Stable Isotope Geochemistry: A Tribute to Samuel Epstein
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An oxygen and hydrogen isotope study of high-grade metamorphism and anatexis in the Ruby Mountains–East Humboldt Range core complex, Nevada

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Abstract—Oxygen isotope analyses were made of 91 whole rock and mineral separate samples from the Ruby Mountains-East Humboldt Range metamorphic core complex and other nearby areas in eastern Nevada. In addition, ten hydrogen isotope analyses were made of the hydrous minerals muscovite, biotite, and hornblende. The samples include plutonic igneous rocks, high-grade metasedimentary rocks, and low-grade sediments that are thought to be their protoliths. The $\delta^{18}O$ values vary systematically in each of these categories. Most of the metasediments were shifted to lower $\delta^{18}O$ values than their protoliths, but the magnitude and pervasiveness of this ^{18}O-depletion varies in different geographic areas, becoming most intense at Lizzies Basin in the East Humboldt Range where the deepest structural levels in the area are exposed. Within the area sampled at this locality, all silicate rock-types are isotopically homogenized over scales of at least tens of meters and shifted to $\delta^{18}O$ values close to +6. Quartz from contrasting igneous and metasedimentary rock-types has a uniform oxygen isotope composition implying that this mineral was very well equilibrated (see also WICKHAM and PETERS, 1990). Elsewhere, exchange was less effective as illustrated by contrasts in the $\delta^{18}O$ values of adjacent marble, quartzite, and leucogranite layers. The $\delta^{18}O$ values of chemically similar leucogranites vary widely within the area studied. The most ^{18}O-rich samples are from the northern Ruby Mountains ($\delta^{18}O > +12$), and these must have been derived by anatexis from sedimentary material. The lower-^{18}O leucogranites were probably derived from similar material that had been isotopically altered at an earlier, metamorphic stage. ^{18}O-depletion in the deep-seated metasediments and igneous rocks was probably the result of exchange with fluids derived from primitive mantle-derived intrusive rocks or with the rocks themselves. This conclusion is supported by the "normal" plutonic igneous δD values shown by these same samples. At high structural levels, mylonites and associated rocks within the low-angle fault zone exposed at Secret Creek gorge were variably affected by meteoric water infiltration, which probably occurred during Tertiary extensional deformation, resulting in anomalously low D/H and $^{18}O/^{16}O$ ratios. Low-grade sedimentary rocks from other areas are also sporadically ^{18}O-depleted, and this is similarly attributable to exchange with meteoric waters. These new isotopic data from Nevada add to, and complement, data from other terranes, such as the Pyrenees (WICKHAM and TAYLOR, 1985), that demonstrate that profound ^{18}O-depletions and isotopic homogenization of metasedimentary rocks can take place during certain types of regional metamorphism. However, it is also becoming clear that these metamorphic ^{18}O-depletions are probably produced by a variety of different mechanisms.

INTRODUCTION

OXYGEN IS THE MOST abundant element in most terrestrial rocks, fluids, and silicate melts. Because of this, and because systematic variations of $^{18}O/^{16}O$ ratios are observed in different terrestrial reservoirs such as the hydrosphere, mantle, and continental crust, oxygen is an exceedingly important tracer in investigations of petrological processes. These include, among others, several of the topics addressed in this study: magma formation by crustal anatexis, magma transport in the crust, and the interaction of aqueous fluids with subsolidus (metamorphic) and supersolidus (anatectic) rocks, during major tectonothermal events.

A characteristic feature of oxygen isotope variations in metamorphosed sedimentary rocks is a lowering of $\delta^{18}O$ values at higher metamorphic grades, and this also may be accompanied by a systematic change in D/H ratio (WICKHAM and TAYLOR, 1985). This ^{18}O-depletion process is commonly between two and four per mil but may be in excess of ten per mil where the sedimentary rocks are ^{18}O-rich carbonates and cherts. With the exception of ^{18}O-depletions caused by decarbonation of impure limestones, these open-system effects are clearly attributable to isotopic exchange with an oxygen reservoir that undergoes a complementary ^{18}O-enrichment. The most common large oxygen reservoirs available to bring about these isotopic shifts are (1) primitive igneous rocks (and associated volatiles) derived from the Earth's upper mantle, which have a relatively constant $\delta^{18}O$ value of $\sim +6$, and (2) meteoric waters or ocean waters with $\delta^{18}O \leq 0$. Previous studies of metamorphic sequences have identified both of these types of low-^{18}O reservoirs as possible agents of metasediment ^{18}O-depletion (*e.g.*, GARLICK and EPSTEIN, 1967; SHIEH and SCHWARCZ, 1974; WICKHAM and TAYLOR, 1985), but it remains uncertain which is dominant during crustal metamorphism, whether in certain circumstances both may become involved, and whether either process may be contingent upon a particular type of tectonic setting.

In this paper we present data from a metamorphic core complex in northeastern Nevada, which provides a well-constrained opportunity to evaluate the cause of ^{18}O-depletions in metamorphosed sedimentary rocks. Two factors make the area particularly attractive to study. First, although the ^{18}O-depletions are variable, in certain areas they are particularly extreme, with metapelite and metacarbonate rocks attaining $\delta^{18}O$ values of +7 to +9 (representing downward shifts of 10 to 15 per mil from their protolith values). Second, the low-grade sedimentary equivalents of these same lithologies are exposed nearby in well-preserved, fossiliferous sedimentary sequences of the Cordilleran miogeocline, so that direct comparisons between low- and high-grade rocks and direct quantitative assessments of ^{18}O-depletions can be made.

GEOLOGY AND PETROLOGY OF THE RUBY MOUNTAINS-EAST HUMBOLDT RANGE

Regional setting

The Ruby Mountains-East Humboldt Range is one of a series of north-northeast striking Late Cenozoic uplifts that characterize the Basin and Range Province of Nevada (Fig. 1). This area comprises one of the largest and best-exposed metamorphic core complexes in the western United States (ARMSTRONG, 1982), exposing high-grade metamorphic and igneous rocks of Mesozoic and Tertiary age. In this complex the metasedimentary rocks include pelite, quartzite, marble, and calc-silicate gneiss chiefly correlative with Late Precambrian and Paleozoic stratigraphic units (HOWARD, 1971; SNOKE and MILLER, 1988). These are intruded by numerous distinct bodies of leucogranite, monzogranite, diorite, and related igneous rocks.

In some areas (such as the southern Ruby Mountains) the metamorphic grade is very low, and the miogeoclinal strata are effectively unmetamorphosed, whereas in other areas (such as the northern Ruby Mountains and the East Humboldt Range) the rocks are pervasively recrystallized, plastically deformed, intruded, and partly melted (in appropriate lithologies). This important feature permits direct geochemical comparisons to be made between the high-grade rocks and their low-grade precursors, making it possible to quantify the geochemical, mineralogical, and isotopic modifications that the miogeoclinal sediments have experienced during their metamorphism.

These rocks preserve a record of polyphase metamorphism and deformation. A complex and poorly understood Mesozoic history includes contractile deformation, polyphase folding, amphibolite-facies metamorphism, and mafic to silicic magmatism. During the Tertiary the area experienced strong and complex extensional deformation, leading to the tectonic emplacement of sheets of very low-grade supracrustal rocks over sections of mid-crustal rocks along low-angle normal fault systems. Mid-crustal extension was facilitated by kilometer-scale zones of plastic flow, represented by well-developed zones of mylonitic rocks, best exposed along the western flanks of the northern Ruby Mountains and East Humboldt Range. Tertiary extension was accompanied by plutonism, volcanism, and a strong low-pressure (sillimanite-grade) metamorphic overprint in the mid-crustal rocks.

Geochronological measurements on igneous and metamorphic rocks from the high-grade terranes have identified both Mesozoic and Tertiary thermal events (SNOKE *et al.*, 1979; KISTLER *et al.*, 1981; DALLMEYER *et al.*, 1986; DOKKA *et al.*, 1986; WRIGHT and SNOKE, 1986; LUSH *et al.*, 1988), but the details of the thermal history, particularly the Mesozoic portion, are still very poorly known. Late Jurassic (~155 Ma) and Late Cretaceous (~80 Ma) igneous events have been documented by Rb-Sr (KISTLER *et al.*, 1981) and U-Pb zircon and monazite (SNOKE *et al.*, 1979; HUDEC and WRIGHT, 1990) techniques. Amphibolite-facies regional metamorphism and deformation accompanied the Jurassic magmatism (HUDEC and WRIGHT, 1990). The Cretaceous metamorphic history is as yet poorly constrained, the best data being U-Pb monazite ages (SNOKE *et al.*, 1979; J. E. WRIGHT and A. W. SNOKE, unpubl. data), but was probably roughly synchronous with magmatism. The Tertiary thermal history has been better documented by U-Pb zircon, $^{40}Ar/^{39}Ar$, and fission track techniques. Tertiary igneous rocks comprise andesitic to rhyolitic volcanic rocks in the unmetamorphosed supracrustal sequence, the Harrison Pass granitoid pluton (36 Ma), and many meter-scale pods and sills of dioritic to granitic orthogneiss in the deep-seated metamorphic complex, including 29 Ma monzogranite and 32 and 39 Ma orthogneisses (WRIGHT and SNOKE, 1986).

Lower plate igneous-metamorphic complex

Most of the isotopic data reported in this paper are from the polyphase amphibolite-facies rocks that comprise much of the study area. Rock-types include quartzite, marble, calc-silicate gneiss, metapelite, and metapsammite intruded by leucogranite, biotite monzogranite, biotite-hornblende quartz diorite, quartzo-feldspathic orthogneiss, and amphibolite. At deep structural levels, the igneous rocks occur mostly as small meter-scale pods and sills, although there are also some hundred-meter-thick sills of biotite-hornblende quartz diorite within the East Humboldt Range. The deep-seated metamorphic complex thus comprises a sequence of many hundreds of igneous and metasedimentary layers, intercalated on a relatively fine scale, and dipping at moderate angles throughout much of the area (Fig. 2).

Although quantitative geobarometry and thermometry is lacking for much of this terrane, HURLOW *et al.* (1991) reported *P-T* conditions of 3.1 to 3.7 kbar and 580–620°C

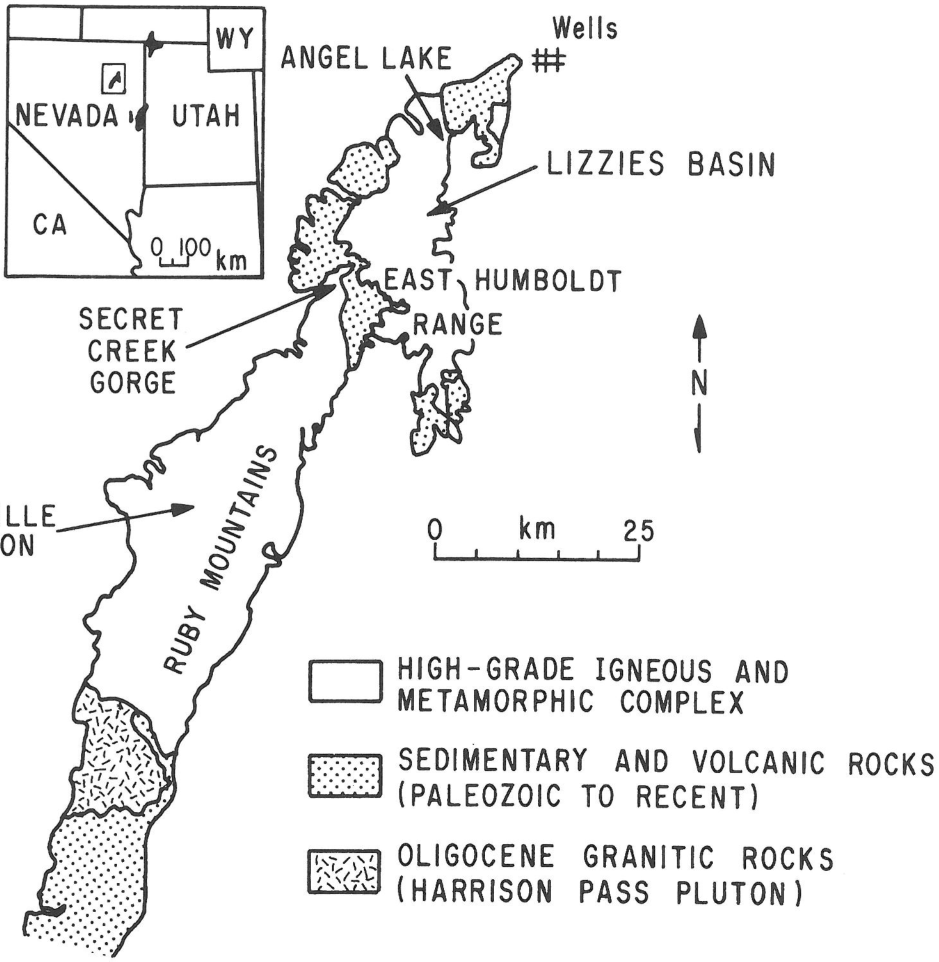

FIG. 1. Location and simplified geology of the Ruby Mountains-East Humboldt Range metamorphic core complex. High-grade metamorphic and plutonic igneous rocks are confined to the northern Ruby Mountains and the East Humboldt Range, while the southern Ruby Mountains comprise low-grade miogeoclinal sediments. The locations of the areas from which samples were taken for this study are indicated by arrows.

for a phase of the Tertiary mylonitization. The most recent metamorphic equilibration at Lizzies Basin (the deepest structural level exposed in the area) is estimated to have been at 5–6 kbar and 650–700°C (M. T. PETERS, pers. comm., 1991). Sillimanite is widespread in metapelitic rocks throughout the terrane and locally postdates kyanite (SNOKE and MILLER, 1988). Some of the sillimanite growth is probably due to Tertiary metamorphism (SNOKE *et al.*, 1990), though some may be Late Cretaceous (SNOKE *et al.*, 1979). The kyanite grew during an earlier high-pressure metamorphism probably in the Late Jurassic or Early Cretaceous (SNOKE and MILLER, 1988). This would suggest that these rocks resided at crustal depths in excess of 20 km during the Mesozoic and at shallower levels of perhaps 10–20 km during the Tertiary.

ANALYTICAL PROCEDURES

Oxygen was extracted from silicates by reaction with fluorine gas at ~550°C (TAYLOR and EPSTEIN, 1962). Oxygen was converted to CO_2 for mass spectrometric analysis by reaction with an electrically heated graphite rod. Silicate samples comprised whole-rock powders and mineral separates of quartz, biotite, and amphibole. Calcite from carbonate samples was analyzed using the H_3PO_4 technique (MCCREA, 1950) corrected using the fractionation factor 1.01020 (modified after SHARMA and CLAYTON (1965) by FRIEDMAN and O'NEIL (1977)). Analytical error for oxygen and carbon isotope ratios is 0.1 to 0.2 per mil. The oxygen isotope data are reported in δ-notation relative to Standard Mean Ocean Water (SMOW). NBS-28 has a $\delta^{18}O = +9.60$ on this scale. The $\delta^{13}C$ values are relative to PDB.

Hydrogen isotope analyses were made using the method of VENNEMAN and O'NEIL (1991). After initial degassing at 150°C, samples were dehydrated by heating to 1400°C and the water evolved converted to hydrogen by reaction with zinc. The precision of the δD values is ±2 per mil. The δD value of NBS-30 biotite is −65 per mil at the University of Michigan.

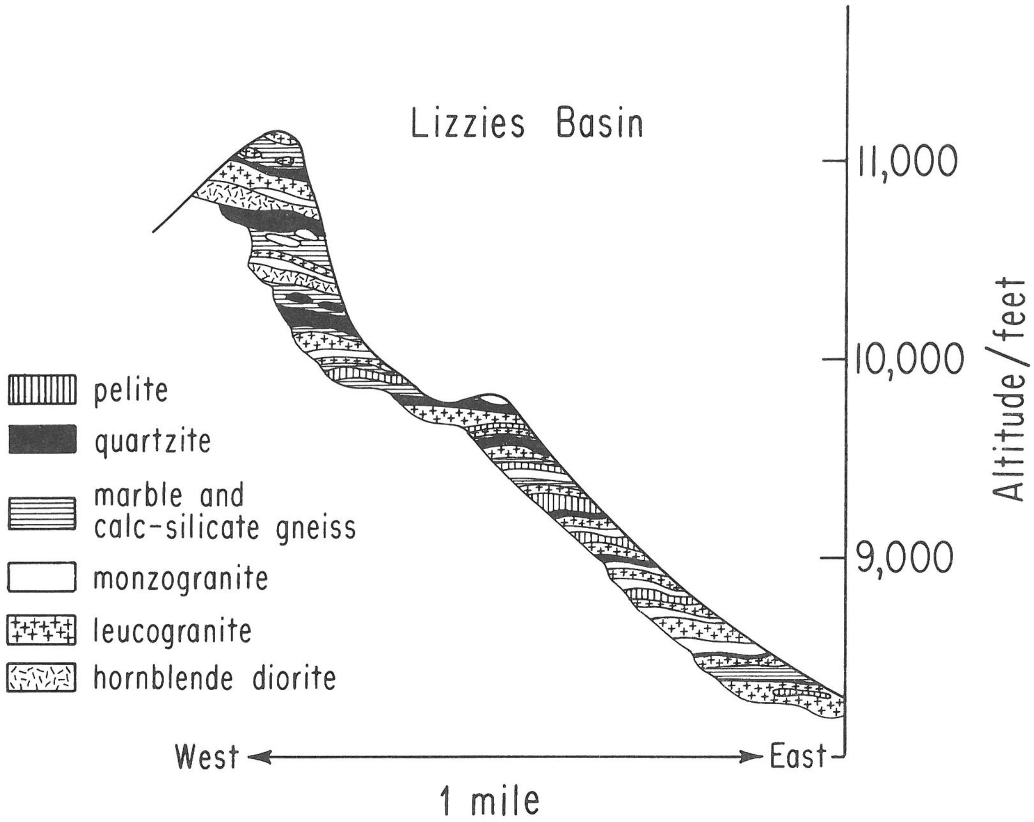

FIG. 2. Cross-section through the lower-plate igneous-metamorphic complex exposed at Lizzies Basin in the East Humboldt Range (after WICKHAM and PETERS, 1990). Strong plastic attenuation has resulted in subhorizontal layering, with many hundreds of individual rock units intercalated on meter to centimeter scales. The proportion of granitic rocks increases towards the bottom of the section, and the proportion of marble increases towards the top.

STABLE ISOTOPE DATA

Previous work

The only previous oxygen isotope study of this area was that of KISTLER *et al.* (1981), who report data for minerals separated from 12 rocks collected from various localities throughout the northern Ruby Mountains. All of the four granitoids analyzed in that study were two-mica granites which had relatively high $\delta^{18}O$ values (*e.g.*, values for quartz are +14.0, +12.3, +11.6, and +14.9), indicating that these magmas were derived from a sedimentary protolith. According to KISTLER *et al.* (1981) these granites are Mesozoic or older, and they were probably in large part derived from shales and psammites of the McCoy Creek Group, which is the lowest stratigraphic unit within the miogeoclinal sequence, and one which can be readily inferred to have had an oxygen isotopic composition similar to that of the two-mica granites mentioned above (*e.g.*, compared with analogous sedimentary rocks of the Belt Series further north studied by ESLINGER and SAVIN, 1973). The other rocks analyzed by KISTLER *et al.* (1981) included several metasediments—quartzite, marble, and mica schist, as well as one amphibolite. These tend to have slightly lower $\delta^{18}O$ than the granites (*e.g.*, $\delta^{18}O$ of quartz in mica schists is +10.2 and +10.1), which implies that those particular metasediments were probably not the immediate source for the granites, or, if they were, that they have since become selectively ^{18}O-depleted.

Northern Ruby Mountains (NRM)

Our new oxygen isotope data from the northern Ruby Mountains (NRM) (for quartz, biotite, muscovite, and whole-rock samples) are given in Table 1. Samples were collected from two localities within Lamoille Canyon (shown in Fig. 1), and include various rock-types within the high-grade igneous-metamorphic complex forming the deepest exposed structural levels. The samples are from two traverses across intercalated metacarbonate, quartzite, and leucogranite, which are the predominant rock-types in this region.

The data for the leucogranites are similar to those reported by KISTLER *et al.* (1981), with quartz ranging between +14.9 and +12.2, confirming the ^{18}O-rich nature of leucogranites in the NRM. However, the quartzites also display high $\delta^{18}O$ values for quartz which are uniform within the samples studied (+12.2 to +12.8), similar to the values in quartz from the granites. The $\delta^{18}O$ values of calcite in the metacarbonates vary more widely (+12.6 to +18.5), but all values are much lower than typical sedimentary carbonate values (+20 to +30). All of the analyzed samples are from amphibolite-facies assemblages, dominated by diopside, scapolite, plagioclase, and calcite; they have all clearly undergone decarbonation, and this process is accompanied by an ^{18}O-depletion of the rocks because of loss of high-^{18}O CO_2 (*e.g.*, NABELEK *et al.*, 1984). The magnitude of the ^{18}O-depletion, however, is generally much more than can be accounted for by simple decarbonation alone, and these metacarbonates therefore must also have exchanged with a low-^{18}O reservoir. In any case, there is no correlation between $\delta^{18}O$ and extent of decarbonation in these samples. The variation in calcite $\delta^{18}O$ contrasts with the relative homogeneity of quartz in the leucogranites and quartzites, and this indicates failure of *all* the carbonate lithologies to equilibrate with adjacent silicates at amphibolite-facies metamorphic temperatures. Locally, however, these lithologies may evidently approach equilibration on meter or 10-meter scales, as illustrated in Fig. 3, profile A. Those samples, collected over a 30-meter traverse, contain calcite and quartz which are relatively homogeneous in $^{18}O/^{16}O$ and are almost equilibrated to plausible 700°C metamorphic temperatures. The δD value of biotite from one of the quartzite samples is −58, a typical value for a sedimentary or metasedimentary rock.

A smaller three-meter section from near Lake Lamoille at the head of Lamoille Canyon (Fig. 3, profile B) is much more heterogeneous, with calcite and quartz samples less than a meter apart being well out of isotopic equilibrium. There has been some local approach toward isotopic equilibrium between metacarbonate and silicate lithologies but clearly no pervasive oxygen isotope homogenization. This may reflect the high proportion of relatively impermeable carbonate rocks within this region, (see below and WICKHAM and PETERS, 1990).

Angel Lake, East Humboldt Range

Angel Lake is located at the northern end of the East Humboldt Range (Fig. 1), within the lower plate igneous-metamorphic complex that makes up most of the range. Detailed mapping at this locality (LUSH *et al.*, 1988; MCGREW and SNOKE, 1988; A. J. MCGREW, unpubl. data) has identified a number of different miogeoclinal stratigraphic units including Cambrian Prospect Mountain Quartzite and Ordovician to Devonian metacarbonates. These metamorphic rocks are interlayered with the full range of igneous lithologies described above, and also with a distinctive gneiss unit that forms a large fold-nappe structure comprising a mixture of orthogneiss, amphibolite, and paragneiss; these rocks may represent the Archaean to Early Proterozoic basement upon which the miogeoclinal metasediments were originally deposited (LUSH *et al.*, 1988).

All of these lithologies are represented in the suite of samples analyzed, many of which were taken from a single ~30-meter profile illustrated in Fig. 4, but also from several other localities in the same vicinity. The data are similar to the NRM data but there are some important distinctions. The carbonates are even more heterogeneous in $^{18}O/^{16}O$, with one sample preserving a $\delta^{18}O$ value (+23.5) close to its sedimentary value. Other samples have undergone strong ^{18}O-depletion, with the lowest value (+12.4) similar to the values observed in the NRM data. Granitic rocks at Angel Lake are in general lower in $\delta^{18}O$ than those in the NRM. Whole-rock samples of two basement orthogneisses are +8.5 and +7.9, with quartz in one sample at +9.5. Quartz separates from two leucogranites have $\delta^{18}O = +10.9$ and +12.1, but are as low as +7.5 in a pelitic migmatite. All of the quartz $\delta^{18}O$ values are lower than quartz from NRM lithologies, although the mean value is only about two per mil lower. Minerals from individual samples typically are near to isotopic equilibrium, with typical high-grade metamorphic fractionations (*e.g.*, $\Delta_{\text{quartz-biotite}} = 5.5$). However, it is clear that, although there has been an approach to equilibrium in these diverse lithologies, the section has not fully equilibrated on a meter scale. Calcite $\delta^{18}O$-values from metacarbonates within the 30-meter profile are within three per mil of their expected equilibrium values with adjacent quartz from intercalated silicate lithologies. This compares with probable 10–15 per mil contrasts that would initially have existed at the pre-metamorphic stage.

Hydrogen isotope analyses of muscovite and biotite from these samples are variable. Muscovite

Table 1. Oxygen, carbon, and hydrogen isotope data for rocks and minerals from the Ruby-East Humboldt Range metamorphic core complex and other locations in north-eastern Nevada. All data are $\delta^{18}O$ values unless otherwise indicated

Sample number	Rock-type	Whole rock	Quartz	Biotite	Muscovite	Calcite	$\delta^{13}C$	% cc
Northern Ruby Mountains (* Stop 9 in Snoke and Howard, 1984; # Lake Lamoille)								
RB30*	marble					+14.50	−3.36	19
RB31*	marble					+12.64	+1.46	<2
RB32*	marble					+13.39	−1.57	6
RB33*	leucogranite	+11.14	+12.22					
RB34*	marble					+15.52	−3.08	9
RB35*	quartzite		+12.43	+7.86 ($\delta D = -58$)				
RB42#	leucogranite	+11.40	+12.36					
RB43#	calc-silicate gneiss					+15.16	−2.61	2
RB44#	marble					+18.50	−1.28	45
RB45#	leucogranite	+13.21	+14.89					
RB46#	marble					+18.35	−2.25	40
RB47#	quartzite	+12.42	+12.25					
RB48#	quartzite	+12.30	+12.76					
Secret Creek Gorge (Stop 12 in Snoke and Howard, 1984)								
RB59	leucogranite	+3.12	+10.94					
RB60	amphibolite	+2.44						
RB61	leucogranite		+10.47		+8.52			
RB62	quartzite		+11.10	+5.03 ($\delta D = -128$)	+8.96 ($\delta D = -115$)			
RB63	quartz vein		+10.74					
RB65	quartzite	+7.37						
RB66	leucogranite	+8.43						
SP3	marble					+13.47	−3.72	55
SP4	quartzite	+14.93						
SP5	limestone					+12.79	+1.64	96
SP5	calcite vein					+1.49	+1.93	97
Angel Lake								
AL14	leucogranite	+12.14	+12.26					
AL15	marble					+12.40	+5.36	4
AL16	biotite gneiss	+8.64	+10.85					
AL17	marble					+13.53	+5.59	12
AL18	pelite	+8.92	+7.49	+6.70 ($\delta D = -88$)				
AL19	quartzite	+10.52						
AL20	leucogranite	+9.86	+10.86		+8.66 ($\delta D = -40$)			
AL21	marble					+16.12	−1.85	74
AL22	leucogranite	+11.99						
AL23	marble					+15.74	−2.59	47
AL24	marble					+23.51	−0.51	13
AL25	quartzite	+12.67						
AL30	orthogneiss	+7.93	+9.42	+4.17 ($\delta D = -108$)				
AL31	amphibolite	+5.92						
AL33	orthogneiss	+8.51						
Lizzies Basin								
LB1	biotitite			+5.28 ($\delta D = -68$)				
LB2	leucogranite	+6.72	+9.67	+5.56				
LB4	vein		+9.57	+5.43 ($\delta D = -58$)				
LB5	leucogranite		+9.03	+4.37				
LB6	amphibolite[1]	+6.60 ($\delta D = -50$)						

Table 1. (Continued)

Sample number	Rock-type	Whole rock	Quartz	Biotite	Muscovite	Calcite	$\delta^{13}C$	% cc
Lizzies Basin								
LB10	calc-silicate gneiss	+7.87						
LB10V	vein		+11.43					
LB11	leucogranite		+9.23					
LB12	calc-silicate gneiss	+7.35	+9.19					
LB13	marble					+12.11	+2.80	93
LB14	calc-silicate gneiss	+8.21						
LB15	marble					+9.42	+0.02	90
LB16	pelite	+7.89	+9.67	+4.08 ($\delta D = -66$)				
LB17	leucogranite	+8.02	+9.19					
Southern Ruby Mountains (Lindsay Creek)								
SR23[2]	limestone		+20.01 (QV)			+14.45	−1.41	83
SR25[2]	limestone					+18.50	+0.61	66
SR29[2]	limestone					+17.51	−4.92	66
SR32[4]	quartzite	+12.35						
Schell Creek Range								
SC7[3]	phyllite	+16.21		Piermont Creek				
SC8[3]	quartzite	+14.35	+15.14 (QV)					
SC14[4]	quartzite	+11.66		Pattersons Pass				
SC17[4]	quartz vein		+13.51					
Egan Range (Lund Canyon)								
EG1[5]	limestone					+16.46	−0.37	83
EG3[5]	limestone					+15.63	−18.96	98
EG4[5]	chert	+19.69						
EG8[6]	quartzite	+13.32						

[1] 98% hornblende.
[2] Middle Cambrian limestone.
[3] McCoy Creek Group (Late Pre-Cambrian).
[4] Prospect Mountain quartzite (Lower Cambrian).
[5] Upper Cambrian limestone and chert.
[6] Ordovician quartzite.
(QV): cross-cutting quartz vein.

from a leucogranite ($\delta^{18}O = +9.9$) has a relatively normal plutonic δD value of −40, but the two biotite samples are anomalously light ($\delta D = -88$ and −108 in a pelite and basement orthogneiss, respectively). This may represent late-stage infiltration of small amounts of meteoric water during uplift of these rocks into the near-surface environment. Alternatively, the infiltration could have occurred synchronous with the most recent phase of deformation as observed in the mylonitic rocks at Secret Creek gorge (see below and FRICKE *et al.*, 1991). In any event, the quantities of water involved were probably tiny, because there was no significant ^{18}O-depletion and only small changes in δD (as compared with the much stronger effects at Secret Creek gorge).

Lizzies Basin, East Humboldt Range

Oxygen isotope data for quartz, biotite, and amphibole separated from silicate lithologies, whole-rock silicates, and calcite from metacarbonates from Lizzies Basin are plotted in Fig. 5. This locality is in the central part of the East Humboldt Range (Fig. 1) and exposes the deepest structural levels seen in the entire terrane. The data are mostly from a two-meter section across various intercalated lithologies and from other sampling sites close by

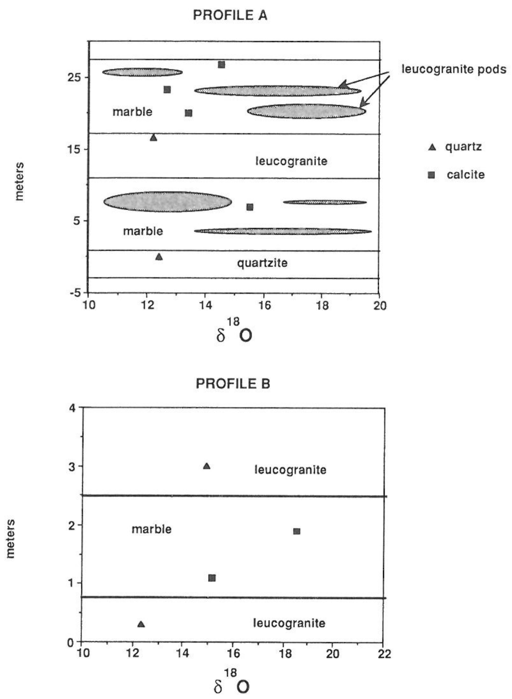

FIG. 3. Profile A: oxygen isotope variation in quartz and calcite from a 30-meter section through intercalated quartzite, leucogranite, and marble layers. All of the calcite $\delta^{18}O$ values are much lower than typical sedimentary carbonate values, and in the case of the upper marble layer are close to a composition that would be in equilibrium with the adjacent leucogranite quartz at amphibolite-facies metamorphic temperatures. Biotite from the quartzite layer has a $\delta^{18}O$ value of +7.86 and a δD value of −58.

Profile B: $\delta^{18}O$ values of quartz and calcite from adjacent leucogranite and marble near Lake Lamoille at the head of Lamoille Canyon. The isotopic heterogeneity exhibited by samples less than a meter apart indicates limited exchange between these layers, but the carbonate samples have clearly experienced some ^{18}O-depletion.

(<100 meters away). Two important features are immediately recognizable. One is the very low $\delta^{18}O$ of the entire suite of rocks. The second is the extreme oxygen isotope uniformity of quartz in all samples.

Despite the fact that these rocks include metasediments that elsewhere characteristically have $\delta^{18}O$ values well in excess of +10, all of the Lizzies Basin samples have $\delta^{18}O < +10$ (except for one carbonate). Most whole-rock silicate values, including a wide variety of both igneous and metasedimentary rocks, lie between +6 and +8, close to the range of primitive, mantle-derived igneous rocks. These values are in striking contrast to those of the mineralogically and compositionally identical leucogranites in the northern Ruby Mountains, which are much more ^{18}O-rich. Note that even the migmatitic paragneiss from Lizzies Basin (which contains leucogranite leucosomes and may represent a leucogranite source material) has a similarly low $\delta^{18}O$, implying that in the Lizzies Basin region, either the leucogranite source materials were strongly ^{18}O-depleted before they were melted or that subsequent ^{18}O-depletion affected *all* lithologies. Certainly, ^{18}O-depletion here was much more profound than anywhere else within the Ruby-East Humboldt igneous-metamorphic complex and involved downward shifts in $\delta^{18}O$ of 5 to 10 per mil in silicate metasediments, and 10 to 15 per mil in metacarbonates, which is probably as extreme as has been observed in any other high-grade terrane worldwide.

In addition to extreme ^{18}O-depletion, mineral pairs within the Lizzies Basin rocks are close to high-temperature isotopic equilibrium, both within and between samples. Quartz-biotite fractionations range from 3.6 to 5.5, indicating equilibration temperatures of 550–800°C (FRIEDMAN and O'NEIL, 1977). This compares favorably with metamorphic temperature estimates of 650–700°C (M. T. PETERS, pers. comm., 1991). Most of the variation in

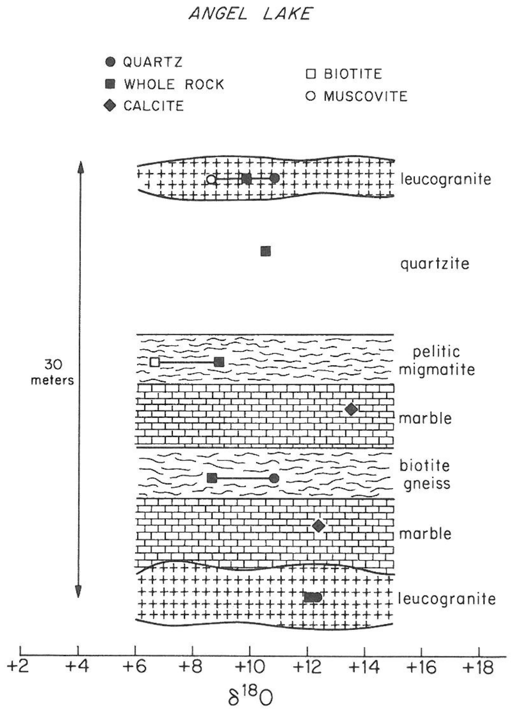

FIG. 4. Oxygen isotope variation across a 30-meter profile through intercalated leucogranite, quartzite, pelite, biotite gneiss, and marble layers at Angel Lake at the northern end of the East Humboldt Range (see Fig. 1). All the metasedimentary rocks (with the possible exception of the quartzite) have $\delta^{18}O$ values considerably lower than those of their inferred sedimentary protoliths.

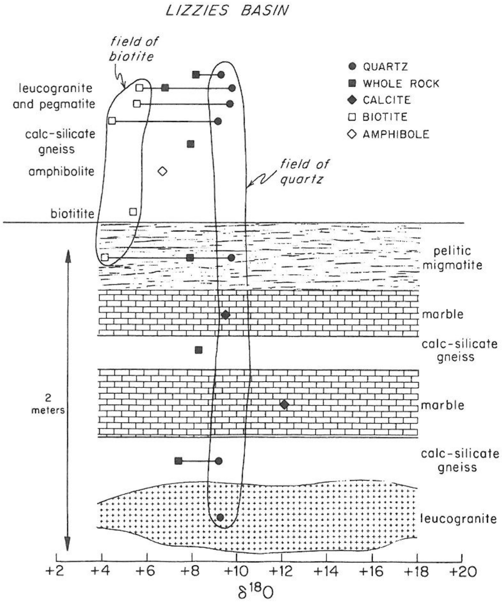

FIG. 5. Oxygen isotope whole-rock and mineral data from Lizzies Basin, including samples from a two-meter section through interlayered metasediments and granites. Other data for samples collected nearby (over an area of ~0.5 km^2) are listed by rock-type and plotted in the upper part of the diagram. Note the extremely narrow range of $\delta^{18}O$ of quartz and biotite from contrasting rock-types; quartz-biotite fractionations of 4–5 per mil are typical of high-grade metamorphic rocks and indicate a close approach to equilibrium in these samples. The two calcite samples are slightly out of equilibrium with the quartz and biotite but are nevertheless very ^{18}O-poor compared with normal limestones, indicating that they have undergone $\delta^{18}O$ shifts in excess of ten per mil.

the $\Delta_{\text{quartz-biotite}}$ values is due to variation in the $\delta^{18}O$ of biotite, which may be due to several factors: (1) the smaller modal abundance of biotite in most samples; (2) the fact that biotite continues to exchange oxygen down to lower temperatures than quartz; or (3) to small amounts of alteration minerals in biotite separates (*e.g.*, interlayer chlorite), although this third possibility is unlikely because the samples are very fresh and do not have abnormally low δD values (see below).

Quartz, on the other hand, is extremely homogeneous in all samples analyzed (with the exception of one quartz vein within calc-silicate gneiss which may be a late-stage phenomenon). Seven other samples all have $\delta^{18}O$ quartz between +9.0 and +9.7, a remarkably narrow grouping considering the diverse range of rock types. This shows that at Lizzies Basin, all lithologies were profoundly ^{18}O-depleted, and also came close to high temperature equilibrium on much longer length scales (at least tens of meters) than is observed anywhere else in the study area. The only rock types not equilibrated are calcite-rich marbles, which, if they were in equilibrium with the quartz at 700°C temperatures, should have attained $\delta^{18}O$ in the range +8.6 to +9.3 (CHIBA *et al.,* 1989). Nevertheless, considering that they would have started out with sedimentary values in the range +20 to +30, their measured values of +9 to +12 represent a close (although not complete) approach to equilibrium. The δD values of three of the biotite samples are relatively constant ($\delta D = -58$ to -68) and have typical plutonic values (as does the amphibolite, LB6), which suggests that no late-stage meteoric-hydrothermal alteration has occurred.

Secret Creek gorge

All data discussed so far have been from high-grade rocks located at deep structural levels within the lower plate of the Ruby-East Humboldt core complex. In the Secret Creek gorge area, a cross-section through the upper plate-lower plate boundary is well exposed (SNOKE and HOWARD, 1984). This consists of a several hundred meter–thick zone of strongly mylonitic lower-plate rocks (including all the main lithologies from the igneous-metamorphic complex) that passes up into an anastomosing system of low-angle normal faults separating the mylonites from a low-grade, brittley deformed sedimentary and volcanic cover (SNOKE, 1980). Movement on this fault zone has been responsible for exhuming the mid-crustal lower-plate rocks (SNOKE and LUSH, 1984).

Preliminary data from the northern Ruby Mountains (KISTLER *et al.,* 1981; FRICKE and WICKHAM, 1990) suggested that certain fault-zone lithologies had been strongly ^{18}O-depleted as a result of interaction with heated meteoric water. In order to investigate this phenomenon further, and to evaluate any connection with the deformational history in this area, we analyzed minerals and whole-rock samples from a variety of lithologies. Results are shown in Fig. 6 and include mostly mylonitic rock-types, variably affected by late-stage brittle deformation. Again, as seen at Lizzies Basin, quartz from leucogranite, quartzite, and a quartz vein (all mylonitized) is relatively uniform in $\delta^{18}O$ (+10.5 to +11.1), although the values are about one per mil higher than at the more deep-seated locality. However, whole-rock values in the various leucogranite lithologies are variable and include one very low value (+3.1 in RB59) that is clearly attributable to meteoric-hydrothermal alteration. Inasmuch as these samples comprise mostly quartz and feldspar, the $\delta^{18}O$ of the feldspars can be calculated by material balance to be even more ^{18}O-

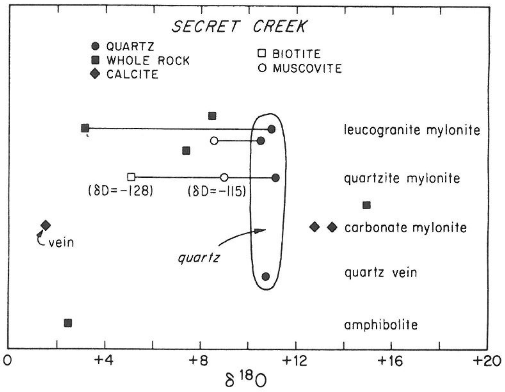

FIG. 6. Oxygen isotope data for whole-rock and mineral samples from Secret Creek gorge. Quartz from various rock-types is fairly homogeneous in isotopic composition and probably corresponds to metamorphic, pre-deformational values. However, some of the whole-rock values must have been affected by interaction with meteoric water because the $\delta^{18}O$ values are less than +6. Biotite and muscovite from a quartzite mylonite have very low δD values that are also consistent with meteoric hydrothermal alteration.

depleted than the +3.1 whole-rock value, underscoring the strong isotopic disequilibrium observed in these samples. This type of disequilibrium is commonly observed in meteoric hydrothermal systems around cooling high-level plutons and the ^{18}O-depletions at Secret Creek gorge may have been generated in a similar way, albeit with a different heat source, namely the rapidly uplifted mid-crustal rocks of the lower plate.

The δD values of muscovite (−115) and biotite (−128) in the quartzite mylonite (RB62) also provide evidence for meteoric water infiltration, even though $^{18}O/^{16}O$ ratios of the minerals in this sample are virtually unaffected (there are no obvious disequilibrium $^{18}O/^{16}O$ fractionations, and $\Delta^{18}O_{\text{quartz-biotite}}$ is ~6, only slightly higher than quartz-biotite fractionations at much deeper structural levels). The biotite in this rock is very fresh and unchloritized, suggesting that mylonitization and water infiltration occurred at moderately high temperatures (>400°C?). HURLOW *et al.* (1991) estimated a temperature of 580–620°C for a stage of the mylonitization, but it is possible that isotopic exchange could have occurred at lower temperatures.

The only other sample in which a strong ^{18}O-depletion is observed is in a calcite vein ($\delta^{18}O = +1.5$) within low-grade limestone of the Devonian Guilmette Formation from a locality immediately above the detachment fault zone. This unit is heavily veined, brittley deformed, but contains no mylonitic textures and cannot have been heated to high temperatures. Similar veins are common throughout the upper-plate rocks and probably indicate infiltration pathways of surface-derived fluids.

Very recently, FRICKE and WICKHAM (1990) and FRICKE *et al.* (1991) have detected strong ^{18}O-depletions ($\delta^{18}O$ as low as −1) in quartzite mylonites from the same locality. Because these samples have high quartz contents >95%, it is certain that even the quartz was strongly ^{18}O-depleted. This may be because fluid infiltration occurred locally at higher temperatures—or more likely that the strong dynamic recrystallization of quartz promoted isotopic exchange at temperatures of perhaps 400–500°C. In the absence of deformation, quartz would normally be very resistant to exchange with water in this temperature range.

Low-grade Paleozoic rocks

One of the great advantages in studying the metasedimentary rocks of the Northern Great Basin is that their low-grade protoliths are exposed nearby within the same region. Amphibolite-facies quartzites, schists, and marbles in the Ruby-East Humboldt Range have been identified as various elements of the miogeoclinal succession (HOWARD, 1971), including the Late Proterozoic McCoy Creek Group, Prospect Mountain Quartzite, and various Lower and Middle Paleozoic carbonate units. Unmetamorphosed fossiliferous sections through the Paleozoic rocks are exposed nearby in the southern Ruby Mountains and the Egan Range, and moderately metamorphosed (greenschist to locally garnet-grade, MISCH and HAZZARD, 1962) McCoy Creek Group rocks are exposed in the Schell Creek Range.

A few samples from these regions were analyzed in order to make direct comparisons between the various low- and high-grade stratigraphic units. The results are given in Table 1, plotted in Fig. 7 and discussed below. The quartzite samples were taken from Prospect Mountain Quartzite from both the southern Ruby Mountains and the Egan Range, and have typical sedimentary quartzite values of +12.3 and +13.3, respectively. Note that these values overlap only with the most ^{18}O-rich of the high-grade silicate samples. The McCoy Creek samples are even heavier, ranging from +11.7 to +16.2 in three samples from the Schell Creek Range. The higher-^{18}O samples are typical of low-grade shales, whereas the other is more typical of metapelites that have experienced some ^{18}O-depletion (at this locality the McCoy Creek rocks have locally been recrystallized to garnet-biotite schists).

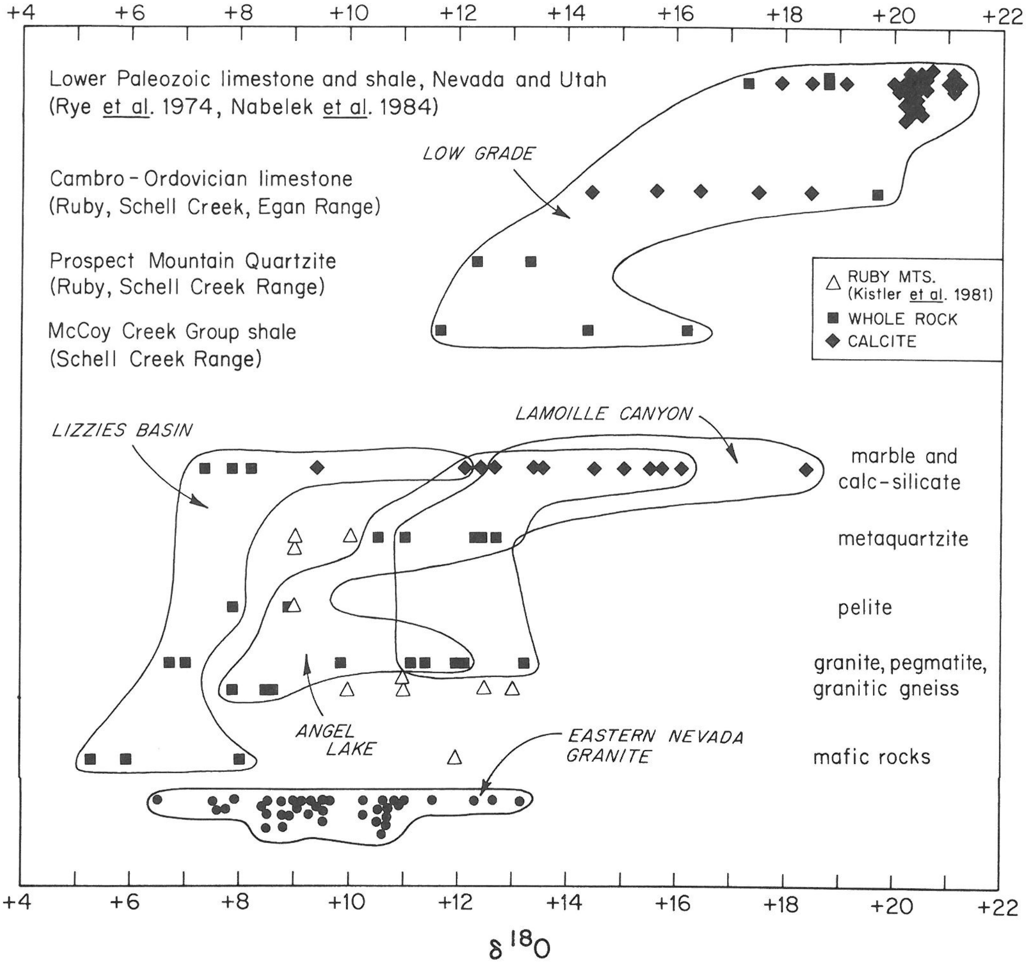

FIG. 7. A compilation of $^{18}O/^{16}O$ data from high-grade rocks of the Ruby Mountains-East Humboldt Range and from low-grade sediments elsewhere in the northern Great Basin, including some possible protoliths to the high-grade metasediments and granites. The high-grade lithologies are fairly homogeneous at a given locality, but vary considerably between localities, with Lizzies Basin being isotopically lightest and Lamoille Canyon being heaviest. Most of the high-grade lithologies have $\delta^{18}O$ values that are much lower than their present-day low-grade equivalent, and almost all the carbonates are much lower than typical sedimentary carbonate values of +20 to +30. These data imply that some of the metasediments have undergone shifts of 5–10 per mil to lighter values during their metamorphic history. Mesozoic and Tertiary granitic rocks span a range of values from +6.5 to +13.5, even though the granites at Lizzies Basin (+7) are mineralogically and compositionally almost identical to those from Lamoille Canyon (+11 to +13.5), implying that all these granites are derived from similar source material and suggesting that the metasedimentary source materials may have been variably depleted in ^{18}O prior to melting. The range is similar to that observed by SOLOMON and TAYLOR (1989) for many granite plutons from throughout eastern Nevada (solid circles at bottom of diagram).

The $\delta^{18}O$ values of limestones range from +14.4 to +18.5 (+19.7 in a chert from within one of the Egan Range limestones). Although these samples are all very low-grade, fossiliferous rocks, they all have $\delta^{18}O$ values considerably lower than those of typical sedimentary limestones (+20 to +30). $\delta^{13}C$ values in these samples are more normal (+0.6 to −4.9), with the exception of one sample (EG3) with a strongly negative $\delta^{13}C$ of −19.0, which probably indicates a strong influence of organic matter on the carbon isotope signature.

The relatively low $\delta^{18}O$ values of these fossiliferous limestones indicates that ^{18}O-depletion processes have operated at quite low grades within certain parts of the miogeoclinal sedimentary sequences, even in seemingly unrecrystallized rocks, presumably either promoted by near-surface hydrothermal activity or occurring during diagenesis. Although none of the samples of limestone are close to any obvious intrusive igneous complexes, these kinds of $\delta^{18}O$ values are in fact typical of exposed carbonate rocks throughout much of the Basin and Range Province, which has had a complex Cenozoic history involving widespread volcanism and shallow plutonism accompanied by considerable low-temperature meteoric-hydrothermal alteration and formation of mineral deposits. Although we cannot as yet prove it with the available data set, it is possible that the ^{18}O-depletions in the low-grade limestones are largely attributable to shallow Cenozoic activity, and this would mean that the deeper-seated carbonate protoliths in the Mesozoic core complexes were not in general subjected to these low-temperature meteoric effects. If true, this would imply that the *metamorphic* ^{18}O-depletions discussed above are even larger than might be inferred from direct comparison of the $\delta^{18}O$ values of the metamorphic rocks with their "unmetamorphosed" protoliths.

DISCUSSION

Origin of ^{18}O-depletions in high-grade metasedimentary rocks

There is a wide variation of $\delta^{18}O$ within low- and high-grade equivalents of the same rock type (*e.g.*, limestones and marbles, shales and pelites), as well as a wide variation in the oxygen isotope composition of the granites, many of which are metasediment-derived. For example, calcite from metacarbonate rocks spans 15 per mil in all samples (+9 to +24 in high-grade rocks, +14 to +19 in low-grade rocks), which covers virtually the entire range of metamorphic and sedimentary values that are commonly reported worldwide. For pelites the range in all samples is 8 per mil (+8 to +16), whereas for leucogranites it is 6.5 per mil (+6.7 to +13.2), covering almost the entire range of $\delta^{18}O$ values in fresh, unaltered igneous rocks.

In general, the higher-grade metamorphic rocks have lower $\delta^{18}O$ values than the lower-grade rocks, though there is also some geographic and geologic control on $^{18}O/^{16}O$. This ^{18}O-depletion effect is particularly apparent in our data in the samples from the Lizzies Basin region of the East Humboldt Range, where the metasediments acquire extraordinarily low $\delta^{18}O$ in the range +7 to +9 (for silicates) and +9 to +12 (for carbonates). WICKHAM and PETERS (1990) analyzed a large selection of samples from the same area and documented similar low values over a considerably wider area, averaging +7.6 in silicate rocks. They also noted that $\delta^{18}O$ increased to higher values at higher structural levels at this locality (average +10.4 in silicates), though these rocks were still markedly ^{18}O-depleted compared with their low-grade sedimentary precursors.

Each of the three high-grade geographic regions sampled in this study exhibits different degrees of ^{18}O-depletion (see Fig. 7), with the Lizzies Basin samples being most extreme, the northern Ruby Mountains samples being least extreme, and the Angel Lake samples being somewhat intermediate. The magnitude of the isotopic shift is different for different rock-types, with the quartzites least affected (a shift in the mean value of about 2 per mil between low- and high-grade samples), the pelites shifted about 5 per mil, and the carbonate rocks variably ^{18}O-depleted from 0 to >10 per mil. The *geographical* variation in ^{18}O-depletion is superimposed on this *lithological* variation.

The most extremely ^{18}O-depleted region also is the most isotopically homogeneous and the one in which the mineral phases are closest to being in isotopic equilibrium (although the more detailed study by WICKHAM and PETERS (1990) has identified less well-equilibrated regions at structural levels above the Lizzies Basin rocks discussed in this work). This correlation between the degree of isotopic equilibration and the magnitude of $\delta^{18}O$ shift suggests a possible common cause. Clearly the isotopic effects require exchange with oxygen from a reservoir having a low $\delta^{18}O$ value—at Lizzies Basin lower than the average whole-rock value of ~ +7.5 that the metasedimentary rocks attain. The most likely oxygen reservoirs are

(1) mantle-derived igneous rocks or magmatic fluids derived therefrom, having $\delta^{18}O$ values of ~ +6;

(2) meteoric waters having a wide range of possible $\delta^{18}O$ values initially lower than or equal to 0;

(3) formation waters contained within the miogeoclinal sedimentary pile.

It seems unlikely that reservoir (2), pristine meteoric water, was responsible for the ^{18}O-depletion effects, because: (a) very low $\delta^{18}O$ values (≤ 0) are not observed in these rocks (except in the special case of the Secret Creek mylonites; see below); (b) the most extreme ^{18}O-depletions are observed in rocks from the deepest structural levels in the area (the "Lower Zone" at Lizzies Basin), and that are not near major fault zones; (c) hydrous silicates in these same rocks (with the exception of Secret Creek and two biotite samples from Angel Lake) do not have abnormally low δD values that would be characteristic of the meteoric ground water of this region in the Mesozoic ($\delta D_{muscovite}$ is −40; $\delta D_{biotite}$ is −58 to −68). However, reservoir (3), composed of relatively ^{18}O-rich formation waters derived originally from surface water, could potentially have played an important role in the ^{18}O-depletion process, particularly if such fluids became mobilized within the miogeoclinal sedimentary pile during metamorphism. Typical formation waters would have isotopic compositions ($\delta^{18}O$ = 0 to +8, CLAYTON *et al.*, 1966) lower than any of the low-grade sediments in the area and could easily account for shifts in $\delta^{18}O$ of several per mil, as suggested for Hercynian metasedimentary terranes in the Pyrenees (WICKHAM and TAYLOR, 1985).

Although formation waters could account for some of the ^{18}O-depletion, it is unlikely that the unusually low $\delta^{18}O$ values observed at Lizzies Basin were generated this way. Not only is this strongly ^{18}O-depleted zone restricted to the deepest structural levels in the area, but the values appear to be limited by +6 as a lowermost limit to $\delta^{18}O$; also, $\delta D_{biotite}$ has typical plutonic values (−58 to −68). This suggests that the isotopic composition is being buffered, not by the isotopic composition of surface-derived pore fluids, but perhaps by mantle-derived igneous rocks and fluids derived therefrom. The average $\delta^{18}O$ of the homogeneous quartz at Lizzies Basin is +9.4, which would be in $^{18}O/^{16}O$ equilibrium with olivine of +5.5, diopside of +6.5, and anorthite of +7.2 at 700°C (CHIBA *et al.*, 1989). In other words, these quartz values could very plausibly be buffered by isotopic equilibration with gabbro with a mantle-type $\delta^{18}O$ of about +6. In this respect, it is important to note that there is abundant geological and geophysical evidence for intrusion of mantle-derived magmas into the lower and middle crust of this area, particularly during Tertiary extension (GANS, 1987; VALASEK *et al.*, 1989; SNOKE *et al.*, 1990; GRUNDER and WICKHAM, 1991). These magmas are required to account for Tertiary mafic volcanism and would have provided a heat-source for the metamorphism and anatexis.

Small quantities of pore fluid circulating within the mantle-derived igneous rocks and adjacent metasediments could have promoted exchange between these two reservoirs (after the mafic igneous rocks had crystallized) while the total quantity of fluid in the system remained quite low. In this respect it is interesting to note that some of the Lizzies Basin mafic rocks analyzed by WICKHAM and PETERS (1990) show significant ^{18}O-enrichment ($\delta^{18}O$ as high as +8) in line with this sort of process. Alternatively, magmatic aqueous fluids released from the crystallizing magmas could also have been instrumental in buffering metasediment oxygen down to values of +6. Material-balance calculations based on a much larger Lizzies Basin dataset, as well as detailed mapping to estimate lithological proportions, will both be discussed in detail in a future publication (PETERS and WICKHAM, 1991).

Isotopic systematics in marbles

Metacarbonate rocks vary widely in isotopic composition, and part of this can be attributed to decarbonation, involving loss of high-^{18}O and high-^{13}C CO_2. However, these effects cannot amount to more than a few per mil (*e.g.*, NABELEK *et al.*, 1984) and are incapable of being the sole explanation of the observed variation. The data can be filtered to exclude low-calcite rocks that have been extensively decarbonated; considering only those samples containing >45% calcite, there is still a wide range of $\delta^{18}O$, and these values exhibit the same general pattern observed in the entire dataset, with the most extreme ^{18}O-depletion at Lizzies Basin and the least in the northern Ruby Mountains.

Carbon and oxygen isotope systematics from many calcite-rich marbles at Lizzies Basin (WICKHAM and PETERS, 1991) define mixing trajectories between sedimentary values ($\delta^{18}O \sim +22$, $\delta^{13}C$ variable but constant within a single layer) and mantle-type values ($\delta^{18}O \sim +6$, $\delta^{13}C \sim -6$). Figure 8 is a plot of $\delta^{13}C$ vs. $\delta^{18}O$ in the most calcite-rich samples from this study, which shows that the Lizzies Basin, Angel Lake, Ruby Mountains, and Low-Grade samples all plot as distinct groups having positive correlations of $\delta^{13}C$ and $\delta^{18}O$. This suggests that these samples were shifted to lower $\delta^{13}C$ values as well as lower $\delta^{18}O$ values by the petrologic processes being considered, consistent with shifts towards mantle-type $^{13}C/^{12}C$ and $^{18}O/^{16}O$.

Timing of ^{18}O-depletion

The high-grade rocks of the study area have experienced multiple intrusive, metamorphic, and deformational episodes. Without detailed geochronology it is very difficult to pin down the timing of the isotopic shifts with any certainty. Indeed, there is every likelihood that there have been multiple isotopic alteration events associated with the various heating episodes. Existing geochronometric data (WRIGHT and SNOKE, 1986; DALLMEYER *et al.*, 1986; SNOKE *et al.*, 1990) suggest that the most recent high-grade metamorphic event was early Tertiary and associated with anatexis and intrusion of various granitoids. This makes it likely that the most recent isotopic equilibration event (*e.g.*, the uniform $\delta^{18}O$ of quartz and uniform $\Delta_{quartz\text{-}biotite}$ at Lizzies

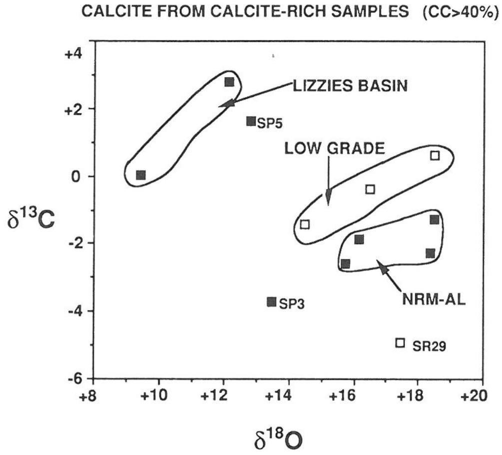

FIG. 8. δ^{13}C and δ^{18}O values of calcite from calcite-rich marble samples. The δ^{18}O values of all samples are significantly lower than the values of typical limestones. δ^{13}C values are variable but are positively correlated with δ^{18}O in the three groups of samples from Lizzies Basin, northern Ruby Mountains and Angel Lake, and three of the low-grade samples (shown as open symbols). This is similar to the correlations observed by WICKHAM and PETERS (1990, 1991) at Lizzies Basin based on a much larger data set. They conclude that carbon and oxygen isotopic compositions are being shifted towards equilibrium with a water-rich C-O-H fluid buffered to mantle-type δ^{13}C and δ^{18}O of −6 and +6, respectively. The two samples from Secret Creek gorge are a low-grade limestone (SP5) and a marble (SP3). The marble lies on the trend of the Ruby Mountains–Angel Lake samples, and it does not appear to have been significantly affected by late-stage meteoric effects.

Basin) may be of this age. The Tertiary was also a favorable time for mantle-derived magmatism which seems necessary to explain the extreme ^{18}O-shifts at Lizzies Basin. However, not all of the ^{18}O-depletion need have taken place at this time. Interaction between the miogeoclinal metasediments and pore fluids could have occurred much earlier in their history, from low-grade diagenetic effects on through any of the Mesozoic or Tertiary high-grade events.

There are clear differences between the low- and high-grade metasediments, and therefore most of the ^{18}O-depletion can be linked to metamorphism. Any heating event is likely to promote aqueous fluid movement within a metasedimentary pile, this fluid originating as either trapped formation water, original surface water, magmatic water, or metamorphic water liberated by dehydration reactions. Such movement of aqueous fluids will promote isotopic homogenization within and between different rock-types. If significant amounts of low-^{18}O fluid are present or can flux through the rocks, exchange at elevated temperatures will cause ^{18}O-depletion. Alternatively, the same kinds of ^{18}O-depletions could occur at relatively low water-rock ratios by fluid-mediated homogenization between primitive igneous rocks and metasediments. Perhaps interaction with pore fluids was more important during an early (Mesozoic) metamorphic cycle when the rocks were more hydrous and perhaps more permeable (as in the single metamorphic episode in the Hercynian of the Pyrenees, WICKHAM and TAYLOR, 1990). During a later stage (*e.g.*, the Tertiary) when the metamorphic pile had become more dehydrated, the metamorphism may have been dominated by isotopically primitive fluids from below (with these later effects only visible at the lowest part of the structurally deepest locality, Lizzies Basin). As indicated above, it is unlikely that any of the δ^{18}O signatures in the high-grade rocks (with the exception of those at Secret Creek gorge, see below) were significantly modified by any late-stage, low-temperature alteration event (although very local effects may be reflected in the anomalously low D/H ratio of the two Angel Lake biotites).

^{18}O/^{16}O systematics in granites

Like the metasediments, the granitic rocks span a wide range of δ^{18}O values from +6.7 to +13.2 (Fig. 7). Although there are different types of granite in the region, this range cannot be explained by compositional variation because the entire δ^{18}O range is observed within a single granite type, namely the leucogranites, which are the dominant igneous rock-type in the area. Leucogranites in the NRM are compositionally identical to those at Angel Lake or Lizzies Basin (S. M. WICKHAM and B. CHAPPELL, unpubl. data) yet vary in δ^{18}O by more than six per mil (see Fig. 7). The δ^{18}O variation cannot be ascribed to late-stage low-temperature hydrothermal alteration because, as noted above, the mineral pairs all have high-temperature equilibrium fractionations. It is thus likely that the δ^{18}O values of the leucogranites are magmatic values.

The leucogranites are compositionally uniform and identical in mineralogy to migmatite leucosomes in anatectic pelites; therefore, they could be derived from similar metasedimentary sources. Clearly the Ruby Mountains leucogranites must be almost exclusively metasediment-derived because they are so ^{18}O-rich ($+11 < \delta^{18}O < +14$). Why then is there a range to much lower δ^{18}O values in the East Humboldt Range? A probable answer lies in the widely varying δ^{18}O of pelitic metasediments in this region. Given that shales or pelites are favorable protoliths for these leucogranites, Fig. 7 shows that these rocks occur with ^{18}O/^{16}O ratios spanning a wide range from +16 to +8. All are compositionally similar (the only important difference being a lower water content in the higher-grade rocks) and all would, on melting, produce leucogranitic silicate melt; however, these different melts would obviously have strongly contrasting isotopic compositions inherited from the variable $\delta^{18}O$ of the source rock.

It thus seems likely that leucogranite petrogenesis probably involved metasedimentary source material first being isotopically altered to take on a range of $\delta^{18}O$ values—low values close to +6 in some areas such as Lizzies Basin, higher, more typical metasedimentary values around +12 or higher in other areas such as the northern Ruby Mountains. This material was then melted to produce leucogranitic magmas which, although derived from similar source rocks, would thus vary widely in $^{18}O/^{16}O$ ratio.

This effect has broad implications for the interpretation of isotopic systematics in crustally derived granitic rocks. Isotopic compositions are frequently used to identify source regions or source materials, and in the case of $^{18}O/^{16}O$ systematics, low $\delta^{18}O$ values $< +8$ are often taken to indicate a primitive igneous source containing little or no sedimentary material. The data from this study show that this interpretation can be flawed. Pelitic rocks and granitic magmas derived therefrom have a wide range of $\delta^{18}O$ values, depending on the degree of ^{18}O-depletion experienced at the diagenetic or metamorphic stage. This type of pre-anatectic isotopic alteration effect has been suggested to be important in a number of different terranes worldwide (WICKHAM, 1990) including the Hercynian of the Pyrenees (BICKLE *et al.*, 1988) and of Brittany (WICKHAM, 1990) but it is particularly well illustrated in this study. All of the leucogranites analyzed have identical major and trace element compositions and thus appear to be derived from similar source materials, yet they span the entire range of normal igneous rock $\delta^{18}O$. We believe this is because they were derived from sedimentary material that was isotopically altered in variable degrees at the metamorphic stage.

In Fig. 7 we show oxygen isotope data from granites from a large part of eastern Nevada, as compiled by SOLOMON and TAYLOR (1989). Although their compilation includes granites of more diverse chemical compositions and emplacement ages than the granites studied in the present work, it is interesting that their dataset covers the same range of values observed in the granites of the Ruby Mountains-East Humboldt Range. Although SOLOMON and TAYLOR (1989) used these data to suggest a model for the deep crustal structure of the northern Great Basin assuming that granites with different isotopic compositions were sampling different source regions, it remains possible that some of the variation is due to isotopic alteration of metasedimentary source material as demonstrated in this study, leading to a broadening of the range of $^{18}O/^{16}O$ ratios of magmas derived from a single unique source-rock.

Meteoric-hydrothermal effects (Secret Creek gorge)

Clear evidence for meteoric water infiltration is absent in most of the high-grade igneous and metamorphic rocks studied, with the exception of the samples from Secret Creek gorge. Here there is both mineralogical evidence for retrogression of higher grade rocks and strong deformational overprinting associated with the mylonite zone immediately underlying the detachment fault in this area. The oxygen and hydrogen isotope compositions of rocks from Secret Creek also show the effects of partial re-equilibration with low-^{18}O aqueous fluids. Several samples of both vein calcite and whole rock have very low $\delta^{18}O$, less than +6, which clearly result from exchange with meteoric fluids (see Fig. 6). In the leucogranite mylonite sample RB59, the whole-rock value of +3.1 is much lower than the value for quartz (+11.1), implying a quartz-feldspar fractionation of more than eight per mil, which is indicative of strong $^{18}O/^{16}O$ disequilibrium in this sample. This is typical of quartz-feldspar systematics in rocks subjected to meteoric-hydrothermal alteration (*e.g.*, CRISS and TAYLOR, 1986).

The quartzite mylonite (RB62) preserves high (amphibolite-facies) temperature fractionations between quartz, biotite, and muscovite, and the bulk $\delta^{18}O$ value for the sample is normal in the sense that it is similar to that of high-grade quartzites elsewhere in the region. However, the δD values of muscovite and biotite in this sample are −115 and −128, respectively, indicating that it has also interacted with meteoric water, although not in sufficient quantity to have disturbed the $^{18}O/^{16}O$ ratios. These data are plotted in Fig. 9 together with the other samples for which both $^{18}O/^{16}O$ and D/H ratios were determined. This diagram illustrates the contrasting isotopic systematics at different structural levels in the study area. The deepest level rocks at Lizzies Basin have "normal" plutonic D/H ratios and preserve no evidence for interaction with meteoric fluids. Two Angel Lake biotites are significantly D-depleted in comparison with these samples, while the Secret Creek micas (from the shallowest struc-

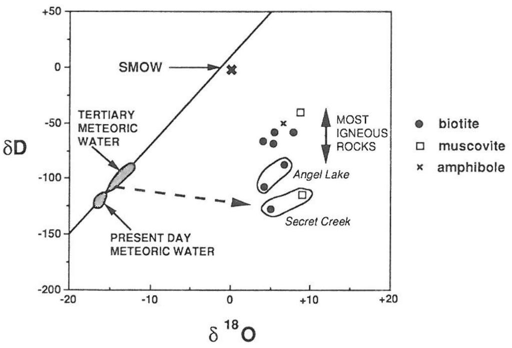

FIG. 9. The variation in $\delta^{18}O$ and δD for biotite, muscovite, and amphibole samples analyzed in this study. With four exceptions, all samples (including the low $\delta^{18}O$ samples from Lizzies Basin) have normal δD values that lie within the typical range observed in most igneous and metamorphic rocks. The anomalous samples all have unusually low δD values that reflect interaction with low-D meteoric water. This is most clearly displayed by biotite and muscovite from the Secret Creek quartzite mylonite (RB62), but the two Angel Lake biotites are also significantly D-depleted. The meteoric water line and the range of compositions observed in both modern day and Tertiary local meteoric water are shown (SHEPPARD *et al.*, 1969). The arrow indicates the likely evolution of such water towards a composition that could have equilibrated with the Secret Creek micas.

tural levels in the lower plate) have the lowest δD values of all. These samples could very plausibly have attained these values by equilibration with local Tertiary meteoric waters that had become ^{18}O-enriched by interaction with the local country rocks that they flowed through (as indicated by the arrow in the diagram). The more detailed study of FRICKE *et al.* (1991) has documented similarly D-depleted rocks throughout the Secret Creek region, coupled with strong ^{18}O-depletion in some samples.

The variation in ^{18}O-depletion observed at Secret Creek presumably reflects a very heterogeneous pattern of fluid infiltration. We find mylonitic high-grade rocks that have both preserved their high-grade mineral $^{18}O/^{16}O$ systematics and also those in which strong disequilibrium effects occur due to exchange with infiltrating meteoric water at moderate temperatures. Infiltration was probably fracture-controlled within the mylonitic rocks in the vicinity of the detachment fault. Fluid movement was probably promoted by the rapid uplift of rocks from mid-crustal levels. Uplift involved movement on the detachment fault, providing a favorable site for fluid infiltration due to the generation of abundant fractures, and the rapid uplift increased thermal gradients, promoting vigorous ground-water circulation within upper-plate rocks down to and including the level at which detachment faulting and mylonitization were occurring. The more comprehensive study of FRICKE *et al.* (1991) documents and discusses these processes in greater detail.

The only other low-temperature effects which have affected these samples are discernible in the very low-grade samples. As described above, some of the low-grade carbonate rocks have rather low $\delta^{18}O$ values compared with typical sedimentary limestones (+15 to +20), though clearly they are not nearly as ^{18}O-depleted as some of the carbonates in the high-grade areas. These low-grade rocks may have been affected by the same type of meteoric hydrothermal system as documented at Secret Creek, since these flow systems must have traversed extensive regions of the upper plate. More extensive studies of upper-plate sequences are now warranted in order to determine the extent of ^{18}O-depletion both in terms of the volume of rocks affected and the magnitudes of the isotopic shifts. Such studies will be important for improving our understanding of the formation of ore deposits hosted in low-grade miogeoclinal sedimentary rocks in northern Nevada (*e.g.*, HOFSTRA *et al.*, 1991). These relatively low-temperature effects may be important precursors to the high-temperature ^{18}O-depletion processes occurring at deeper structural levels and higher metamorphic grades, or conversely, it is possible that the deeper samples never were subjected to such effects. A great deal of further work will be required to sort out these problems.

CONCLUSIONS

The generally observed ^{18}O-depletions in high-grade metasedimentary rocks, first documented by GARLICK and EPSTEIN (1967), provide testimony to the importance of aqueous fluid-rock interaction in metamorphic environments. In a previous study of this phenomenon in the Hercynian rocks of the Pyrenees (WICKHAM and TAYLOR, 1985, 1990) widespread lowering of $\delta^{18}O$ values in metapelites was attributed to interaction with surface-derived marine pore fluids during the single episode of prograde regional metamorphism that affected that area. This conclusion was based on regionally high δD values, and an absence of a local source of low-^{18}O primitive igneous rocks with which the metasediments could have exchanged. Similarly, in Hercynian rocks of the Black Forest, D/H and $^{18}O/^{16}O$ systematics were again instrumental in identifying surface water (this time meteoric) as the probable cause of regionally low $\delta^{18}O$ values in the metasediments and anatectic granites (TAYLOR *et al.*, this volume).

Although striking ^{18}O-depletions are also observed in the Ruby Mountains-East Humboldt Range core complex, this area differs significantly from the above Hercynian terranes in that much more carbonate and much less pelite are present in the sedimentary section. Also, Nevada has experienced multiple Mesozoic and Cenozoic metamorphic events. The extreme ^{18}O-depletion observed at Lizzies Basin, where the rocks approach mantle-like $^{18}O/^{16}O$ ratios yet also have normal plutonic δD values, probably occurred during the most recent (Cenozoic) metamorphic event. These systematics suggest that the $^{18}O/^{16}O$ and D/H ratios in these rocks may have been buffered by the isotopic compositions of mantle-derived magmas rather than by surface-derived pore fluids (although pore fluids certainly played an important role in the isotopic exchange process).

We do not rule out the possibility that aqueous fluids were an important low-^{18}O reservoir during the earlier (Mesozoic) metamorphic events experienced by this terrane. In particular, the first metamorphic event experienced by a thick sedimentary sequence is perhaps more likely to be dominated by the large scale movement of pore fluids, as evidently occurred in the European Hercynian terranes. In this way it is possible that both of these types of low-^{18}O reservoirs were involved in bringing about the variable degrees of ^{18}O-depletion observed in the Ruby Mountains-East Humboldt Range rocks. However, the details of the Mesozoic history of this terrane will be virtually indecipherable without a great deal more geochronological work. On the other hand, because it has not been overprinted, the most recent (Cenozoic) metamorphic event and associated buffering of the rocks to mantle-like isotopic compositions is accessible to detailed geochemical and petrological studies. The results of these investigations will be discussed more fully in future publications (WICKHAM and PETERS, 1991).

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