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AN EVALUATION OF EVIDENCE PERTAINING TO THE ORIGIN OF VEIN DEPOSITS EXPOSED IN TRENCH 14, NEVADA TEST SITE, NEVADA

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ABSTRACT

Large vein-like deposits of calcite and opaline silica that infill the Bow Ridge fault are exposed by Trench 14 at the Nevada Test Site. The origin of the deposits has been the center of considerable controversy because the deposits occur on the edge of Yucca Mountain, which is being characterized geologically as a possible site for the nation's first high level nuclear waste repository, and the various proposed modes of origin have differing implications for the performance of a geologic repository.

Isotopic data for oxygen, carbon, strontium, and uranium in the carbonates preclude deposition by upwelling waters by any mechanism from either of the regionally extensive aquifers known to exist beneath Yucca Mountain. Data from the adjacent Ash Meadows flow system further suggest that the isotopic compositions of ground water in southern Nevada have not changed markedly during the last 300 to 600 ky, and that therefore, conclusions based on present-day water compositions are probably valid for at least the last 600 ky.

Geologic and paleontologic data are inconsistent with a shallow perched water spring origin for the veins, but are consistent with a pedogenic origin. Mineralogic and isotopic data match well with those for pedogenic deposits with perhaps minor modification from entrained or reacted wall rock. Taken as a whole, the data show that the carbonate and opaline silica deposits exposed in Trench 14 must have formed by a pedogenic process. Preliminary results suggest that veins in the sand ramps west of Busted Butte formed by the same mechanism.

INTRODUCTION

Trench 14, located on the west side of Exile Hill (fig. 1), was excavated across the Bow Ridge fault in 1982 as part of the investigation of the history 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) that was much more extensive than mineralogically similar infillings noted at other trenched faults. In 1984, the trench was deepened to 4m in an attempt to further elucidate the origin of this anomalously extensive deposit. In 1986, two workshops were convened by the Department of Energy (DOE) to discuss possible modes of origin for the deposit and to devise a plan of study. A plan for scientific investigation was subsequently prepared and was reviewed in 1987 by a peer review panel. The panel 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 movement of hot water (T> >30°C) up 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.

Yucca Mountain has been selected for geologic characterization because it is a possible site for the nation's first geologic repository for high-level radioactive waste. The various modes of origin proposed for the calcite and opaline silica in Trench 14 and similar deposits in the sand ramps on the west side of Busted Butte yield differing scenarios with regard to the performance of a repository, if the conditions that existed during deposition of the fault infilling can reasonably be expected to reoccur in the future. This paper summarizes work completed to date for the origin of the Trench 14 veins with the caveats that deeper sections of the veins are yet to be exposed and analyzed, and that isotopic characterization of the ground water in the vicinity of Yucca Mountain is incomplete. Tentative conclusions for the origin of veins in the sand ramps west of Busted Butte are also presented.

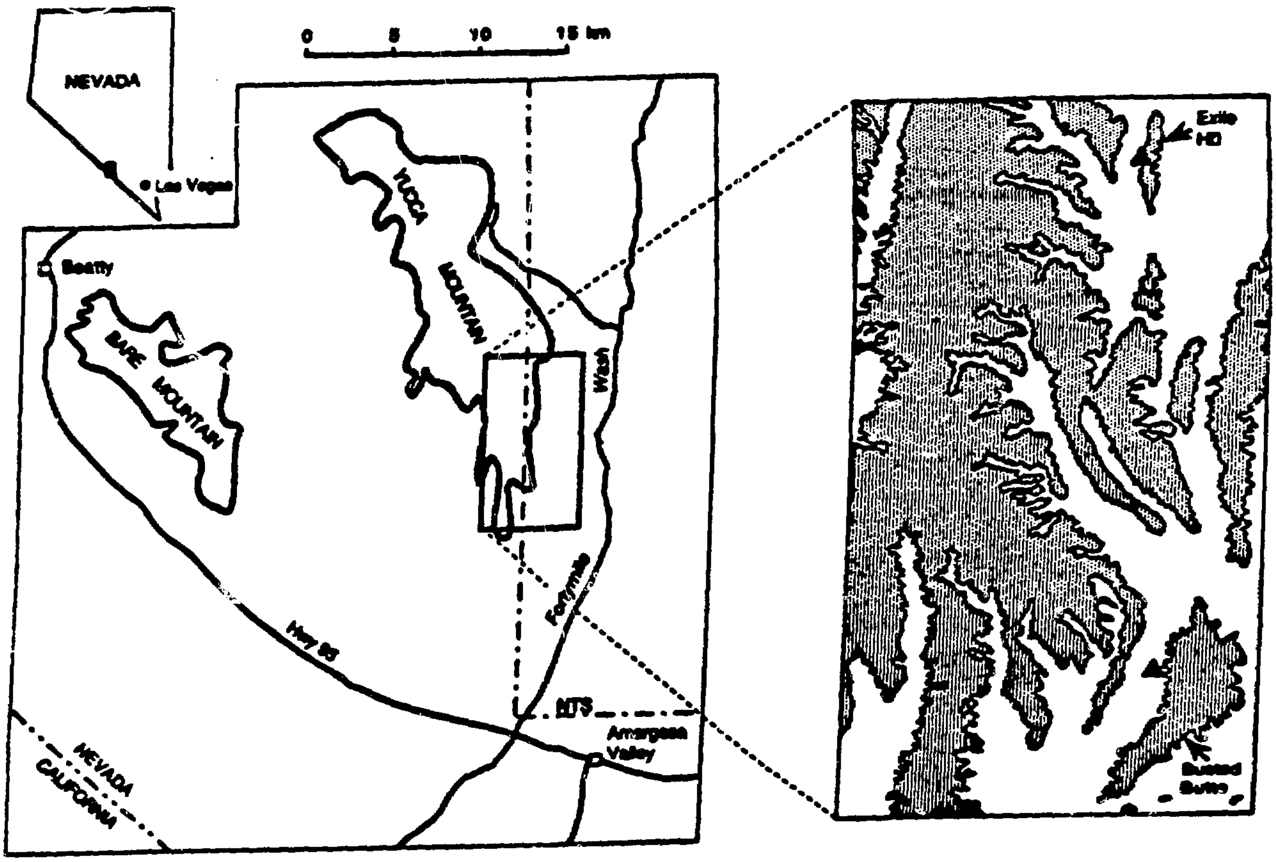

Figure 1.-- Map showing the location of Trench 14 (triangle near Exile Hill) and the Busted Butte sampling site (southern triangle).[18]

DISCUSSION

Field and mineralogical data

Taylor and Huckins compared field relations exposed by Trench 14 with those of typical pedogenic and spring deposits and concluded that the evidence favored a pedogenic origin.[2] For example, Trench 14 exposes calcic soil horizons that follow topography and that are laterally much more extensive than would be typical of spring mounds of similar thickness. These calcic horizons can be traced back to the vein infillings where locally the two depositional forms merge.[2] In addition, both the calcite in the veins and in the calcic soil horizons is *microcrystalline*, which is typical of pedogenically deposited calcite. The calcite in the Trench 14 veins is porous and poorly indurated which contrasts to the typically dense and competent calcite veins found in feeder veins below spring deposits. Finally, calcite-silica veins contain infillings of basaltic ash that apparently washed into open fractures from above. Such a morphologic relationship would be difficult to produce if water were issuing from an open fissure.

Vaniman and coworkers compared the mineralogy of the Trench 14 deposits with that of several possible analogs and concluded the depositional process did not require transport of material from depth and that the closest analog seemed to be apparent pedogenic deposits in the sand ramps around Busted Butte.[3] Specifically, hot and warm spring deposits (temperature greater than about 35 °C) typically 1) contain different crystal forms of opal than the opal-CT (a largely amorphous form of silica with short-range tridymite- and cristobalite-type stacking) found at Trench 14, 2) contain sulfurous minerals not found at Trench 14, and 3) have little or no calcite, which is abundant at Trench 14.

Although cold springs can have a mineralogy similar to that noted at Trench 14, these deposits are typically accompanied by remains of bull rushes and have calcite tubules; neither are found in or near Trench 14. Furthermore, spring deposits typically lack opal, which is abundant at Trench 14. Where silica does occur in spring deposits, it typically occurs as a late replacement feature rather than a coprecipitate or in alternating precipitation with calcite.[4] The vein deposits at Trench 14 show many alternating cycles of calcite and

Figure 2.– Photograph of the south wall of Trench 14 showing the large vein deposits of calcite and opaline silica.

opal deposition that have evolved on a microsite scale (only a few millimeters); this type of texture would be unlikely in a saturated environment typical of springs (D.T. Vaniman, LANL, written communication, 1990).

Several features are difficult to reconcile with an explosive or hydrothermal origin (D.T. Vaniman, written communication, 1990). The wall rock adjacent to the veins shows no signs of reddening which is typical of rhyolitic rocks that have been exposed to hydrothermal solutions. In addition, many delicate features, such as ooids, opaline root casts, and fragile micrite depositional clusters, have been preserved. These should have been destroyed in any violent depositional environment.

The slope parallel and fault-filling deposits at the sand ramps of Busted Butte occur as thin veins through and as mantles on dozens of meters of unconsolidated materials. From these physical relationships and a similarity to typical soil morphology, Vaniman and coworkers concluded that deposition by other than pedogenic processes seemed highly unlikely.[3] The sand ramp deposits have textures and relative abundances of calcite and opal-CT similar to those noted at Trench 14, and minor mineralogies are similar as well.

Stable isotope data

Quade and coworkers have shown that the isotopic compositions of both carbon and oxygen in pedogenic deposits become lighter with increasing elevation and that there is, therefore, a good linear relationship for $\delta^{13}C$ and $\delta^{18}O$.[5] Quade and Cerling have found that data for 22 samples from Trench 14 plot along the isotopic trend for pedogenic carbonates (fig. 3).[6] In contrast, data for spring deposited carbonates from Ash Meadows and Devils Hole plot well off the pedogenic trend. Quade and Cerling also analyzed organic carbon that was occluded within the carbonate fracture filling and found that the isotopic fractionation between the two types of carbon sites of 14.6°/$_{oo}$ matched that observed for soils (14 to 16°/$_{oo}$).[6] According to these authors, the isotopic compositions suggest that the vein deposits formed when the climate was cooler and at a temperature of about 15°C. They conclude that the carbon and oxygen isotope data show that the carbonates in the fractures are pedogenic in origin.

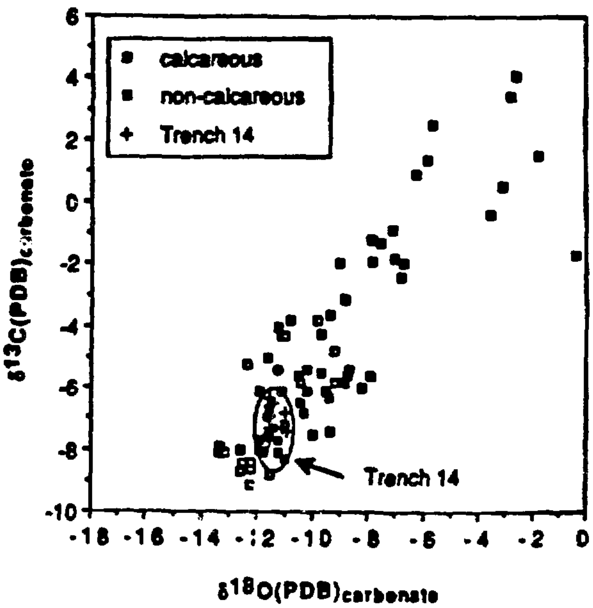

Figure 3.– Graph showing the relationship between $\delta^{13}C$ and $\delta^{18}O$ for pedogenic carbonates and samples from the Trench 14 veins.[6]

Whelan and Stuckless 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 were virtually identical for the two locations and the two types of deposits (soils and veins) except that a few of the Busted Butte soil carbonates were slightly enriched in ^{13}C and ^{18}O (fig. 4).[7,8] This enrichment suggests that some of the soils at Busted Butte may have formed under slightly warmer conditions than those prevailing during formation of most of the analyzed samples. However, the variability in the data is small enough such that all of the soil and vein carbonate could have formed by a single pedogenic mechanism.

Comparison of the isotopic compositions for the soil and vein carbonates with the calculated compositions of calcites (assuming temperatures currently observed at the water table) that would be formed in equilibrium with ground waters of the Yucca Mountain area (fig. 4) shows that the veins could not have formed directly from ground waters like those that exist in the region today. Most of the available ground water data are for the Tertiary/Quaternary aquifers of Winograd and Thordarson.[9] Depth to ground water in these aquifers ranges from 460 to 700m in the vicinity of Yucca Mountain.[10] The calculated isotopic compositions of oxygen for calcites precipitated from these waters can be brought into better agreement with the observed compositions of the vein calcites if lower temperatures than those actually measured are used, but some of the waters would have to be cooled to impossibly low temperatures (0°C and below) in order to precipitate calcite with the appropriate isotopic composition (fig. 5). Reasonable temperatures for deposition can be calculated if the source fluids had an isotopic composition similar to modern precipitation (fig. 5).

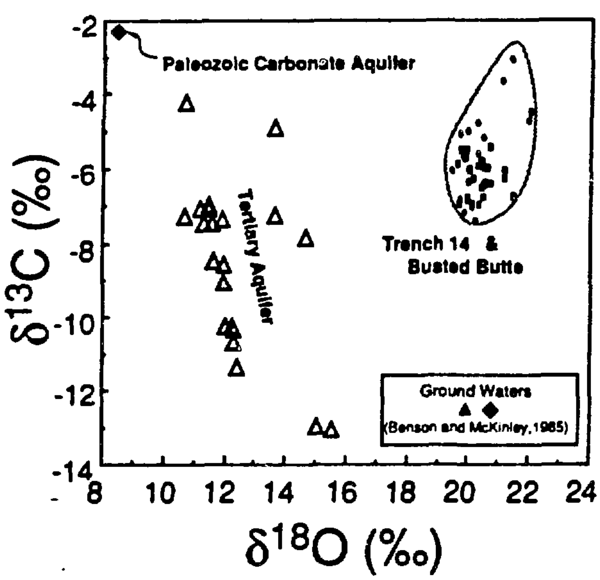

Figure 4.– Graph showing the relationship between $\delta^{13}C$ and $\delta^{18}O$ for carbonates from the Trench 14 (squares) and Busted Butte (ovals) compared with the calculated compositions of calcites precipitated in equilibrium with waters from beneath Yucca Mountain (triangles for Tertiary aquifer and diamond for the Paleozoic aquifer).[7]

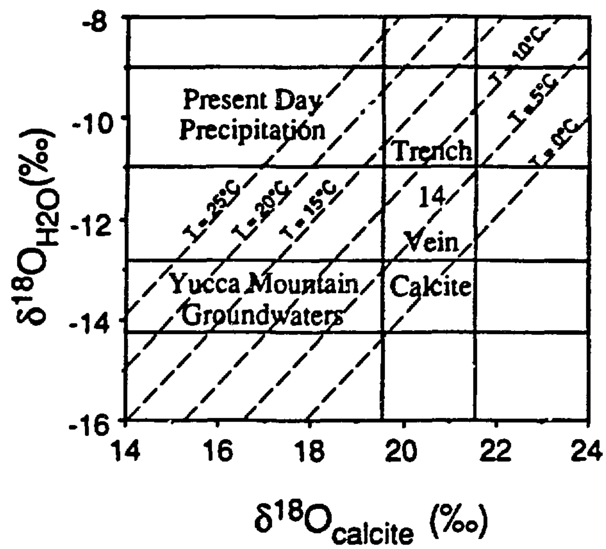

Figure 5.– Graph showing the relationship between $\delta^{18}O$ in calcite vein samples[8] and $\delta^{18}O$ for water[12,23] as a function of temperature . If a calcite has a $\delta^{18}O$ of about $20^{\circ}/_{oo}$ and formed from a water with a $\delta^{18}O$ of about $-13.8^{\circ}/_{oo}$, the calcite must have formed at about 5°C.

Some of the carbon isotopic compositions of ground waters cannot be made to agree with those observed in the veins. About half of the water samples are either too enriched or too depleted in ^{13}C to be possible sources for the vein carbonates. This is especially true for the one sample analyzed from the Paleozoic aquifer which is strongly enriched in ^{13}C relative to the vein calcites, and therefore, cannot be genetically related to the calcite veins.

Apparent ^{14}C ages for ground waters beneath Yucca Mountain are less than 20,000 yrs in the Tertiary aquifer and about 30,000 yrs in the Paleozoic aquifer,[12] but the deposits in Trench 14 yield ages of 228 to greater than 400 ka[1,13]. Although there is no direct way to check the isotopic composition of ancient ground waters in the Yucca Mountain region, data do exist for the Ash Meadows flow system, which is located just to the east of the Yucca Mountain area.[9] Winograd and coworkers have used uranium series dating to obtain ages for individual laminae within a vein of continuously deposited calcite at Devils Hole.[11] Oxygen isotope analyses of this calcite shows a variation of about 1 $1^{\circ}/_{oo}$ 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. However, even a $1^{\circ}/_{oo}$ increase (at currently observed temperatures) for ground water beneath Yucca

Mountain would not precipitate calcites with the isotopic compositions of those observed at Trench 14 (fig. 4).

Radiogenic tracer isotope data

The use of strontium and other heavy radiogenic isotopes as tracers in hydrologic and paleohydrologic studies has recently been reviewed by Stuckless and Peterman.[14] The isotopic composition of strontium can be measured with great accuracy (± 0.00005 or better), and thus small differences can be detected easily. Furthermore, strontium isotopes do not fractionate during terrestrial geochemical processes,[15] although there can be disequilibrium between the isotopic composition of water and that for a whole-rock sample of the aquifer due to preferential dissolution of a phase that has become more or less enriched in radiogenic strontium by virtue of decay of ^{87}Rb. For example, if the dissolved phase has a greater Rb/Sr than the average whole-rock system, water can be more radiogenic than its host aquifer. More commonly, a low Rb/Sr phase, such as plagioclase, is preferentially attacked, and water is less radiogenic that its host rock.[16,17] However, disequilibrium between solid and liquid during precipitation does not occur, and therefore, the isotopic composition of a solid and of the water from which the solid precipitated must be identical.

Strontium isotope studies in the Yucca Mountain area support a pedogenic origin for the veins exposed in Trench 14 and argue against a genetic relationship between ground waters and the calcite veins.[18,19] Figure 6 shows that there is almost no overlap between the isotopic compositions of strontium for ground waters in the Tertiary aquifer and for vein carbonates. The separation is even more pronounced for the Yucca Mountain area. The two most radiogenic water samples for the Yucca Mountain area were taken from drill holes in the unsaturated zone following a precipitation event; the two least radiogenic samples were taken from the saturated zone. A single bailed sample from the Paleozoic aquifer (identified by Pz on figure 6) is also significantly different from the Trench 14 veins, and thus none of the ground waters sampled to date in the Yucca Mountain area can be related genetically to the deposits in Trench 14.

The isotopic composition of ancient ground waters in the Yucca Mountain area can again be evaluated by use of the data for the adjacent Ash Meadows flow system. Figure 7 shows the isotopic composition of strontium for the vein calcite at Devils Hole as a function of age of deposition. Although the variation of $^{87}Sr/^{86}Sr$ exceeds experimental error, the average composition has not changed greatly during the last 600 ky.[18] 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 likely not changed since the Tertiary. Therefore, the water should never have been radiogenic enough to have been a source for the strontium in the Trench 14 deposits. Preliminary data suggest that the same conclusion is true for the Busted Butte veins as well.

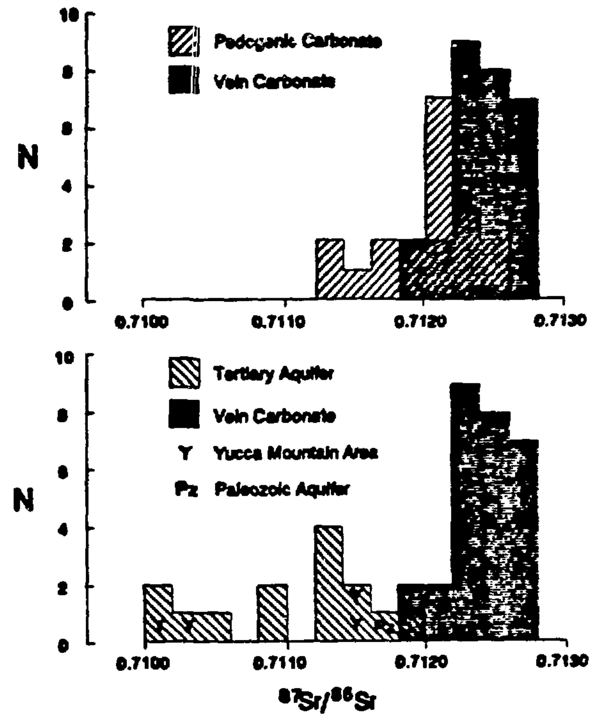

Figure 6.– Histograms showing the distribution of strontium isotopic compositions for the vein carbonates, pedogenic carbonates, and the Tertiary/Quaternary aquifer.[18,19] Also shown are results for one sample of the Paleozoic aquifer obtained from UE-25p#1 (Z.E. Peterman, unpublished data).

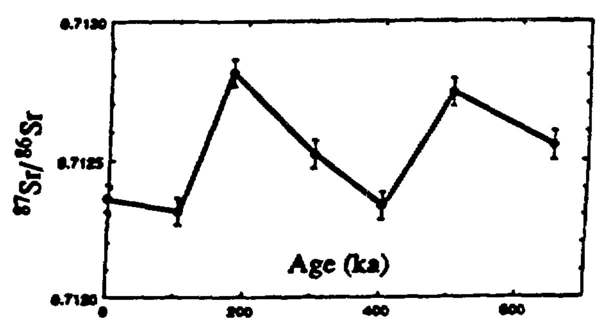

Figure 7.– Variations in the isotopic composition of strontium at Devils Hole, Nevada as a function of age.[18] Analytical error for strontium at the 95 percent confidence level is shown by vertical error bars.

The isotopic compositions of strontium in the vein and pedogenic deposits at Trench 14 show a fairly close correspondence, but the vein materials are, on average, somewhat more radiogenic (fig. 6). There is evidence that the isotopic composition of the vein carbonate is influenced in part by entrained solid material, and that it may be affected by the host wall rock as well. For example, the two least radiogenic vein carbonate samples (0.71190 and 0.71187) were collected adjacent to a basaltic ash lens (0.70888); other parts of the same vein yield values of 0.71246 to 0.71261.[19] The wall rock for the veins contains much more radiogenic strontium than the vein carbonate[19] such that a small input of volcanic strontium into the pedogenic strontium could account for the separation between vein and pedogenic carbonate noted on figure 6.

Lead isotopic compositions show the effects of admixed volcanic detritus on the carbonate veins even more clearly.[20] Mild HCl leaches of the vein material yield apparent carbonate compositions that are only slightly more radiogenic than the host volcanic rocks (half-filled squares on fig. 8). However, a milder leach by CH_3COOH yields a more radiogenic composition for the vein carbonate (open squares on fig. 8) and leaves a residue that is isotopically indistinguishable from the volcanic host rock (solid squares on fig. 8). These results are not totally analogous to the strontium system because most of the vein strontium is contained in the carbonate phase whereas most of the vein lead is contained in the silicate phase, and thus the type of chemical attack used in the analysis does not explain the isotopic differences between pedogenic and vein carbonate for strontium. The data only show that volcanic material could have been a contributing factor to the isotopic composition of vein carbonate during the time of deposition, such that carbonate veins of pedogenic origin could differ slightly in isotopic composition from the soil carbonate.

Like the strontium isotopes, the lead isotopic compositions vary beyond the limits of analytical error (fig. 8). However, unlike the data for strontium, the lead data show no clear separation between isotopic compositions for vein and pedogenic samples. In general, the vein and soil samples have overlapping compositions for both the carbonate fraction and for the entrained silicates. Thus the lead data are consistent with a pedogenic origin for the veins.

The isotopic composition of uranium can also be used to fingerprint waters that have deposited carbonates. As with other heavy elements, the isotopes of uranium do not fractionate during chemical reactions or by virtue of phase changes. Thus, the isotopic composition of uranium in water and a solid precipitated from that water will be identical. Disequilibrium

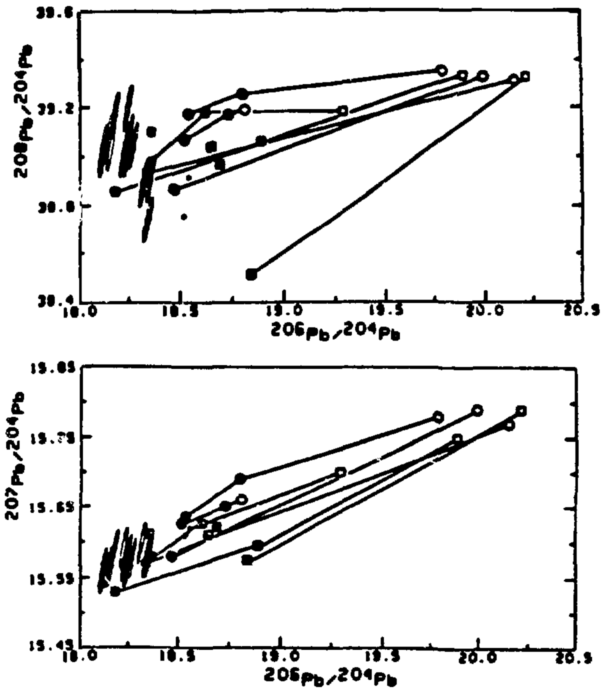

Figure 8.-- Isotopic compositions of lead from volcanic rocks (shown by error ellipses), vein samples (shown by squares), and pedogenic samples (shown by circles). Closed symbols represent results for acid leach residues, open symbols represent results for mild (CH_3COOH) leaches, and half-filled symbols represent results for dilute HCl leaches.[20]

between ^{234}U and its parent isotope ^{238}U can develop in ground water over time by alpha recoil and related processes.[21] The degree of disequilibrium is expressed by the activity $^{234}U/^{238}U$, which by definition is 1.0 at equilibrium.

The $^{234}U/^{238}U$ for ground water in southern Nevada is typically greater than 2.0 for both the Paleozoic and the Tertiary/Quaternary aquifers, but vein calcites and rhizoliths were largely deposited by waters with a $^{234}U/^{238}U$ less than 1.5 (fig. 9). The difference between water and 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 (B.J. Szabo, USGS, written communication, 1990), and the two analyzed vein samples are less than 1.4.[13] These waters cannot have precipitated the vein material at either Trench 14 or Busted Butte. In contrast, the $^{234}U/^{238}U$ for soils of the Yucca Mountain area is less than 2.00 and generally less than 1.40.[22] These values agree well with those observed for the carbonate veins (fig. 9), and therefore, support a pedogenic origin for the fault infillings.

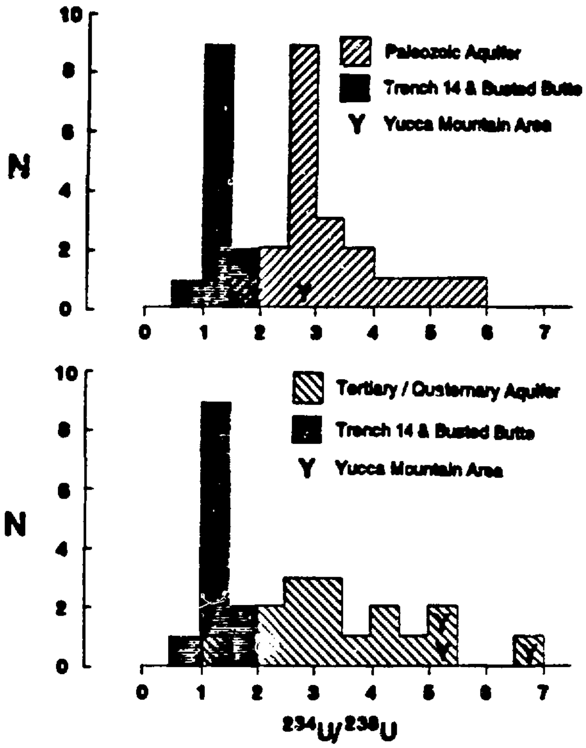

Figure 9.– Histograms showing the isotopic composition of uranium in Tertiary/Quaternary and Paleozoic aquifers and carbonates from Trench 14 and Busted Butte. The carbonate samples include 2 vein samples, 3 calcrete samples (all from Trench 14), and 7 rhyzoliths (from calcic horizons at Busted Butte).[13,21,24,25,26] (Where two or more analyses exist for a single site, results have been averaged. In cases where there are significant disagreement between analyses, the most recent results have been used.)

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 10 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.

None of the isotopic data are particularly useful in evaluating a possible perched spring origin for the deposits exposed in Trench 14; however, geologic and paleontologic data make this alternative highly unlikely. Perched water within the volcanic rocks of southern Nevada is trapped above aquitards such as air-fall tuffs[9] or nonwelded and unfractured tuffs.[10] Such aquitards are more than 100 m deep in the vicinity of Exile Hill. Furthermore, the welded tuff at Trench 14 is highly fractured, and therefore, very permeable. This fact, combined with the relatively small catchment area upgradient from Trench 14, argue against a perched spring origin for the vein deposits at Trench 14.

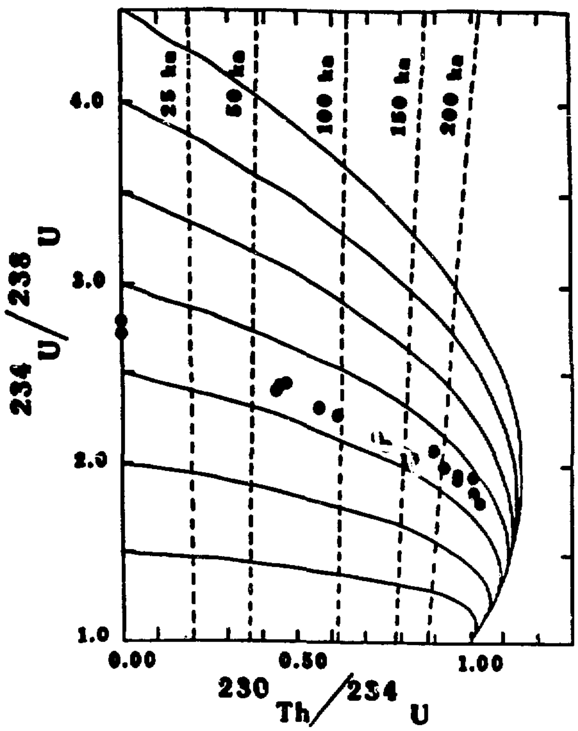

Figure 10.– Uranium evolution diagram for water and calcite samples from Devils Hole, Nevada showing constancy of the initial $^{234}U/^{238}U$ as a function of time.[25] Because thorium is nearly insoluble in water, analyses for water or recently precipitated calcite must plot on the left-hand side of the diagram ($^{230}Th/^{234}U$ = 0). With time, the isotopic compositions in calcite change along curved evolution lines like those 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.

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 (R.M. Forester, USGS, written communication, 1989; 1990). 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. However, there are abundant root casts in the veins of Trench 14, and it is therefore possible that respired CO_2 created an acid enough environment to prevent preservation of calcareous microfossils. Deeper samples will be needed to evaluate this possibility.

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 (D.P. Adam, USGS, written communication, 1990). 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 (D.P. Adam, USGS, written communication, 1990). 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 indirectly support a pedogenic mode of deposition for the veins.

SUMMARY

Data for natural tracer-isotope systems of $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ can be used to prove that the vein fillings exposed in Trench 14 did not form by ascending waters like those currently found in the regional aquifers beneath Yucca Mountain. Neither ^{87}Sr and ^{86}Sr nor ^{234}U and ^{238}U fractionate during chemical reactions or phase changes, and therefore, 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 for 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 data in terms of both comparison of mineral assemblages of Trench 14 to those of known spring deposits and by microscale textures. Furthermore, geohydrologic conditions are not favorable for sustaining a perched-spring system.

All of the data are consistent with a pedogenic origin. Figure 11 shows schematically how such a genesis might work. In brief, meteoric water (largely rain) dissolves or washes dust high in carbonate into

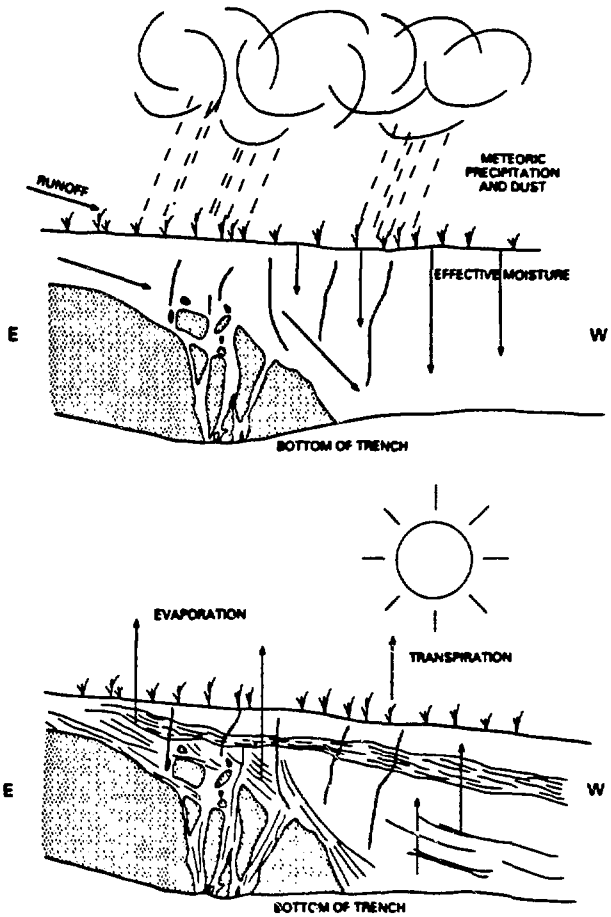

Figure 11.– Model for a pedogenic origin of the veins exposed in Trench 14. (1) Bedrock (v-pattern) is faulted, and alluvium/colluvium (unpatterned) accumulates in the low, down-thrown area. (2) Dust, rich in $CaCO_3$, accumulates on the land surface. (3) Meteoric precipitation (rain and melting snow) 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.

permeable zones, such as fractures and porous immature soil. In addition, some soil CO_2 combines with calcium from the bedrock or soil; this too dissolves in the vadose water. Next evaporation and transpiration remove water from the vadose zone thereby increasing concentrations of dissolved species to a point where calcite and opaline silica precipitate. The force of crystallization pushes blocks apart on a microscopic scale such that over time, blocks are left separated from one another with pedogenically precipitated minerals forming bands that are concentric to the blocks or parallel to vein walls.

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