CHARACTERIZATION OF FAULT-FILLING DEPOSITS IN THE VICINITY OF YUCCA MOUNTAIN, NEVADA

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ABSTRACT

The origin of calcite and opaline silica vein-like deposits that infill faults and fractures in the vicinity of Yucca Mountain has been the center of considerable controversy because the area is being characterized geologically as a possible site for the nation's first high-level nuclear waste repository. Various proposed modes of origin have differing implications for the performance of a geologic repository. A number of lines of evidence now converge and show that upwelling of ground water, either catastrophically in response to tectonic forces or passively in response to a regional rise in water-table elevation, was not responsible for the vein-like deposits. Field observations and mineralogic, petrographic, and paleontologic data all suggest an origin related to soil-forming processes. Isotopic data for carbon, oxygen, strontium, uranium, and lead all support this conclusion and further rule out involvement of any of the local aquifers.

INTRODUCTION

Yucca Mountain has been selected for geologic characterization as a possible site for the nation's first geologic repository for high-level radioactive waste. The area contains abundant hydrogenic deposits of calcite and opaline silica in both near vertical fault filling and surface parallel configurations. If the conditions that existed during deposition of the fault infillings can reasonably be expected to reoccur in the future, the various modes of origin proposed for the calcite and opaline silica in Trench 14 and similar deposits have very different implications for the performance of a repository.

The largest fault-filling exposure is at Trench 14 on the west side of Exile Hill (Fig. 1) across the Bow Ridge fault. This trench was excavated in 1982 as part of the investigation of Quaternary faulting in the vicinity of Yucca Mountain, Nevada (1). The 2-m-deep excavation exposed a vein-like deposit of calcium carbonate and subordinate opaline silica (Fig. 2). In 1984, the trench was deepened to 4m in an attempt to further elucidate the origin of this anomalously extensive deposit, and in 1991, the trench was deepened again to its current depth of 8m. In 1986, a peer review panel convened by the Department of Energy (DOE) summarized four main categories of depositional models as: 1) pedogenic, which would include any origin by meteoric waters interacting with surficial materials and depositing minerals along fractures formed by faults, 2) cold springs, which would include all origins by movement of regional or perched ground water along faults and deposition of minerals, 3) hydrothermal springs, which would involve ascent of hot water (T > >30°C) along faults and deposition of minerals, and 4) seismic pumping, which would involve movement of hot or cold water up along faults as a direct result of faulting.

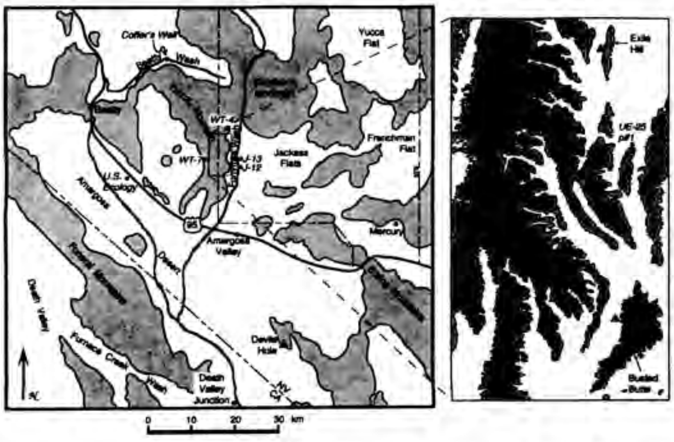


Fig. 1. Map showing the location of Trench 14 (triangle near Exile Hill) and the Busted Butte sampling site (southern triangle) (2).

Fig. 2. Photograph of the south wall of Trench 14 showing the large vein deposits of calcite and opaline silica and the rapid pinch out of the vein with depth.

DISCUSSION

Field and Mineralogical Data

Taylor and Huckins (3) compared field relations exposed by Trench 14 with those of typical pedogenic and spring deposits and concluded that the field evidence favored a pedogenic origin. For example, Trench 14 exposes slope-parallel calcic soil horizons (Fig. 2) that are laterally much more extensive than typical spring mounds of similar thickness (Fig. 3). The calcic horizons at Trench 14 can be traced back to the fault infillings where locally the two depositional forms merge (3). In addition, the new exposures at Trench 14 show that the veins pinch out and become discontinuous at depth whereas feeders for spring mounds typically maintain sub-parallel walls over depths of tens to hundreds of meters. Finally, calcite-silica veins contain infillings of basaltic ash that could have only washed into open fractures from above. Such a morphologic relationship would be difficult to produce if water were issuing from an open fissure.

The vein infilling at Trench 14 is porous and poorly indurated which contrasts to the typically dense and competent calcite veins found in feeder veins below spring deposits. The Trench 14 deposit consists of centimeter-scale bands including 1) laminae with abundant ooids and pellets, 2) laminae with abundant root casts, 3) relatively dense laminae with some evidence of tectonic shearing, 4) thin (<5mm) laminae of opal, and 5) rare laminae rich in sepiolite. Banding is megascopically present in spring deposits, but laminae in spring deposits tend to be microscopically similar to one another. Detrital minerals are rare or absent in veins that feed spring mounds; in contrast, about 20 percent of the vein material at Trench 14 is detrital. Figure 4 illustrates the considerable difference in texture between a typical spring deposit (Devils Hole) and the deposits in Trench 14.

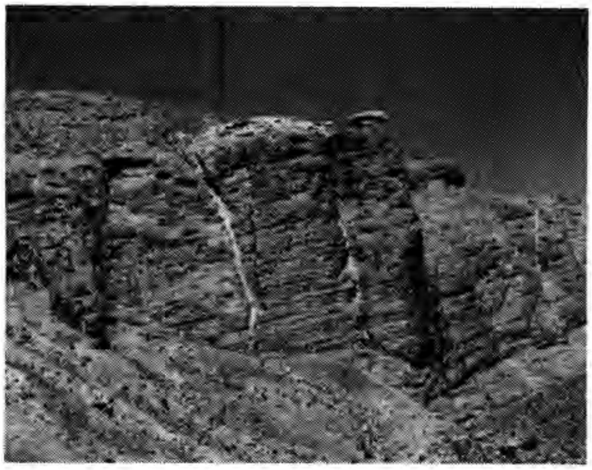


Fig. 3. Photograph showing a fossil spring mound and more than 60 m of feeder vein at Travertine Point along Furnace Creek in the Death Valley National Monument.

Opal occurs as opal-A (completely amorphous silica) and more commonly as opal-CT (a largely amorphous form of silica with short-range cristobalite- and tridymite-type stacking). Initial opal-A deposition typically occurs as a fossilization of the outer cell walls of millimeter-scale rootlets that are common in these deposits. The more abundant opal-CT may originate by dissolution and redeposition of the biogenic opal, but the wall rock for the veins and the entrained detrital material also provides an abundant source of silica that can be easily mobilized. In either case there is no need to appeal to deep-seated warm waters as a source of silica, and furthermore, such waters typically deposit spring mounds containing opal-A (4).

Unlike the silica in opal, there is no abundant local source for the calcium in calcite and thus the calcium must be transported by either wind or water. Dust in the arid southwest has a large calcium-carbonate component, and therefore, dryfall and wetfall could be the source for calcium at Trench 14.

Textural features are inconsistent with an explosive or hydrothermal origin. Many delicate features such as extremely fragile opaline root casts and "needles" of calcite (1-5 by 10-100 m) are preserved even in the first-formed or oldest laminae. Such features would have been destroyed in any high-energy depositional environment. Finally, the wall rock adjacent to the veins shows no signs of the oxidation (reddening) which is typical of rhyolitic rocks that have been exposed to hydrothermal solutions.

Stable Isotope Data

Quade and Cerling (5) showed that the carbon and oxygen isotopes in the vein carbonates at Trench 14 matched those in pedogenic carbonate collected over a wide area of southern Nevada (Fig. 5) and concluded that the isotopic

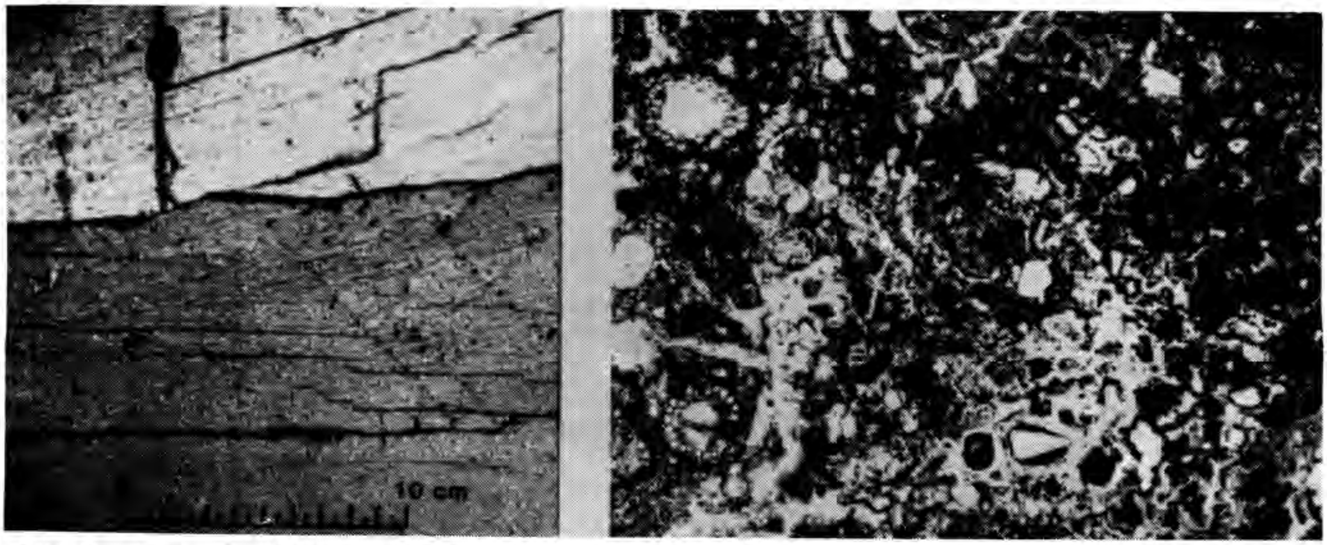


Fig. 4. Photomicrographs of (a) a sample of a typical spring-deposited vein and (b) a vein sample from Trench 14. Fields of view are approximately 2.5 mm across. Note the coarse crystal size in the former and the abundant detrital material and roots in the latter.

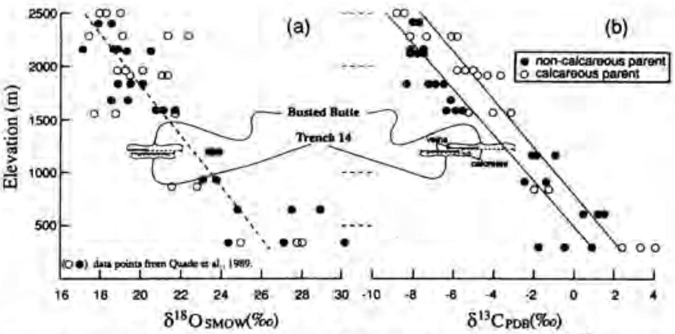


Fig. 5. Graph showing the relationship between $\delta^{13}C$ and $\delta^{18}O$ for pedogenic carbonates (6) and samples from the Trench 14 veins (7).

compositions suggested pedogenic deposition of the vein deposits and that the climate was cooler than at present with a mean temperature of about 15°C.

Whelan and Stuckless (7) analyzed 42 samples of soil carbonates and vein infilling from both Trench 14 and Busted Butte and found that the isotopic compositions of oxygen and carbon of most samples were virtually identical for the two locations and for the two types of deposits (soils and veins). A few of the Busted Butte soil carbonates were slightly enriched in ^{13}C and ^{18}O (Fig. 6), but the variability in the data is small enough such that all of the soil and vein carbonate can be explained by pedogenesis.

The calculated carbon and oxygen isotopic compositions of hypothetical calcites formed in equilibrium with ground waters of the Yucca Mountain area are very different from those measured for the vein calcites (Fig. 6). This difference shows that the veins could not have formed directly from ground waters like those present in the region today. Most of the available ground water data are for the Cenozoic aquifer for which the water table is at a depth of 460 to 700m in the vicinity of Yucca Mountain (8). Calculations based on lower temperatures for calcite precipitation would produce better agreement with the observed oxygen compositions of the vein calcites, but some of the waters would have to be cooled to impossibly low temperatures (0°C and lower) to precipitate calcite with the appropriate isotopic composition (Fig. 7). Isotopic compositions similar to those of modern precipitation would provide a closer match to the Trench 14 calcites and at reasonable temperatures (Fig. 7).

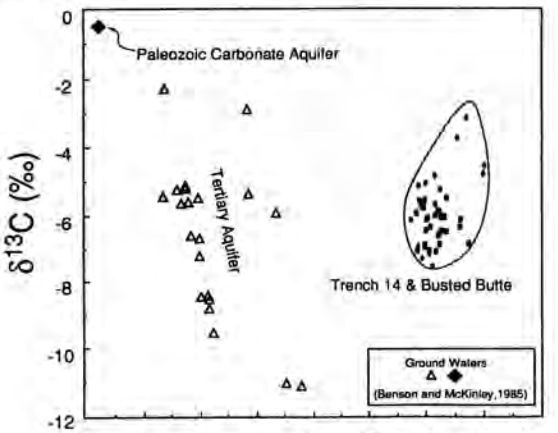


Fig. 6. Graph showing the relationship between $\delta^{13}C$ and $\delta^{18}O$ for carbonates from the Trench 14 (squares) and Busted Butte (ovals) compared with the calculated compositions of calcites precipitated in equilibrium with waters from beneath Yucca Mountain (triangles for Tertiary aquifer and diamond for the Paleozoic aquifer) (7).

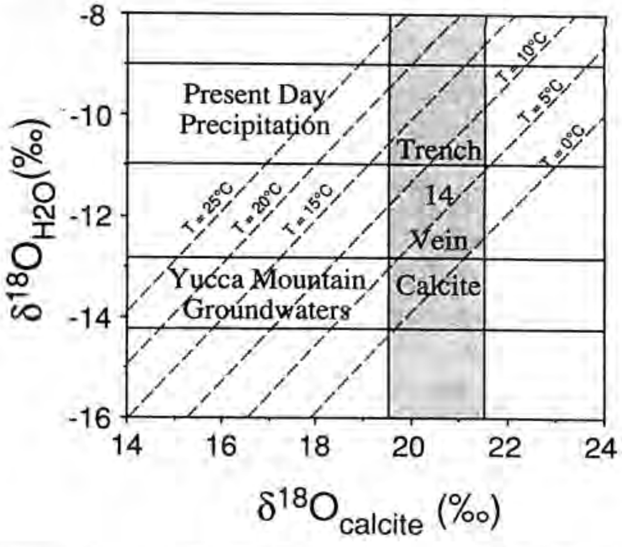


Fig. 7. Graph showing the relationship between $\delta^{18}O$ in calcite vein samples and $\delta^{18}O$ for water (9, 10) as a function of temperature. If a calcite has a $\delta^{18}O$ of about 20°/oo and formed from a water with a $\delta^{18}O$ of about -12.8°/oo, the calcite must have formed at about 5°C.

Carbon isotopes do not fractionate significantly between dissolved carbon and calcite at the temperatures in question. About half of the ground water samples, including the one sample analyzed from the Paleozoic aquifer, are either too enriched or too depleted in ^{13}C to be possible sources for the vein carbonates. Based on the similarity of carbon isotopic data in soils and the Trench 14 deposits, the most likely source for carbon in the Trench 14 calcites is biogenic.

The preceding discussion assumes that the isotopic composition of ground water beneath Yucca Mountain is representative of ground water that might have formed the Trench 14 veins. However, ground waters beneath Yucca Mountain have apparent ^{14}C ages of less than 20,000 yrs in the Tertiary aquifer and about 30,000 yrs in the Paleozoic aquifer (9), whereas the deposits in Trench 14 are much older with ages of 228 to greater than 400 ka (1).

The isotopic composition of ancient ground waters in the Yucca Mountain region cannot be determined. However, the Ash Meadows flow system, which is located just to the east of the Yucca Mountain area (11), has left a long-term record at its discharge site. Winograd, et al. (12) report uranium series ages for individual laminae within a vein of continuously deposited calcite at Devils Hole, and oxygen isotope analyses of these laminae show a variation of only ±1°/oo during the last 320 ky. A similar variation for waters beneath Yucca Mountain would be reasonable because the isotopic composition of both flow systems should be governed by the same climatic conditions. Even if a similar 1°/oo increase (at currently observed temperatures) did occur for ground water beneath Yucca Mountain, precipitated calcites would not have the isotopic compositions of those observed at Trench 14 (Fig. 6).

Radiogenic Tracer Isotope Data

The isotopic composition of strontium can be measured with great accuracy (±0.00005 or better in $^{87}Sr/^{86}Sr$ at the 95% confidence level), and thus small differences can be readily detected. Strontium isotopes do not fractionate during terrestrial geochemical processes (13), and therefore, the isotopic composition of strontium in calcite will be the same as that in the water from which the calcite precipitated. Studies of strontium isotopes in calcite from the Yucca Mountain area support a pedogenic origin for the veins exposed in Trench 14 and argue against a ground water origin (2, 14, 15). There is almost no overlap between the isotopic compositions of strontium for ground waters in the Tertiary aquifer and for Trench 14 vein carbonates (Fig. 8), especially in the Yucca Mountain area. The two water samples with the highest $^{87}Sr/^{86}Sr$ for the Yucca Mountain area were taken from drill holes in the unsaturated zone following a precipitation event. The three samples with the lowest $^{87}Sr/^{86}Sr$ were taken from the saturated zone, and the lowest of these is in the presumed up-flow direction from Trench 14 (Fig. 9). A bailed sample from the Paleozoic aquifer (Fig. 8) is also significantly different from the Trench 14 veins. Thus none of the saturated-zone waters sampled to date in the Yucca Mountain area can be related genetically to the calcite deposits in Trench 14.

Data from Devils Hole can again be used to evaluate the likely compositional changes in ancient ground water beneath Yucca Mountain (Fig. 10). Although the variation of $^{87}Sr/^{86}Sr$, as a function of age, exceeds analytical error, the average composition has not changed greatly during the last 600 ky (2). Water within the Tertiary/Quaternary aquifer in the Yucca Mountain area probably behaved in a similar fashion because the recharge area and host aquifer have most probably not changed during the Quaternary. Thus, it is highly unlikely that water beneath Yucca Mountain ever had high enough $^{87}Sr/^{86}Sr$ values to have been a source for the strontium in the Trench 14 deposits.

The isotopic compositions of strontium in calcite in the near-vertical vein (Fig. 8) and sub-horizontal deposits at Trench 14 show a fairly close correspondence, but the vein materials, on average, have a somewhat higher value. Over a broader region around the Nevada Test Site, the correspondence between vein and pedogenic calcite is much stronger

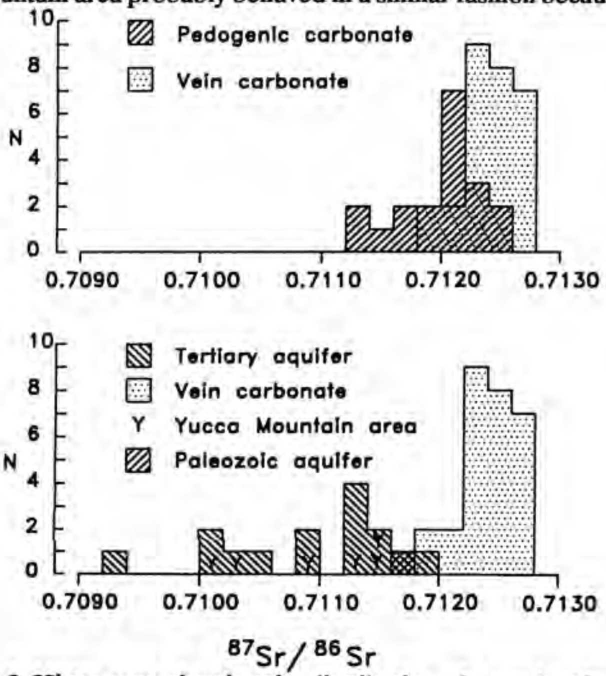
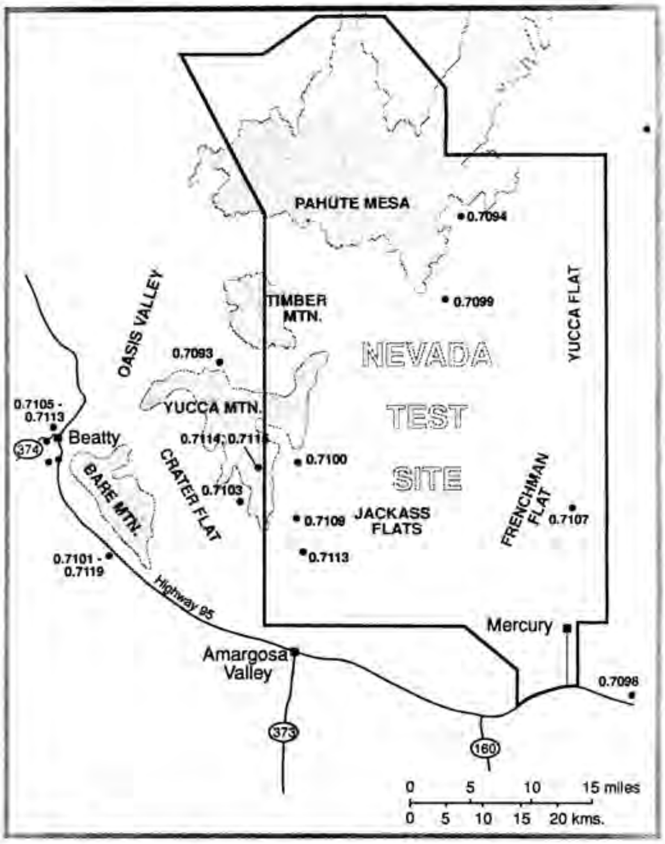


Fig. 8. Histograms showing the distribution of strontium isotopic compositions for the vein carbonates, pedogenic carbonates, and the Tertiary/Quaternary aquifer. Also shown are results for one sample of the Paleozoic aquifer obtained from UE-25p#1 (15).



$^{87}Sr/^{86}Sr$ Ratios of the Tertiary/Quaternary Aquifer

Fig. 9. Map showing the distribution of isotopic compositions of ground water in the vicinity of Trench 14.

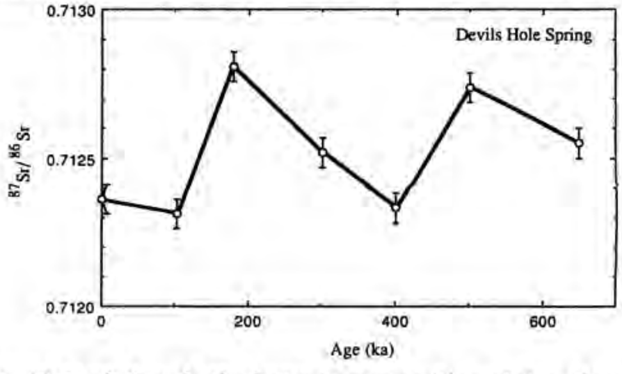


Fig. 10. Variations in the isotopic composition of strontium at Devils Hole, Nevada, as a function of age (2). Analytical error for strontium at the 95 percent confidence level is shown by vertical error bars.

0.71238±0.00026, N=39 and 0.71233±0.00028, N=37, respectively (14).

The isotopic composition of the vein carbonate may have been influenced in part by reaction of depositing fluids with entrained solid material, and the isotopic composition may also be affected by reaction with the host wall rock as well (2). However, most of the strontium in the sub-horizontal deposits (and, by geochemical analogy, calcium as well) seems to come from a well homogenized source such as wind-blown dust. Lead isotopic data yield the same general conclusions as strontium (16).

The remarkable homogeneity of strontium isotopic composition in hydrogenic deposits over a broad geographic region argues against deposition from ground water because the isotopic composition of ground water is very inhomogeneous in the vicinity of the Nevada Test Site (Fig. 9). Water emerging at the surface would impart this inhomogeneous characteristic to deposited calcite.

Uranium isotopes can also be used to fingerprint waters that have deposited carbonates. Like strontium, the isotopes of uranium do not fractionate during chemical reactions. Thus, the isotopic composition of uranium in water and a solid precipitated from that water will be identical. ^{238}U decays to ^{234}U, and when the two isotopes are in secular equilibrium the activity ^{234}U/^{238}U is 1.0. A 100% excess of ^{234}U relative to the ^{238}U parent would yield an activity ratio of 2.0. Disequilibrium between ^{234}U and ^{238}U can develop in ground water over time by alpha recoil and related processes (17).

Ground water in southern Nevada is typically anomalous with ^{234}U/^{238}U greater than 2.0 for most samples from both the Paleozoic and the Tertiary/Quaternary aquifers, but vein

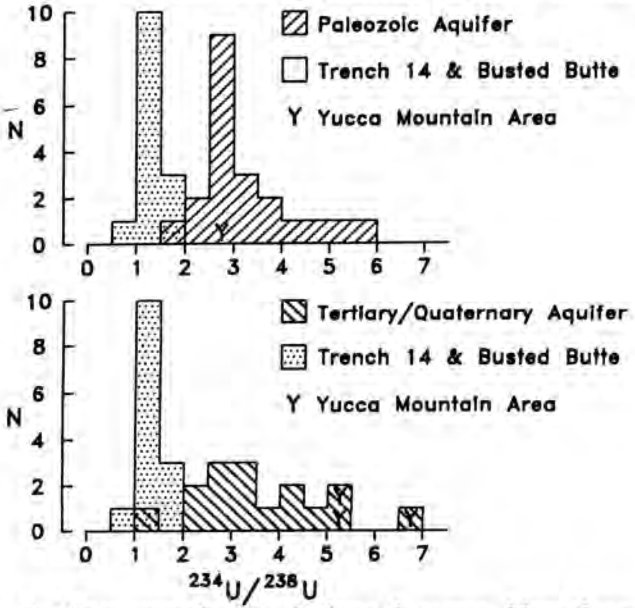
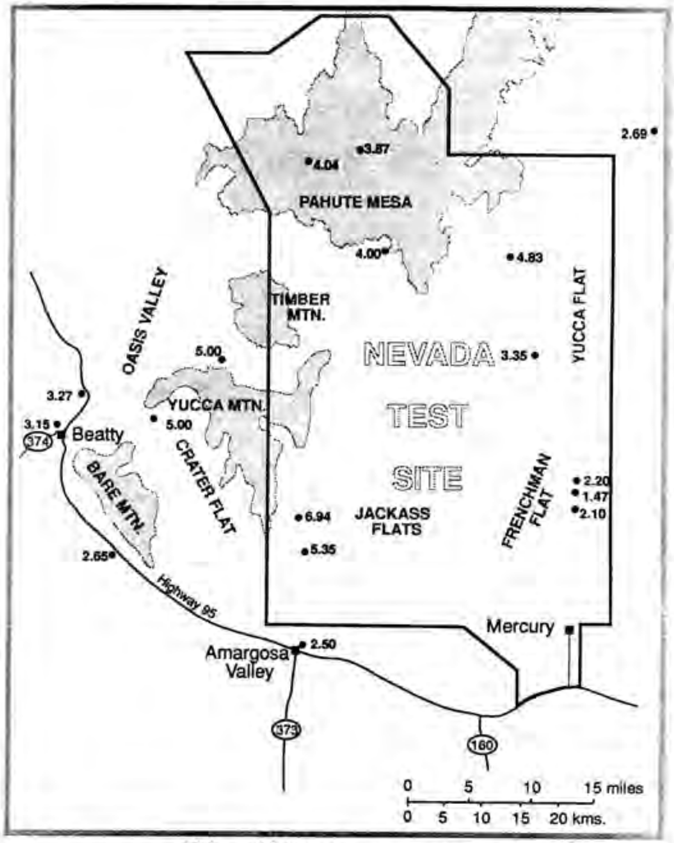


Fig. 11. Histograms showing the isotopic composition of uranium in Tertiary/Quaternary and Paleozoic aquifers and initial ratios for carbonates from Trench 14 and Busted Butte. The carbonate samples include 2 vein samples, 3 calcrete samples (all from Trench 14), and 7 rhyzoliths (from calcic horizons at Busted Butte) (18, 19, 17). (Where two or more analyses exist for a single site, results have been averaged. In cases where there are significant disagreements between analyses, the most recent results have been used.)



^{234}U/^{238}U Ratios of the Tertiary/Quaternary Aquifer

Fig. 12. Map showing the distribution of isotopic compositions of ground water in the vicinity of Trench 14.

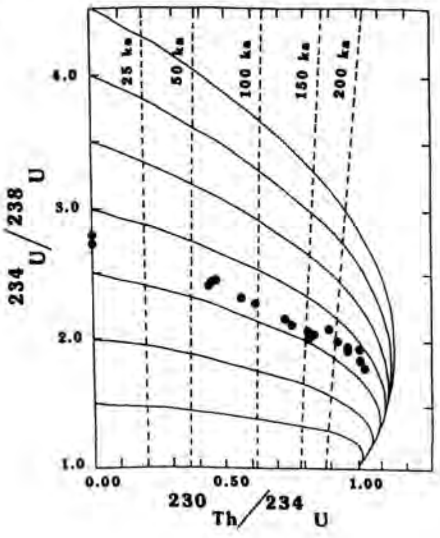


Fig. 13. Uranium evolution diagram for water and calcite samples from Devils Hole, Nevada, showing constancy of the initial ^{234}U/^{238}U as a function of time. Because thorium is nearly insoluble in water, analyses for water or recently precipitated calcite must plot on the left-hand side of the diagram (^{230}Th/^{234}U = 0). With time, the isotopic compositions in calcite change along curved evolution lines like tnose shown for 0.5 increments in the initial ^{234}U/^{238}U until both the ^{234}U/^{238}U and ^{230}Th/^{234}U equal 1.0.

and soil calcites were largely deposited by waters with a $^{234}U/^{238}U$ less than 1.5 (Fig. 11). The difference between water and initial vein compositions is even more pronounced *in the* vicinity of Yucca Mountain where three samples from the Tertiary/Quaternary aquifer have values greater than 5.0 and one sample from the Paleozoic aquifer is 2.71±0.09 (Fig. 12). The two analyzed vein samples have initial $^{234}U/^{238}U$ less than 1.4. Thus the veins and ground waters cannot be genetically related. In contrast, the initial $^{234}U/^{238}U$ for soils of the Yucca Mountain area is generally less than 1.40 with only one value as high as 2.0 (20). These values agree well with those observed for the carbonate veins (Fig. 11), and therefore, support a pedogenic origin for the fault infillings.

The record from Devils Hole can again be used to evaluate the variability of the $^{234}U/^{238}U$ during the past 300 ky. Figure 13 shows that the ratio in Devils Hole calcites has ranged from 2.53 to 2.85. If a similar variability has occurred in waters beneath Yucca Mountain, the veins at Busted Butte and Trench 14 cannot have been precipitated from either of the regional aquifers.

The isotopic data are not particularly useful in evaluating a possible perched spring origin for the deposits exposed in Trench 14, because isotopic data are not available for perched waters. However, geologic and paleontologic data suggest that a perched origin is highly unlikely. Perched water occurs above aquitards such as air-fall tuffs (11) or nonwelded and unfractured tuffs (8). Such aquitards are more than 100 m deep in the vicinity of Exile Hill, and the veins pinch out along the fault contact with the welded tuff at Trench 14 which is highly fractured and very permeable. These facts, combined with the relatively small catchment area upgradient from Trench 14, argue against a perched spring origin for the vein deposits at Trench 14.

Paleontological Data

Eight samples of soil and vein carbonate were taken from the Trench 14 area to determine if calcareous microfossils were present. No ostracodes or other aquatic animals such as mollusks were found. The absence of such fossils implies that the carbonate veins were not deposited in an environment that was saturated with water for periods longer than about one month, which is roughly the time needed for the animals' life cycle. Ostracodes are common in saturated environments of southern Nevada today including lacustrine settings, perched springs, and discharge points for the regional aquifers and temperatures of 0 to 55°C.

Eleven soil and vein samples were collected from the Trench 14 area to look for chrysophyte cysts (the resting stage of certain forms of algae). Rare cysts were found in two vein samples. In the modern environment, cysts are far more common in places where dilute surface waters are entering the hydrologic system (recharge areas) than in places where relatively concentrated ground water is emerging (discharge areas). In fact, modern chrysophyte cysts have been found in mud at the bottom of Trench 1 on Yucca Crest. Taken together, the two types of paleontological data argue against any type of spring environment for deposition of the Trench 14 calcite and opaline silica veins, and therefore, the data are consistent with a pedogenic mode of deposition for the veins.

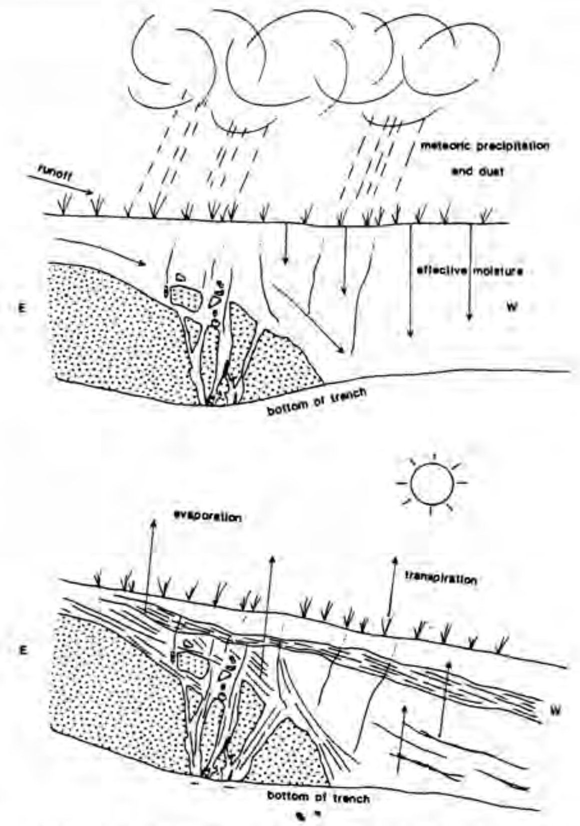


Fig. 14. Model for a pedogenic origin of the veins exposed in Trench 14. (1) Bedrock (v-pattern) is faulted, and alluvium/colluvium (unpatterned) accumulates in the low, down-thrown area. (2) Dust, rich in $CaCO_3$, accumulates on the land surface. (3) Meteoric precipitation (rain and melting snow) dissolves some calcium carbonate in the dust and also washes dust into permeable materials or over the impermeable bedrock to fractured and highly permeable areas where it is temporarily held in the vadose zone. (4) Meteoric water rapidly acquires its isotopic composition for strontium, lead, and uranium from dissolved carbonate dust. The isotopic compositions of strontium and lead (and possibly uranium) are modified slightly by reaction with bedrock and its physical debris. The isotopic composition of carbon becomes dominated by abundant carbon in the vadose zone. (5) Evaporation and transpiration remove water from the vadose zone leaving mineral matter such as calcite and opaline silica behind. As minerals precipitate, they force pieces of bedrock or colluvium apart.

SUMMARY

Data for natural tracer-isotope systems of $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ show that the calcite vein fillings exposed in Trench 14 did not form by ascending waters like those currently found in the regional aquifers beneath Yucca Mountain because the large differences observed between isotopic compositions of ground water (or old ground water deposits) and isotopic compositions of vein carbonate at Trench 14 preclude a genetic relationship between the two. This conclusion is further supported by the isotopic compositions of carbon and oxygen in the vein carbonates and ground water samples. Thus, all modes of origin that require bringing water from depth to form the Trench 14 deposits can be ruled out.

The lack of calcareous micro-fossils suggests that no shallow- seated or perched spring that would create a saturated environment was involved in vein formation. This conclusion is supported by mineralogic and petrographic data in terms of both comparison of mineral assemblages of Trench 14 to those of known spring deposits and by micro-scale textures. Furthermore, geohydrologic conditions are not favorable for sustaining a perched-spring system.

All of the data are consistent with a pedogenic origin. Figure 14 shows schematically how such a genesis might work. In brief, meteoric water (largely rain) dissolves or washes dust high in calcium into permeable zones, such as fractures generated along faults and porous immature soil. Soil CO_2 combines with this calcium and some from the bedrock or soils which has been dissolved by vadose water. Next evaporation and transportation remove water from the vandose zone thereby increasing concentrations of dissolved species to a point where calcite and opaline silica precipitate. The force of crystallization and action of plant roots push blocks apart on a microscopic scale such that over time, blocks are left separated from one another with precipitated minerals forming bands that are concentric to the blocks or parallel to vein walls.

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