and Nd isotope ratios that cluster near bulk Earth values. The radiogenic isotope data, however, do not exclude a crustal component in the Jurassic magmas that is apparent in the peraluminous nature of some of the Jurassic granites and the presence of inherited zircons. The Pb isotope data indicate a crustal component in the Jurassic plutons of the eastern Great Basin (Wright and Wooden, 1991). A crustal component in Jurassic magmas east of the 0.706 line is evident in $\delta^{18}O_{Zrc}$ values but is not evident in samples west of the 0.706 line or in the Walker Lane. The average $\delta^{18}O_{Zrc}$ value of Jurassic igneous rocks analyzed east of the 0.706 line is 7.71‰ ± 0.71‰, over 2‰ higher than the mantle (Fig. 5) (Mattey et al., 1994; Valley et al., 1998), and $\delta^{18}O_{Zrc}$ is high regardless of whether the pluton is metaluminous or peraluminous (Fig. 6). Pb and O isotope ratios of Jurassic plutons in the central and western Great Basin do not indicate as large an old, high-$\delta^{18}O$ crustal component as in the eastern plutons. In the Walker Lane and other areas west of the 0.706 line, zircon $\delta^{18}O$ values are similar to what would be expected from primitive-mantle–derived melts. The $\delta^{18}O_{Zrc}$ values indicate the necessity of a high-$\delta^{18}O$ crustal component in the magma, but high ε_{Nd} values also require that this crustal component be relatively juvenile (Fig. 9). Young ocean crust altered at low temperature or young sedimentary rocks are possible inputs to magma that would result in high $\delta^{18}O$ values and low $^{87}Sr/^{86}Sr_i$ ratios in the plutons.

Cretaceous plutons in the Great Basin are similar to Jurassic plutons in terms of their $\delta^{18}O_{Zrc}$ distributions (Fig. 8). Cretaceous plutons east of the 0.706 line have highly elevated $\delta^{18}O_{Zrc}$ values, whereas plutons located west of the 0.706 line, including those in the Walker Lane, are only slightly elevated relative to mantle values (Table 1). Wright and Wooden (1991) determined that Late Cretaceous plutons are compositionally and isotopically (Sr, Nd, Pb) distinct from Jurassic plu-

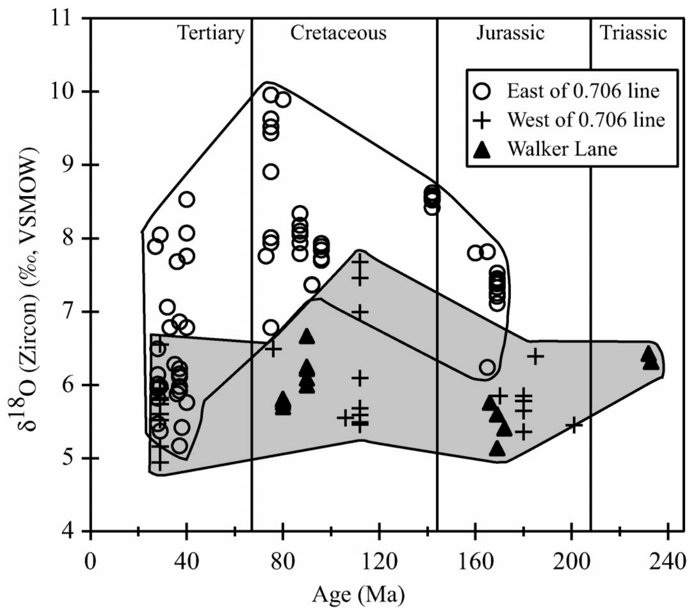

Figure 8. Plot of δ¹⁸O values for zircon vs. age of plutons (Tables DR1 and DR2 [see footnote 1 in text] present geochronology data and references). The shaded area indicates plutons located west of the 0.706 line. δ¹⁸O values increase through the Jurassic and Cretaceous until a break in plutonism at ca. 70 Ma. Tertiary magmatism returns to lower δ¹⁸O values.

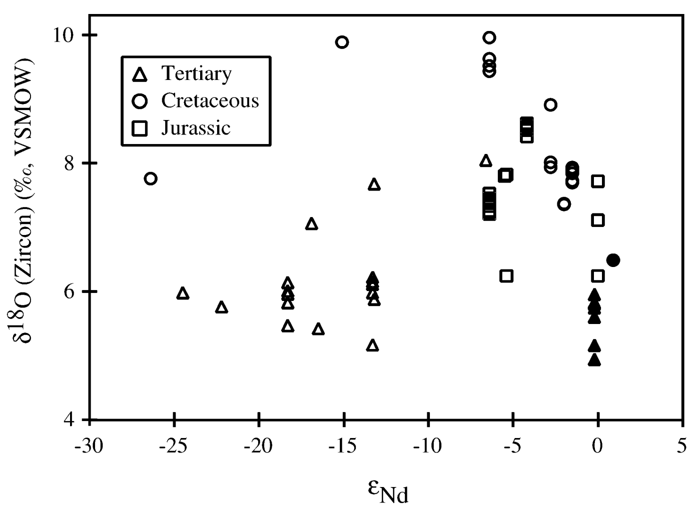

Figure 9. Plot of δ¹⁸O values for zircon vs. ε_{Nd} values for plutons of various ages within the Great Basin. Filled symbols are samples located west of the 0.706 line. Tables DR1 and DR2 (see footnote 1 in text) present data and references. Cretaceous plutons show a clear trend of increasing $\delta^{18}O_{Zrc}$ with decreasing ε_{Nd}. The $\delta^{18}O_{Zrc}$ values of Tertiary plutons appear insensitive to variation in ε_{Nd}; however, plutons located west of the 0.706 line have significantly lower ε_{Nd} values with little variation in $\delta^{18}O_{Zrc}$ compared to plutons east of the 0.706 line.

tons. The Late Cretaceous plutonic suite east of the 0.706 line tends to be strongly peraluminous, and isotope ratios indicate significant crustal components in the magmas (ε_{Nd} from −13 to −23, initial $^{87}Sr/^{86}Sr$ ratios from 0.7109 to 0.7261 (Wright and Wooden, 1991)). Some Cretaceous plutons are likely the product of crustal melting resulting from crustal thickening and an elevated geotherm during the Sevier orogeny (Barton, 1990).

Barton (1990) documented a progression during the Cretaceous of an increasing sedimentary component in granitic magmas, particularly those located east of the 0.706 line. Late Cretaceous plutons have higher initial $^{87}Sr/^{86}Sr$ ratios, higher whole-rock δ¹⁸O values, and lower ε_{Nd} values and are more peraluminous than Early Cretaceous plutons (Barton, 1990). The highest $\delta^{18}O_{Zrc}$ values of plutons east of the 0.706 line increase from ~8.5‰ to as high as 10‰ through the Cretaceous (Fig. 8) and agree with the proposed trend of increasing sedimentary influence on magmas through the Cretaceous. The model proposed for Cretaceous magmatism is a progressive increase of conductive heat in the region during the time period, with renewed magmatic activity leading to increased crustal components in magmas (Barton, 1990). The increase of a crustal signature in granitic magmas is not just due to an elevated geotherm associated with crustal thickening, but also an increased magmatic travel path through the crust as crustal thickening occurred, resulting in longer crustal residence times. Crustal thicknesses in the Late Cretaceous increased to as much as 50–60 km (Barton, 1990).

Magmatism in the Great Basin resumed in the middle Tertiary after an abrupt break at the end of the Cretaceous and a >20 m.y. hiatus (Fig. 8). Tertiary plutonic $\delta^{18}O_{Zrc}$ values are significantly lower than the values of previous plutons (6.25‰ ± 0.87‰ compared to 7.20‰ ± 1.30‰). Plutons east of the 0.706 line are still slightly elevated relative to mantle values, but nearly 2‰ lower than Cretaceous plutons east of the 0.706 line. Nd and Sr isotope ratios of Tertiary plutons indicate a mixture of mantle and crustal reservoirs in the magma source, and these plutons plot between mantle-like Jurassic plutons and crustal Cretaceous plutons in terms of initial $^{87}Sr/^{86}Sr$ and ε_{Nd} (Wright and Wooden, 1991). This Tertiary suite of plutons was generated and emplaced in the crust during Basin and Range extension. Although some Tertiary plutons in the Great Basin are nonetheless peraluminous, a decreased crustal component in the granitic magmas is in agreement with the model of mantle upwelling and decreasing crustal thickness during extension. The significant decrease of $\delta^{18}O_{Zrc}$ between the Cretaceous plutons and Tertiary plutons indicates a decreased crustal component in these magmas.

CONCLUSIONS

This study demonstrates that zircons from igneous bodies in the Great Basin preserve magmatic δ¹⁸O values and reveal temporal as well as spatial trends of magmatic evolution that have not been seen by other oxygen isotope studies emphasizing analysis of whole-rock samples. Zircon $\delta^{18}O$ values are capable of seeing through subsolidus alteration that frequently affects quartz and whole-rock $\delta^{18}O$ values and can indicate subtle source variations. The $^{87}Sr/^{86}Sr_i$ = 0.706 line has previously been identified as the boundary between the North American craton and accreted volcanic-arc terranes. This crustal suture zone is reflected by an oxygen isotope discontinuity with higher $\delta^{18}O_{Zrc}$ values east of the 0.706 line and lower $\delta^{18}O_{Zrc}$ values west of the 0.706 line. The 0.708 line, or $\varepsilon_{Nd} = -7$, has been interpreted to represent the westernmost extent of crystalline basement. Lying between the 0.706 and 0.708 line is the thickest sequence of continentally derived Precambrian and Paleozoic sedimentary rocks. As the 0.706 line is approached from the east, the increased thickness of high-$\delta^{18}O$ sedimentary rocks derived from the craton is also apparent in the Great Basin plutons' $\delta^{18}O_{Zrc}$ values that increase from east to west.

Oxygen isotope ratios of zircon also record changes in magma source through the protracted geologic history of the Great Basin. For Jurassic plutons east of the 0.706 line, the combination of radiogenic and stable isotope ratios suggests the mixture of a juvenile magma source and high-$\delta^{18}O$ supracrustal rocks (Wright and Wooden, 1991). Cretaceous $\delta^{18}O_{Zrc}$ values indicate a greater involvement of crustal rocks in magma genesis as the crust was thickened during the Sevier orogeny. Tertiary plutonic $\delta^{18}O_{Zrc}$ values decreased and became more mantle-like as the crust was thinned during Basin and Range extension. Radiogenic isotope studies have identified crustal discontinuities controlled by the difference in the composition and age of the crust. The stable isotope discontinuity in central Nevada identified by $\delta^{18}O_{Zrc}$ values further suggests a significant change in the lithology of the crust.

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