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Oxygen isotope study of the fossil hydrothermal system in the Comstock Lode mining district, Nevada

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Abstract—$\delta^{18}O$ analyses of >250 samples of volcanic and intrusive rocks from outcrops, mine workings, and drill cores are used to deduce numerous characteristics of the important hydrothermal system that was active in the Comstock Lode mining district in Miocene time. A bimodal distribution of whole-rock $\delta^{18}O$ values is observed: a group with $\delta^{18}O \approx +5$ to $+9$ made up of fresh to weakly altered samples, and a group with $\delta^{18}O \approx -4$ to $+3$ made up of samples that have been intensely altered by heated, low-^{18}O fluids derived from meteoric waters. The spatial variations of the $\delta^{18}O$ values are extremely regular on a regional scale, and the variations are small on the outcrop scale, even when samples having marked differences in appearance are compared. These observations provide strong confirmation of the pervasive nature of fluid-rock interactions in fracture-controlled meteoric-hydrothermal systems. A contour map of whole-rock $\delta^{18}O$ values reveals a 75 km^2 isotopic anomaly that was produced by this fluid-rock exchange event. The 2 km^2 Davidson Granodiorite occupies the central part of the anomaly, suggesting that the hydrothermal system was principally driven by this intrusion. The discrepancy in size between the altered zone and its central intrusion is significant, but can be explained if the region represents the remains of a major stratovolcano, a feature of appropriate areal size in which successive pulses of magma utilize the same central vent. Analogous relations at Bohemia, OR, Yankee Fork, ID, and Pilot Mountain, NC, suggest that these mining districts likewise represent ancient stratovolcanic centers, and imply that this geologic environment may be conducive to the formation of precious metal deposits.

The original configuration of the Comstock isotopic anomaly has been disturbed by displacements on large normal faults. The anomaly appears to have been extended in a southeastern direction by normal slip, and significant right-lateral distortion of the anomaly also may have occurred. A pronounced NNE-trending discontinuity in the $\delta^{18}O$ contours coincides with the trace of the mineralized Comstock fault. An intricate relation between faulting and hydrothermal activity is indicated, whereby fault displacement occurred both during and after the period of intense fluid circulation. An isotopic cross-section of the Comstock Lode, primarily based on analyses of outcrops and on samples collected by BECKER (1882) along the six-km-long Sutro tunnel and the one-km-deep Combination Shaft, displays: (1) a steep vertical $\delta^{18}O$ gradient in the hanging wall rocks directly beneath Virginia City, (2) a sharp, sloping, eastern margin for the hydrothermal system, (3) a pronounced, plume-like deflection of the $\delta^{18}O$ contours near the Comstock fault, and (4) an apparent one-km vertical offset of the $\delta^{18}O$ contours by the Comstock fault. We interpret these features as indicating that hot, buoyant groundwaters were strongly focussed upward along the Comstock fault, and that during subsequent rapid cooling and decompression these fluids deposited the most spectacular epithermal bonanzas ever discovered in the United States.

INTRODUCTION

ECONOMICALLY IMPORTANT concentrations of ore minerals commonly result from the migration of moderate- to high-temperature aqueous fluids in the Earth's crust. Oxygen isotope studies have unparalleled potential in deciphering the nature of hydrothermal processes, in part because (1) oxygen is *the* major constituent of water and crustal rocks; (2) oxygen isotope data can be used to estimate both the temperature of fluid-rock interactions and the isotopic composition of the fluid, which is, in many instances, indicative of the fluid source (*e.g.* UREY, 1947; CLAYTON and EPSTEIN, 1958; TAYLOR, 1974); (3) the $\delta^{18}O$ values of unaltered rocks fall within rather narrow and well-understood ranges, so that deviations produced by alteration are readily apparent (*e.g.* TAYLOR, 1968, 1971); (4) contour maps of $\delta^{18}O$ values provide remarkably regular images of the integrated intensity of fluid circulation in fossil hydrothermal systems (TAYLOR, 1971, 1977; TAYLOR and FORESTER, 1971, 1979; GREGORY and TAYLOR, 1981; CRISS and TAYLOR, 1983, 1986; LARSON and TAYLOR, 1986); and (5) many different types of ore deposits are hosted in rocks with anomalous $\delta^{18}O$ values, with mineralization being particularly concentrated in zones where ^{18}O

gradients are steepest (see BEATY and TAYLOR, 1982; ENGEL *et al.*, 1958; TAYLOR, 1973, 1977; O'NEIL *et al.*, 1973; RYE, 1986; SHEPPARD *et al.*, 1971; SHEPPARD and TAYLOR, 1974; CRISS and TAYLOR, 1983, 1986; CRISS *et al.*, 1983, 1985).

Previous $\delta^{18}O$ and δD studies of the Comstock Lode mining district by SUGISAKI and JENSEN (1971), TAYLOR (1973), O'NEIL and SILBERMAN (1974), and VIKRE (1989) disclosed the relation of the main-stage mineralization to fluids of meteoric origin. An indication of the size and shape of the fossil hydrothermal system in this region was provided by the preliminary oxygen isotope map discussed by CHAMPION and CRISS (1987) and CRISS *et al.* (1988).

This paper provides the first detailed discussion of the oxygen isotope contour map in the Comstock Lode mining district. In addition, these surface data are combined with data on samples from mine workings to provide a detailed vertical section of the $\delta^{18}O$ relations in the district. This three-dimensional isotopic image provides significant new and independent insights into the nature of this fossil hydrothermal system, including the geologic controls on the fluid circulation, the amount of post-alteration displacement on the principal faults, and the paleoenvironment of the district during Miocene time.

GEOLOGIC SETTING

The Virginia City area of western Nevada is famous for the Comstock Lode mining district, which produced more than 8 million ounces of gold and nearly 200 million ounces of silver, mostly during the period of 1863 to 1880 (BECKER, 1882; SMITH, 1943; WHITEBREAD, 1976; HUDSON, 1987). The district is principally comprised of a gently dipping sequence of volcanic flow deposits, mostly Miocene andesites of the Alta and the Kate Peak Formations, which overlie Mesozoic metasedimentary and metavolcanic rocks that have been intruded by Cretaceous granitic plutons (Fig. 1; THOMPSON, 1956). The Alta Formation, the main host of the ore deposits, is intruded by the *ca.* 2 km^2 Davidson Granodiorite, and the Alta and Kate Peak Formations are intruded by small bodies of andesite porphyry (THOMPSON, 1956).

This important mining district attracted the attention of many early geologists, all of whom commented on the widespread occurrence of gray-green andesites, termed "propylites" by von Richtofen in 1868 (see COATES, 1940). BECKER (1882) probably first recognized that this aspect of the rock was the result of some type of secondary alteration process, and these early studies therefore give the Comstock district the distinction of being the "type locality" for "propylitization" (COATES, 1940). Much discussion of this phenomenon followed, and geologists now recognize that propylitic assemblages, generally defined by the presence of epidote and/or chlorite plus other secondary minerals, are the product of moderate-temperature hydrothermal processes (*e.g.* COATES, 1940; ROSE and BURT, 1979). WHITEBREAD (1976) made a detailed chemical and mineralogical study of alteration in the Virginia City area, subdivided the propylitic assemblages into several subtypes, recognized the existence of alunitic and argillic alteration types, and noted a zonal arrangement of these assemblages around the main channelways of fluid transport.

The principal ore bodies in the Comstock district occur as wide, high-grade stockworks that are closely associated with major normal faults, principally the Comstock, Silver City, and Occidental faults (see Fig. 1; BECKER, 1882; HUDSON, 1987). Some of the displacement on these faults predates, or is synchronous with, the mineralization, whereas some displacement is also known to postdate the mineralization (COATES, 1940; HUDSON, 1987). The economically important main-stage mineralization occurred at 13 Ma, approximately synchronous with deposition of the Kate Peak Formation (WHITEBREAD, 1976). However, VIKRE *et al.* (1988) found that most of the alunite assemblages formed between 17 and 14 Ma, significantly before the formation of the principal lodes.

METHODS

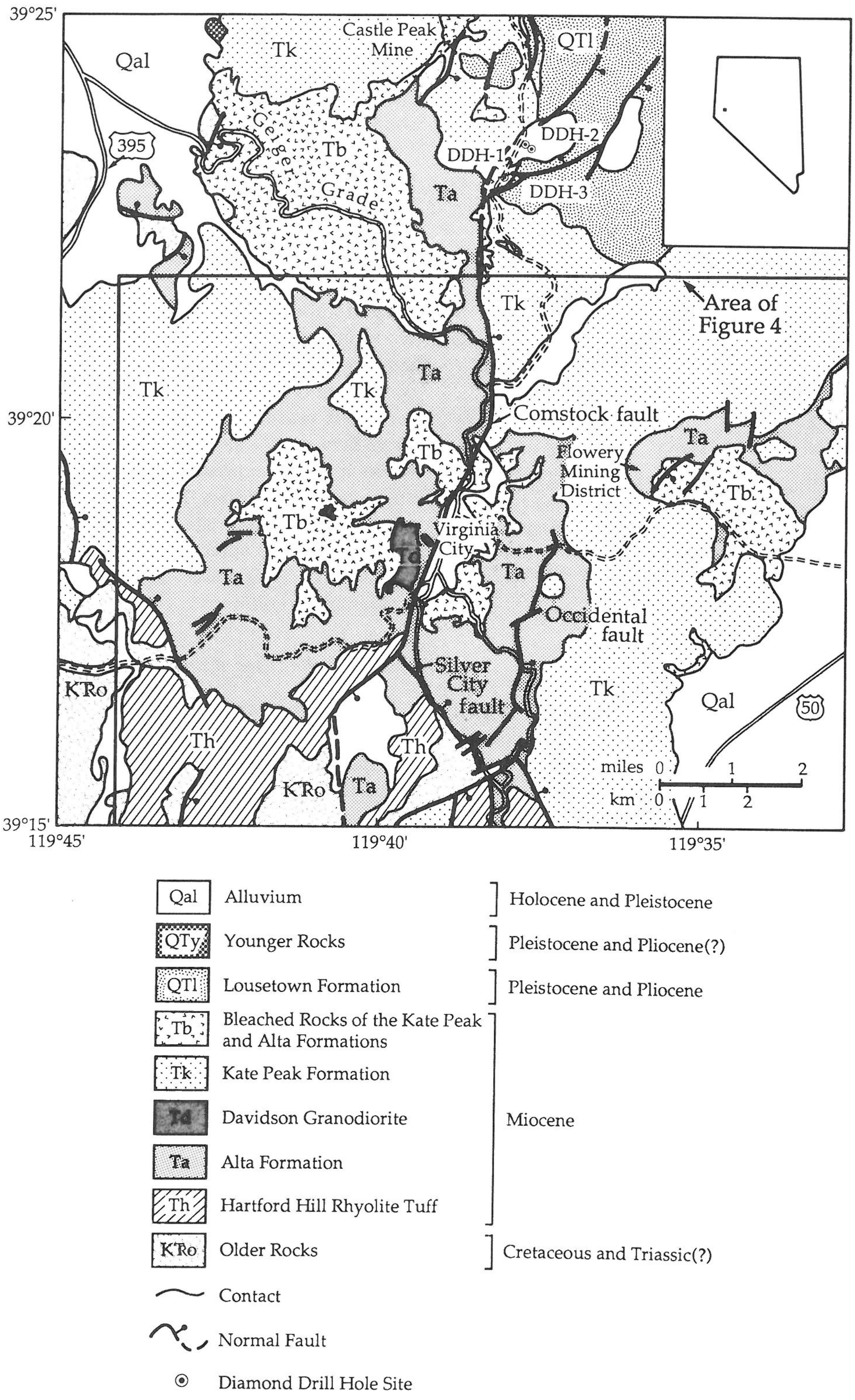
Standard fluorination techniques were used to extract oxygen from igneous rocks and vein materials (CLAYTON and MAYEDA, 1963; BORTHWICK and HARMON, 1982). The oxygen isotope ratios were determined on CO_2 gas in a mass spectrometer and are reported as per mil deviations from SMOW; precision is ±0.2 per mil. NBS-28 has $\delta^{18}O = +9.6$ on the scale we are using. All analyses reported here represent crushed but otherwise untreated whole-rock materials.

$\delta^{18}O$ VARIATIONS IN THE COMSTOCK LODE MINING DISTRICT

Subsurface vs. outcrop samples

The whole-rock $\delta^{18}O$ values of igneous rocks (mostly andesites) from the Comstock Lode mining district vary from $+11.7$ to -4.3. Two histograms (Fig. 2), one for outcrops and one for subsurface samples, were made to investigate this range and to determine whether weathered surface rocks provide an appropriate representation of the rock volume. Each of the two histograms exhibits two populations: a group with $\delta^{18}O$ values of about $+5$ to $+9$, and a group that has anomalously low $\delta^{18}O$ values ($< +2$). Questions arise as to the origin of these groups and of the sparsely populated range between them.

It is clear that the high-$\delta^{18}O$ group ($+5$ to $+9$) represents fresh or weakly altered igneous rocks in the region. Such values are typical of essentially unaltered, isotopically "normal" igneous rocks throughout the world (*e.g.*, TAYLOR, 1968). Also, most such rocks in the Virginia City area occur several kilometers from the zones of intense alteration and mineralization, although important exceptions


39°25'
39°20'
39°15'
119°45'
119°40'
119°35'
Qal
Tk
Castle Peak Mine
QTl
395
Geiger Grade
Tb
Ta
DDH-1
DDH-2
DDH-3
Area of Figure 4
Comstock fault
Flowery Mining District
Virginia City
Td
Occidental fault
Silver City fault
KTRo
Th
50
miles 0 1 2
km 0 1 2
Qal Alluvium
QTy Younger Rocks
QTl Lousetown Formation
Tb Bleached Rocks of the Kate Peak and Alta Formations
Tk Kate Peak Formation
Td Davidson Granodiorite
Ta Alta Formation
Th Hartford Hill Rhyolite Tuff
KTRo Older Rocks
Holocene and Pleistocene
Pleistocene and Pliocene(?)
Pleistocene and Pliocene
Miocene
Cretaceous and Triassic(?)
Contact
Normal Fault
Diamond Drill Hole Site

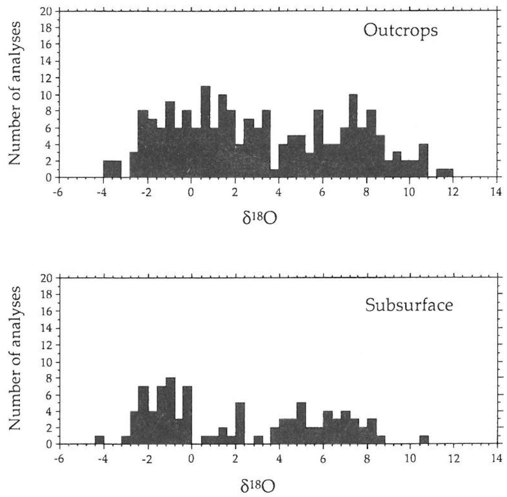


FIG. 2. Histograms of whole-rock $\delta^{18}O$ determinations for outcrop and subsurface samples from the Comstock Lode mining district. Both histograms display a population of isotopically "normal" rocks ($\delta^{18}O > +6$), a population of "strongly altered" rocks ($\delta^{18}O < +2$) affected by exchange with significant volumes of low-^{18}O fluid, and an intervening "gap" representing values typical of the perimeter of the hydrothermal system.

occur, as discussed below. The tails of this "normal" population on the high and low-^{18}O sides probably represent rocks that were hydrothermally altered at low and moderate temperatures, respectively.

It is equally clear that the low-$\delta^{18}O$ population represents "strongly altered" rocks that have undergone significant degrees of interaction and exchange with large volumes of heated, low-^{18}O fluids derived from meteoric waters. TAYLOR (1971, 1973, 1974, 1977) demonstrated that such hydrothermally altered rocks occur worldwide and are common in the western United States, as has been borne out by many subsequent studies (see CRISS and TAYLOR, 1986). All previous stable isotope studies of the Comstock Lode mining district have demonstrated that the rocks and vein materials bear the distinctive signature imparted by meteoric-hydrothermal fluids (SUGISAKI and JENSEN, 1971; TAYLOR, 1973; O'NEIL and SILBERMAN, 1974; CHAMPION and CRISS, 1987; CRISS *et al.*, 1988; VIKRE, 1989).

The sparsely populated "gap" between these "normal" and "strongly altered" populations mostly represents "peripheral zone" rocks collected near the edge of the fossil hydrothermal system. Such zones are typically characterized by very steep lateral or vertical $\delta^{18}O$ gradients (TAYLOR and FORESTER, 1979; CRISS and TAYLOR, 1983, 1986). Accordingly, the volume of rock exhibiting $\delta^{18}O$ values in this intermediate range is small relative to the volumes of essentially unaltered or highly altered rocks, and this translates into their low abundance, as seen in the histograms.

A difference between the outcrop and subsurface samples is that the latter seem to be systematically lower in ^{18}O (Fig. 2), exemplified by the fact that the altered population has a higher average $\delta^{18}O$ value in outcrop than in the subsurface. Also, the "peripheral zone" samples have $\delta^{18}O$ values that range from approximately +2 to +5.5 in outcrop, but from 0 to +4 in the subsurface. Last, rocks having very high $\delta^{18}O$ values of > +9 almost exclusively occur in outcrop; these probably represent alteration very close to the paleosurface. In total, the differences between the surface and subsurface samples probably do not represent some recent weathering effect, but rather the fact that the subsurface samples were altered at systematically higher temperatures than those of the outcropping rocks, a direct consequence of their lower average structural and stratigraphic positions.

Pervasive character of the alteration

Some reports in the current literature emphasize the importance of "channelized flow" in hydrothermal systems, wherein the fluid flux is presumed to be largely confined to a few large, identifiable structures. Although permeabilities will typically be enhanced along major faults, for example, along caldera ring faults (CRISS and TAYLOR, 1983; LARSON and TAYLOR, 1986) and along large normal faults such as the Comstock fault (see below), we have concluded from studies of this and numerous other fossil hydrothermal systems that, in general, pervasive flow typically dominates the fluid flux and the oxygen isotopic relations.

The most direct and straightforward way to determine whether the fluid flow in a fossil hydrothermal system was channelized or pervasive is to examine lateral $\delta^{18}O$ variations on different scales. If the subsurface flow was dominantly channelized on a regional scale, then extremely sharp gradients in the $\delta^{18}O$ values should occur near the major structures, and rocks further away should all have normal values. If the flow was dominantly channelized but on a smaller scale, then different samples from individual outcrops should have highly variable $\delta^{18}O$ values, depending on the proximity to controlling minor structures such as small faults and joints. If, on the other hand, the flow was dominantly pervasive, the $\delta^{18}O$ values should exhibit smooth lateral variations on a large scale, and different samples from single outcrops would have similar $\delta^{18}O$ values.

Figure 3 compares the $\delta^{18}O$ values of multiple (in most cases, two) samples collected from individual outcrops. These samples were generally collected within 2 and 30 meters of each other. This comparison is an extreme one, because in all cases the multiple samples were collected because the rocks at the outcrop exhibited notable differences in appearance; some of the plotted pairs even compare dikes, and in one case vein matter, with wall rocks. The order of assignment of the data pairs to the cartesian coordinates of the graph is random.

Figure 3, like the histograms discussed above, demonstrates the dominance of the "normal" and "strongly altered" rock populations, as well as the intermediate "gap" where the "peripheral zone" samples would plot. In none of our investigated outcrops do isotopically normal rocks occur with strongly ^{18}O-shifted ones. Thus, visibly different samples from single outcrops exhibit, within a few per mil, similar $\delta^{18}O$ values. This result, together with the smooth and regular $\delta^{18}O$ variations on larger scales (see Figs. 4, 5, and 6, below), confirms the pervasive character of the alteration in the Comstock Lode mining district.

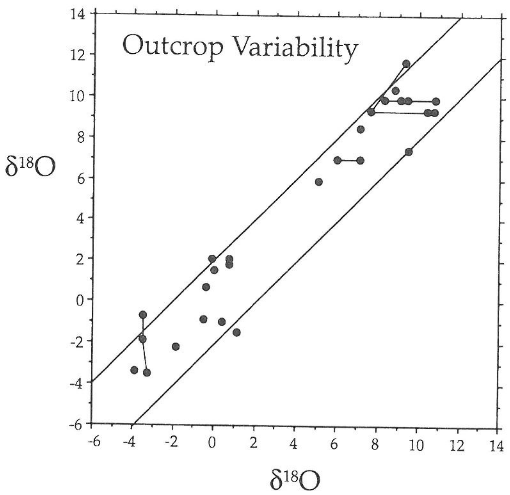


FIG. 3. Graph comparing the $\delta^{18}O$ values of multiple rock samples collected at single outcrops. In most cases each point represents two rock samples from a single site, but in cases where more than two samples were analyzed, the points representing that outcrop are connected by line segments. Even though the samples at each site exhibit notable differences in appearance, their $\delta^{18}O$ values are similar, demonstrating the pervasive character of the alteration. See text.

GEOGRAPHIC $\delta^{18}O$ VARIATIONS IN THE VIRGINIA CITY REGION

$\delta^{18}O$ contour map

A contour map of $\delta^{18}O$ values in the Virginia City region (Fig. 4) reveals two separate zones of anomalously low ($< +6$) values. The most important of these comprises a regular, equant, 75 km^2 zone that encompasses Virginia City. The very lowest (<0) $\delta^{18}O$ values occur along and west of the famous, NNE-trending Comstock lode and its southern extension, the Silver City lode, and along the subparallel Occidental lode. In addition, a few kilometers to the east of Flowery Peak is a separate, somewhat smaller (*ca.* 20 to 40 km^2) low-^{18}O zone that includes the Flowery Mining district. These two anomalous areas represent the former locations of important meteoric-hydrothermal systems.

Most of the anomalous areas are directly underlain by andesites of the Alta Formation (*cf.* Fig. 1; THOMPSON, 1956; WHITEBREAD, 1976). As already mentioned, the term "propylite" was coined by von Richtofen to describe these rocks, although many years passed before their indurated character was attributed to alteration by heated meteoric groundwaters (TAYLOR, 1973; this study).

The geographic variations of the $\delta^{18}O$ values in the 75 km^2 system are very smooth, comprising a coherent pattern that is approximately centered on the small (2 km^2) composite granodiorite stock at Mt. Davidson (Fig. 4). This variation would conform to a simple concentric, or "bullseye," pattern were it not for later distortion and a few rather abrupt discontinuities caused by faulting. The most important discontinuity coincides with the trace of the NNE-trending Comstock fault, which dips approximately 45°E. The first-order consequence of the displacement on this fault is that a "high-^{18}O tongue" of rocks, representing downdropped rocks of the hanging wall directly underlying Virginia City, divides the most altered rocks, *i.e.* those with $\delta^{18}O < 0$, into two separate zones. Because the vertical displacement on the Comstock fault is considerable—approximately one km, as discussed below—relative motion along it has extended the isotopic anomaly to the southeast. The $\delta^{18}O$ pattern additionally suggests that perhaps as much as two kilometers of right-lateral distortion has occurred, perhaps also representing fault displacement.

$\delta^{18}O$ variations along the Sutro Tunnel

Because of the economic importance of the Virginia City area, more than 1000 km of workings

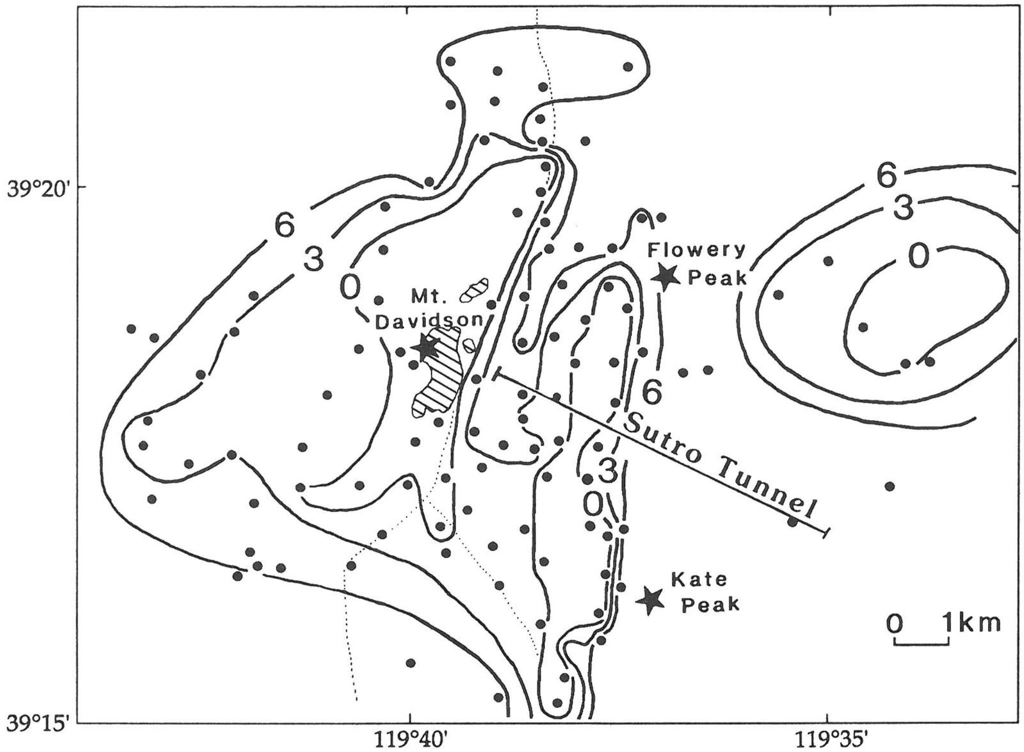


FIG. 4. Contour map of whole-rock $\delta^{18}O$ values (dots) from intermediate composition volcanic rocks of the Comstock Lode mining district. A 75 km^2 zone of low ^{18}O rocks ($-4 < \delta^{18}O < +6$), produced by interactions of the rocks with low-^{18}O fluids, is centered on a small, 2 km^2 stock at Mt. Davidson (ruled pattern) that represents an ancient volcanic center. The famous Comstock Lode ore deposits occur near and along the prominent, NNE-trending Comstock and Silver City faults (dotted lines). See Fig. 1 for geologic and geographic features. Modified after CRISS *et al.* (1988).

were excavated for exploration and production. One of the most famous ventures was the six-km-long Sutro Tunnel, dug between 1869 and 1878 for drainage, exploration, and haulage (SMITH, 1943; see Fig. 4 for location). Although this and most other old workings in the district are now either caved, flooded, or otherwise inaccessible, nearly 1500 subsurface samples were collected more than 100 years ago by George Becker and his associates; these collections have been carefully curated by the Smithsonian Institution. Becker collected samples every 100 feet along the Sutro Tunnel, and sometimes at shorter intervals, so that more than 270 samples are available in the Smithsonian Institution collection along this transect. A separate collection of Sutro Tunnel samples is curated by the U.S. Geological Survey.

Figure 5 is a graph of $\delta^{18}O$ variations vs. distance along the Sutro Tunnel. Because distances along the tunnel were very accurately known, we have experienced no difficulty in combining the results for the Smithsonian Institution collection with those obtained on the samples curated by the U.S.G.S. We originally were unaware of the extensive Smithsonian Institution collection and were delighted to learn of it, in part because the U.S.G.S. collection does not include any samples in the particularly interesting interval between 8,000 and 13,000 feet.

Figure 5 clearly illustrates the pronounced isotopic contrast between the "normal" (> +6) rocks outside the hydrothermal system and the "strongly altered" (−4.3 to +1.5) rocks within it. It is interesting that many of these low-^{18}O rocks occur about 500 meters directly beneath surface rocks, with $\delta^{18}O$ values as high as +7.4 (*cf.* Fig. 4), indicating that a steep vertical ^{18}O gradient existed in the hydrothermal system. Also obvious is the sharp but continuous character of the $\delta^{18}O$ variations in the peripheral zone, again demonstrating the relative rarity of rocks with $\delta^{18}O$ values that lie between those of the "normal" and "strongly altered" populations. CRISS and TAYLOR (1983, 1986) emphasize the im-

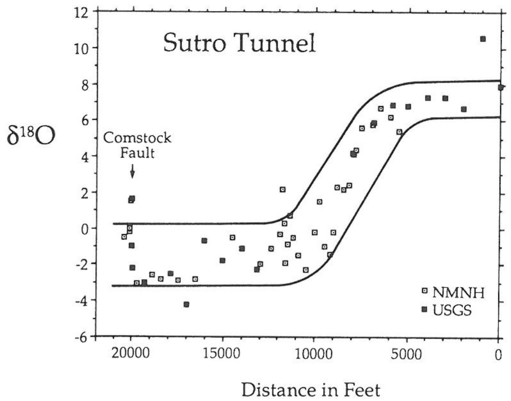


FIG. 5. Variations in the whole-rock $\delta^{18}O$ values of samples along the Sutro Tunnel. Solid squares represent samples curated by the U.S. Geological Survey, and open symbols represent samples from the extensive Becker collection of the National Museum of Natural History. Note that the isotopically normal samples near the tunnel portal are separated from the strongly altered samples by a zone of high-^{18}O gradients between approximately 6,500 and 9,000 feet.

portance of such peripheral "high-^{18}O gradient" zones in fossil hydrothermal systems, but these new results provide the best documented example.

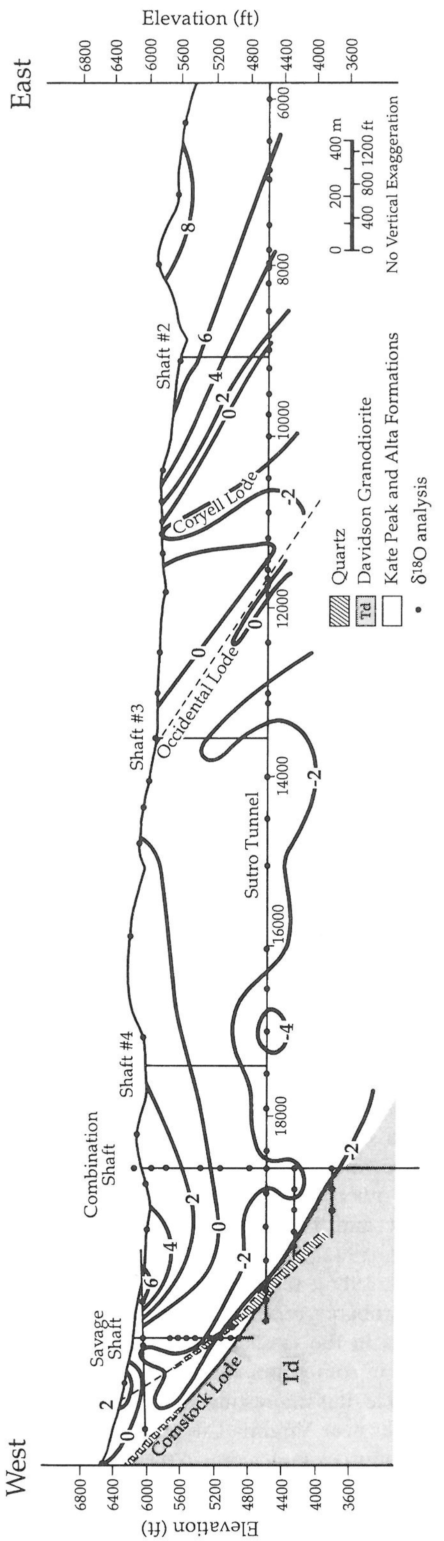
The uniform $\delta^{18}O$ values of rocks in the strongly altered zone provide probably the best confirmation to date that the alteration in meteoric-hydrothermal systems is generally of a pervasive character even in systems whose permeability is dominantly controlled by faults and fractures. This is because the rocks along the Sutro Tunnel (a) represent 100% exposure, so the data are not influenced by any effects such as differential preservation of altered and unaltered rocks, and samples could be collected at uniform intervals; (b) have not been exposed, and so cannot be affected by any surface effects such as weathering; and (c) were not collected by us or by any person involved with this type of study whose sampling techniques might be biased. In virtually all other fossil hydrothermal systems that have been studied, the notion of pervasive fluid infiltration has been derived from $\delta^{18}O$ analyses of surface samples (*e.g.*, TAYLOR, 1971; TAYLOR and FORESTER, 1979; CRISS *et al.*, 1985; CRISS and TAYLOR, 1983, 1986). All previous surface studies except for the Skaergaard intrusion, which is almost continuously exposed as fresh, glacially polished outcrop (TAYLOR and FORESTER, 1979), have suffered from this problem. It follows that none of the above-mentioned potential problems have previously arisen in any serious way, and that the concept of $\delta^{18}O$ mapping as originally practiced by H. P. Taylor and his coworkers is valid.

Isotopic cross-section of the Comstock Lode hydrothermal system

The $\delta^{18}O$ results for outcrops can be combined with the above described results along the Sutro Tunnel to construct the most detailed isotopic cross-section yet available of a hydrothermal system in an important mining district. This effort is enhanced because BECKER (1882) also collected numerous samples along the one-km-deep Combination Shaft, the Savage Shaft, the North Potosi Tunnel, and the Lightning Drift, all of which can be projected laterally for short distances into the vertical plane of the Sutro Tunnel. In addition, we have recently made a much more extensive collection of surface samples directly above the Sutro Tunnel than is indicated on Fig. 4.

The contours of Fig. 6 represent the available $\delta^{18}O$ results, superimposed on the vertical geologic cross-section along the line of the Sutro Tunnel drawn by BECKER (1882). The apparent large-scale features, from east to west, are (a) the isotopically normal rocks from the portal (0 feet, not shown) to a distance of about 6500 feet at tunnel level; (b) the sharp, east-sloping zone of high-^{18}O gradients, between about 6,500 and 9,000 feet at tunnel level, representing the effective eastern perimeter of the hydrothermal system; (c) the strongly altered zone that extends from this high-gradient zone to and beyond the tunnel terminus near the Comstock fault; and (d) the significant deflections of the isotopic contours along and above the Comstock fault.

It is interesting to examine in more detail the geometry of several noteworthy isotopic features that occur within the strongly altered zone. For example, a steep vertical ^{18}O gradient is present everywhere; analogous effects have been observed in several other fossil hydrothermal systems (*e.g.* TAYLOR and FORESTER, 1979; GREGORY and TAYLOR, 1981; CRISS *et al.*, 1984; LARSON and TAYLOR, 1986). In general, these vertical ^{18}O gradients probably reflect steep vertical temperature gradients in the fossil hydrothermal systems and possibly in some cases indicate the position of the water table. It is interesting to note that the hanging wall rocks near Virginia City, a short distance east of the Comstock fault, contain the most pronounced ^{18}O gradient in the region, ranging upward into rocks with essentially normal $\delta^{18}O$ values. Apparently, this part of the hanging wall was originally located very near the paleosurface directly above



the central part of the fossil hydrothermal system; these rocks were probably preserved by significant downdropping (see below).

In addition, the $\delta^{18}O$ contours on either side of the Comstock fault seem to exhibit a very substantial vertical offset. Simply stated, the $\delta^{18}O$ values of the footwall at the summit of Mt. Davidson (elev. 7864 feet ASL; see Fig. 4) are quite similar to those of the hanging wall at the Sutro Tunnel Level (*ca.* 4600 feet ASL)! The straightforward interpretation is that the original, hydrothermally produced $\delta^{18}O$ contours have been vertically offset by approximately 3200 feet (one km). Additional improvements in this isotopic cross-section and the construction of others may serve to refine this estimate, but our result is in reasonable agreement with geologic estimates of displacement (see summary in VIKRE *et al.,* 1988).

The Comstock fault did not merely displace the $\delta^{18}O$ anomaly, however. The vein material and associated mineralization clearly indicate that this major fault was in existence, and probably repeatedly active, while the hydrothermal system was active. This relation is also indicated by the pronounced, "plume-like" upward deflection of the $\delta^{18}O$ contours in a broad zone of enhanced permeability along the fault (Fig. 6). Because this zone is several hundred meters wide, however, the fluid flow is seen even in this case to have had an extremely pervasive character. An important effect of this buoyant plume is that it brought high-temperature fluids very close to the paleosurface, further steepening the already steep ^{18}O gradients referred to above. It is no accident that the rocks in this zone hosted several of the most spectacular epithermal bonanzas ever exploited. Again, this zone is characterized by several very important features, including: (1) the spatial association of a major fault near the central intrusion of a hydrothermal system; (2) the repeated activity of this fault during (and after) mineralization; (3) the preservation of hanging wall rocks that were originally located very close to the paleosurface; and (4) the existence of one of the steepest ^{18}O gradients ever observed in a meteoric-hydrothermal system. A close association between

FIG. 6. $\delta^{18}O$ cross-section of the Comstock Lode along the line of the Sutro Tunnel. The contours define a meteoric-hydrothermal system with a vertical extent of several km that featured focussed, buoyant uprise of deep, hot, fluid along the highly mineralized Comstock fault. See text.

steep ^{18}O gradients and economic mineralization has also been found in several other mining districts (CRISS *et al.,* 1983, 1985; CRISS and TAYLOR, 1983, 1986).

Other areas of interesting isotopic structures occur in the altered zone. A plume-like structure is associated with the "Coryell Lode" mapped by BECKER (1882), about 10,500 feet from the portal of the Sutro Tunnel. It is not known whether this zone represents a fault zone or perhaps a small intrusion. Another example is near the Occidental fault, where an upward, plume-like deflection of the contours occurs in the footwall, yet an oppositely directed isotopic structure (an "antiplume") occurs in the hanging wall. It is interesting to speculate that this coupled isotopic structure could represent a convective gyre *centered on* the fault, and driven by a temperature difference between the hanging-wall and footwall rocks. Very different types of fluid flow might then be associated with faults, depending on conditions.

THE COMSTOCK LODE PALEOENVIRONMENT

The $\delta^{18}O$ map (Fig. 4) indicates that the 75 km^2 altered zone is much too large to be accounted for by the associated igneous intrusions (primarily the 2 km^2 Davidson Granodiorite) if the aggregate size of the latter is judged by their outcrop extents. For example, an intrusive mass of such size simply would not contain sufficient heat energy, by a factor of perhaps 100, to heat up the large volumes of fluid and rock involved in the fossil hydrothermal system. CRISS *et al.* (1988) suggest that this size discrepancy can be explained if the hydrothermal system was related to a repetitively active Miocene stratovolcanic center correlative to the Kate Peak Formation. Stratovolcanoes are of appropriate areal size, and could produce the andesitic and granodioritic rocks at Comstock. Also, they are generally subaerial and so would typically be associated with meteoric groundwaters, and would logically be associated with symmetrical geologic features such as "bullseye" isotopic anomalies. Even more importantly, the heat-balance problem mentioned above could be explained because successive pulses of magma could utilize the same central vent.

In following up on the stratovolcano concept of CRISS *et al.* (1988), VIKRE (1989) concluded from his fluid inclusion data that the important mineralization in the Comstock lode district was related to a Miocene stratovolcano at Cedar Hill, approximately one mile north of Virginia City. He also argued that the bonanzas are located "somewhat distal to thermal centers." The feature that VIKRE (1989) is describing is much too small and in the wrong area to produce either the isotopic patterns evident in Figs. 4 and 6 or the ore deposits that are clearly related to them.

If stratovolcanic environments indeed are associated with the types of oxygen isotope effects documented in the Comstock district, then one would expect that similar anomalies would be relatively common elsewhere. As pointed out by CRISS *et al.* (1988), available data suggests that this is indeed the case. "Bullseye" type meteoric-hydrothermal anomalies that are approximately 50 to 75 km^2 in areal extent have been found and extensively studied in: (1) the Miocene volcanic rocks of the Western Cascades, particularly in the Bohemia mining district, Oregon (TAYLOR, 1971); (2) Eocene rocks of the Challis volcanic field, Yankee Fork mining district, Idaho (CRISS *et al.,* 1985); and (3) late Precambrian metavolcanic rocks of the Carolina slate belt at Pilot Mountain, North Carolina (KLEIN and CRISS, 1988). All three of these areas are characterized by large piles of andesitic rocks that include zones of propylitic or sericitic alteration associated with major zones of ^{18}O depletion. Associated with these altered areas in every case are anomalous concentrations of precious and base metals. Significant orebodies were discovered at Yankee Fork and Bohemia. Last, in all three cases the area of the central intrusion appears to be *much* smaller than that of the low-^{18}O country rocks.

CONCLUSIONS

$\delta^{18}O$ determinations of volcanic and intrusive rocks from the Comstock Lode mining district have been used to obtain an image of the important meteoric-hydrothermal system that operated there in Miocene time. Extreme ^{18}O depletions occur in a 75 km^2 zone where pervasive fluid-rock interactions resulted in regional propylitization. The pervasive character of these interactions is proved by the extremely regular variations of the $\delta^{18}O$ values on a regional scale, together with the small $\delta^{18}O$ variations among visibly different rocks at the outcrop scale. The low-^{18}O zone may to first order be described as a set of concentric $\delta^{18}O$ contours centered on the rather small granodiorite stock at Mount Davidson. Several geologic and isotopic features are explained if a stratovolcanic center formerly existed in the region.

The significant relief and numerous historical samples from mine workings have been exploited to define the ^{18}O variations in the vertical dimension. The results confirm the sharp lateral boundary of the fossil hydrothermal system and show that a sharp vertical ^{18}O gradient is present throughout the altered area. Several plume-like areas of fluid upwelling are identified; the most important of these is associated with the Comstock fault and appears to be largely responsible for the deposition of the epithermal bonanzas for which the district is famous.

Post-alteration displacement along major faults in the region has distorted the original shape of the $\delta^{18}O$ anomaly. Significant vertical displacement along NNE-trending normal faults has extended the altered zone in a NW-SE direction. It also appears that significant right-lateral distortion of the isotopic anomaly has occurred. Detailed examination of the $\delta^{18}O$ contours indicates as much as one km of post-alteration vertical displacement along the Comstock fault. One consequence of this latter displacement is that rocks originally located near the paleosurface and directly above the central part of the hydrothermal system are preserved directly beneath Virginia City. Many of the most valuable orebodies were deposited in these rocks, including the famous Con Virginia bonanza. Additional isotopic data should help clarify the ancient geological and geochemical environment at the Comstock Lode, the relationship of fluid circulation to faulting, and the relationship of $\delta^{18}O$ contours to zones of economic mineralization.

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