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REVIEW OF THE DOE REPORT: "THE ORIGIN OF CALCITE-SILICA DEPOSITS AT TRENCH 14 AND BUSTED BUTTE AND METHODOLOGIES USED TO DETERMINE THEIR ORIGIN"

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REVIEW OF THE DOE REPORT: "THE ORIGIN OF CALCITE-SILICA DEPOSITS AT TRENCH 14 AND BUSTED BUTTE AND METHODOLOGIES USED TO DETERMINE THEIR ORIGIN"

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Introduction

In the DOE's Yucca Mountain Site Characterization Report on the "Origin of Calcite-silica Deposits at Trench 14 and Busted Butte and Methodologies Used to Determine their Origin", herein referred to as the "DOE Report", it is stated in the Abstract that

> *Based upon the data presented in this report, DOE concludes that these two specific deposits (at Trench 14 and Busted Butte) are not due to upwelling water. Most likely they are the result of pedogenic processes. The DOE finds no basis to continue to study the origin of these specific deposits... (p. ii).*

We find this judgment to be both unwarranted and premature based on the data presented in the DOE Report and also on DOE data omitted from this report. Far from being of esoteric concern, the subject of the calcite-silica deposits at Trench 14 and Busted Butte (and other locations at Yucca Mountain, including the vadose zone) is of paramount importance to assessment of the suitability of Yucca Mountain as a high-level radioactive waste repository site. If the calcite-silica is pedogenic in origin then geological processes expressed through these deposits pose no threat to the site, but if the calcite-silica was precipitated from solutions ascending up faults to the topographic surface, then such solutions might potentially breach the repository in the future. In the latter case, uncertainties regarding performance of the repository are sufficiently high to disqualify Yucca Mountain as a potential site of this repository.

Section 1. Objection to Scientific Interpretation of Data

This section discusses the field, mineralogy and texture data, as well as elemental abundances and isotopic analyses presented in the DOE Report. Other aspects of the DOE Report will be covered in subsequent sections. We do not question the quality of observations, or the techniques of investigation and analyses as presented in the Report, but we do question the interpretation of data.

1.1. Field Data

The field data are presented in the DOE Report under two Sections: 2.2.1 and 2.3.1. However, the amount of actual field observations presented in the DOE Report is amazingly meager. In essence these observations are:

Observation:

> *Trench 14 exposes slope-parallel calcium carbonate enriched zones that are laterally extensive for thousands of square meters... The slope-parallel deposits are physically typical of carbonate enriched pedogenic deposits that occur throughout the southwestern United States... (p. 42)*

Comments:

What is missing from this statement is that these slope-parallel deposits are developed mostly downslope of vertical calcite-silica veins, which in turn are developed along fault zones (see Fig. 16 on p.24 of the DOE Report), as should be expected for water

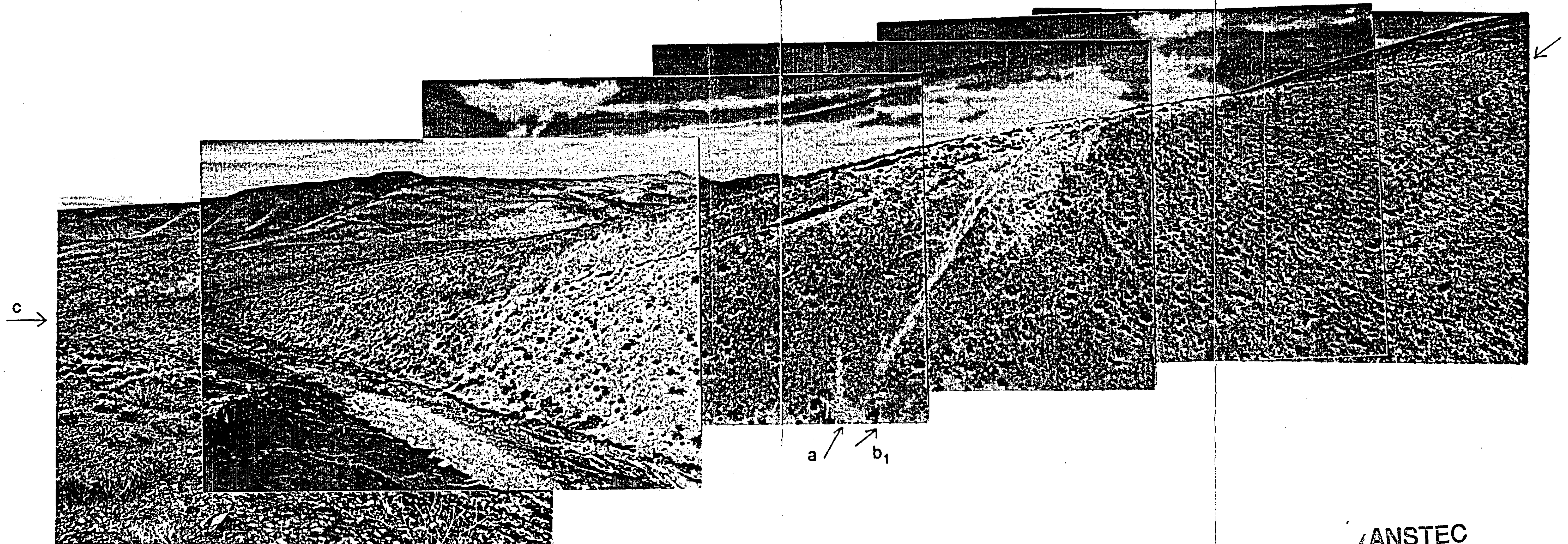

Figure 1 - Composite photo of dissected sand ramp, west Busted Butte, showing calcite/opal vein along the Paintbrush Canyon fault (a) and an angle from fault ($b_{1,2}$), and slope calcrete ("travertine-like" material) which emanates from the vein and continues down gradient to the toe of slope and beyond (c). The highest slope calcrete is at b_2, which position corresponds to the b_1-b_2 vein and this slope calcrete is not traceable above the fault system. It is important that such calcite-silica slope calcrete is not found on sand ramps uncut by faults. (e.g., on some parts of east Busted Butte). If this slope calcrete is pedogenic in origin, it should occur everywhere on the sand ramps and not just along, or downslope from, faults. Photo composite: C. A. Hill.

which has come up the faults and then flowed down and away from faults (e.g., Busted Butte, **Fig. 1**). Geochemically vein- and slope calcites are indistinguishable (see Section 1.4. of this report).

Observation:

> *The carbonate-enriched horizons exposed in Trench 14 can be traced upslope and over the fault vein fillings. (p. 42)*

Comments:

This is a true statement (at least for Trench 14). These "carbonate enriched horizons" may be "true" pedogenic formations (see description below). However, this does not necessarily mean that <u>all</u> calcite-silica material deposited in Trench 14 is pedogenic. In other words, Trench 14 may represent a mixed system, the veins and "travertine" being hypogene material reworked, in part, by pedogenic process, and "carbonate enriched horizons upslope of the vein fillings" being "true" pedogenic horizons typically formed in all arid regions of the southwestern United States. Another possible explanation is that "upslope" calcite was derived from smaller subsidiary fissures-feeders that were not recognized in the field. Note, that carbonate horizons upslope of the veins are not documented in otherwise scrupulous geological sections given in Appendix D of the DOE Report.

In addition, at Busted Butte the calcite-silica calcrete layers are <u>not</u> traceable above the fault system (**Fig. 1**). Also at Busted Butte the supposedly-pedogenic, calcite-silica calcrete material does not extend completely around the butte but occurs only along, or downslope from, faults. If the calcite-silica were of "true" pedogenic origin, then all age-equivalent slopes on Busted Butte should display these same thick layers of calcite-silica, but they do not.

Observation:

> *...the newly deepened portion of Trench 14, in the area of the near-vertical veins, exposes the veins pinching out and becoming discontinuous with depth... (p. 42)*

Comments:

This observation is considered in the DOE Report as favoring the pedogenic origin for the veins because

> *...veins formed pedogenically as fillings of fractures and faults should pinch out rapidly with depth ... as a consequence of the narrowing of the apertures of the fractures and faults that were opened by various erosional phenomena... (p. 18).*

We wish to point out, however, that it has not been demonstrated, either in Trench 14 or at Busted Butte that veins die out or become discontinuous with depth. The Busted Butte calcite-silica veins are over 30 m deep and give no evidence of "pinching out" (**Fig. 1**). Trench 14 was deepened in 1991 to 7 m depth and still the veins do not pinch out; rather, splayed veins near the surface merge into "feeder" veins as is typical of epithermal deposits (see Fig. 6 on p.20 of the DOE Report). On the southern wall of the trench the veins do

> *...diminish from a thickness of nearly 1 m near the top of the trench to 2-3 cm over a depth of only 7 m (p. viii),*

but they do not die out -- the wider splayed veins merely merge into less-wide "feeder" veins. In the northern wall, however, the nearly 1 m thick vein occurs in the entire exposed section. Thus, the observation above is just not correct.

Observation:

> *...the calcite-silica veins contain a basaltic ash and other detrital materials that must have washed or fallen into open fractures. Such ashes would be difficult to explain within veins in an environment where water is issuing rapidly from an open fissure (p. 42)*

Comments:

The observation above is valid but its interpretation is purely speculative. The velocity of water issuing along the fault zone was not necessarily high, and, generally speaking such velocities are highly variable in geological time. The content of detritus is, primarily, the function of the medium in which the ascending waters were discharging. The calcite and opal in Trench 14 and Busted Butte veins were formed near the topographic surface, so, the presence of detritus should be expected there.

Summarizing this brief discussion, it is certainly accurate to point out that the data presented in the DOE Report are equivocal and not sufficient, and that DOE's conclusions that:

> *Field data are consistent with a pedogenic origin for the calcrete deposits at Trench 14 and Busted Butte (p. viii),*

and:

> *In respect to all these criteria the actual field evidence favors a pedogenic origin (p. 18)*

are unwarranted.

When considering a *per descensum vs. per ascensum* model of formation of calcic deposits developed in soil horizons, such as those exposed in Trench 14 and Busted

Butte, DOE scientists would have been well advised to have kept in mind the following remarks by Machette (1985):

> *Laterally flowing, $CaCO_3$-rich ground water commonly forms deposits that are misidentified as calcic soils or pedogenic calcretes. This process calls for Ca^{++}-charged ground water to either discharge onto a stream bottom or reach a near-surface position where Ca^{++} is concentrated by evaporation. Supersaturation of Ca^{++} causes precipitation of $CaCO_3$ and subsequent cementation of relatively pervious sands and gravels. Such ground-water calcretes are typically well indurated to depths of 10 m or more, are characterized by gravel clasts that have grain-to-grain contact, and generally lack the horizonation and morphologic structures common in calcic soils. Ground-water calcretes form quickly but at differing times as the subsurface or surface flow shifts laterally into more permeable material. Surface runoff may add to or redistribute this same $CaCO_3$ and produce laminar zones that resemble pedogenic calcretes of Stage IV and V morphology. In southeastern New Mexico, Bachman and Machette (1977) found ground-water calcretes that had laminae as much as 1 cm thick along highway drainage culverts in limestone-rich alluvium. These laminae prove gulley-bed cementation can occur rapidly... However, my investigations of calcretes in the Las Vegas area suggest that many of them are pedogenically modified ground-water calcretes. Bachman and Machette (1977) found calcretes of similar origin west of Roswell and Carlsbad, New Mexico; near the Whetstone and Tombstone Mountains of southern Arizona; and south of the Hueco Mountains in west Texas. (p. 7)*

Another aspect which must be considered here is the omission of pertinent and available field information. Several important examples are as follows:

1. ***Calcite-silica deposits along faults.*** The calcite-silica deposits are localized along Quaternary faults recognizable in the field by offset beds, well-exposed and slickensided surfaces, or brecciated and mineralized zones. In places where faults are well-exposed, the calcite-silica occurs primarily as sub-vertical seams or veins along or near the fault plane, and either die out away from the fault (e.g., Wailing Wall, **Fig. 2**), or form "travertine"-like deposits downslope from the faults and veins (e.g., Busted Butte, **Fig. 1**). A number of the calcite-silica deposits are located along major faults: Trench 14 along the Bow Ridge fault, Busted Butte along the Paintbrush Canyon fault (**Fig. 1**), Trench 8, New Trench and WT-7 along the Solitario Canyon fault; Wailing Wall along the Stagecoach Road fault (**Fig. 2**), and Crater Flat along the Windy Wash fault. This almost universal association of calcite-silica with faults indicates a genetic connection where water used faults as avenues for ascension, descension or both.

2. ***"True" pedogenic deposits.*** There are "slope-parallel calcium carbonate enriched zones that are laterally extensive" at Yucca Mountain and which are

> *...physically, isotopically and biologically typical of carbonate enriched pedogenic deposits that occur throughout the southwestern United States (p. viii)*

These are what Hill et al., (1994) referred as "true" pedogenic deposits, i.e. deposits formed within soil horizon and with heavy involvement of fluids originating directly from meteoric precipitations. "True" pedogenic deposits in arid regions (like Yucca Mountain) display the following features: (a) they occur as calcic or petrocalcic horizons just beneath the land surface and are oriented approximately parallel to this surface (**Fig. 3**); (b) they are laterally continuous with geomorphic surfaces which, in

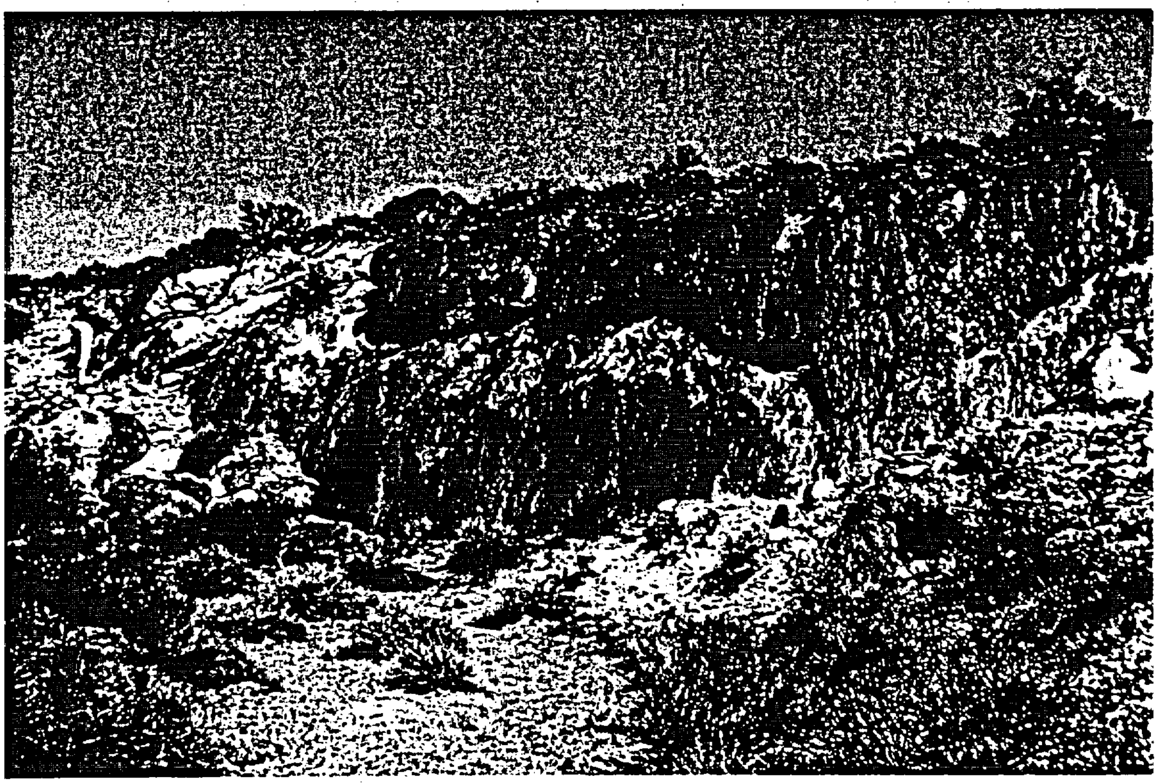

Figure 2 - Calcite-silica (white material) directly along the Stagecoach Road fault, Wailing Wall. Away from the fault the mineralization dies out. The fault is part of the Stagecoach Road fault system and is recognizable by slickensides and offset beds. Photo: C. A. Hill.

many instances, cover tens to hundreds of km^2; (c) they typically consist of a detrital fabric impregnated by calcite crystals (**Fig. 4**); (d) they become more complex within progressively older geomorphic surfaces; and (e) they accumulate slowly, with stage I carbonates in soils of late Pleistocene age and with stage V-VI carbonates being hundreds of thousands to millions of years old (Machette, 1985). "True" pedogenic carbonate deposits occur on geomorphologically old surfaces at Yucca Mountain (e.g., Fortymile Wash-Midway Valley, **Fig. 3**), but these do not necessarily have the same origin as the controversial calcite-silica calcrete deposits along faults or downslope from faults.

3. ***Cross-cutting morphology of veins.*** At Trench 14 at least five episodes of cross-cutting mineralized faults can be identified on a large scale (**Fig. 5**), and "multiple episodes of fracturing and cross-cutting deposition (p.44)" can be found on a small scale. Such large scale cross-cutting relationships are typical of epithermal vein deposits but it is difficult to imagine how such relationships could have developed pedogenically. Different episodes of faulting, with pedogenic calcite-silica infilling these cross-cutting faults, may be responsible, but then why should this calcite-opal be as young as 38±10 Ka (Swadley et. al., 1984)? As previously discussed, pedogenic deposits meters thick (**Fig. 5**) should be hundreds of thousands to millions of years old (Machette,1985).

4. ***Veins in sand.*** At Busted Butte the calcite-silica veins are emplaced in unconsolidated sand ramps. How could these faults stayed open long enough for pedogenic material to have accumulated within them, and again, this calcite-silica can be very young (29±1 Ka; see Table on p. A-19 in the DOE Report).

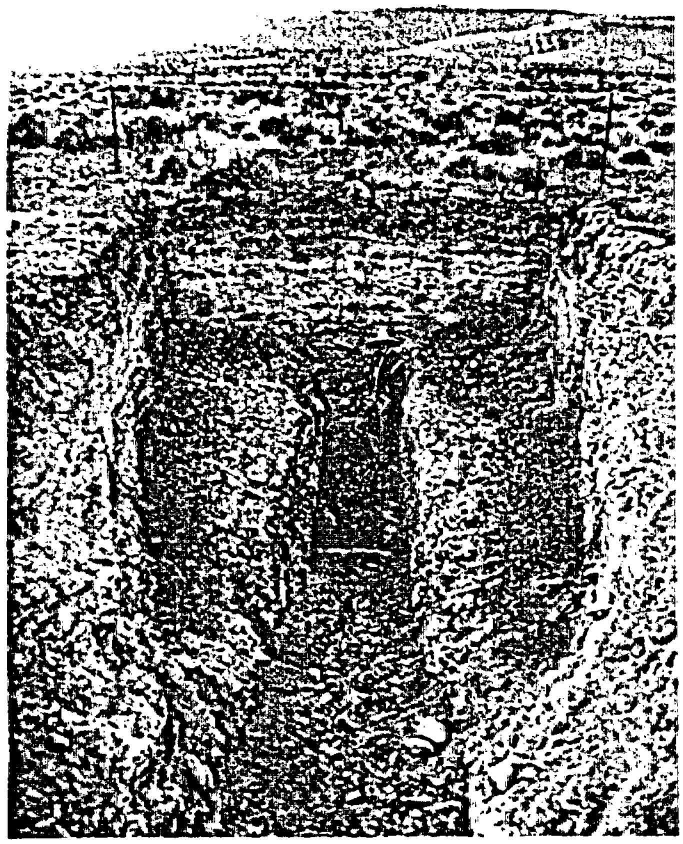

Figure 3 - A "true" pedogenic deposit about 1 m thick, Fortymile Wash-Midway Valley. A pedogenic calcrete horizon this thick would have taken hundreds of thousands (or more) years to have formed. This "true" pedogenic carbonate horizon is not located along a fault but is laterally extensive across the valley. Photo: C. A. Hill.

BB-19

T14-1

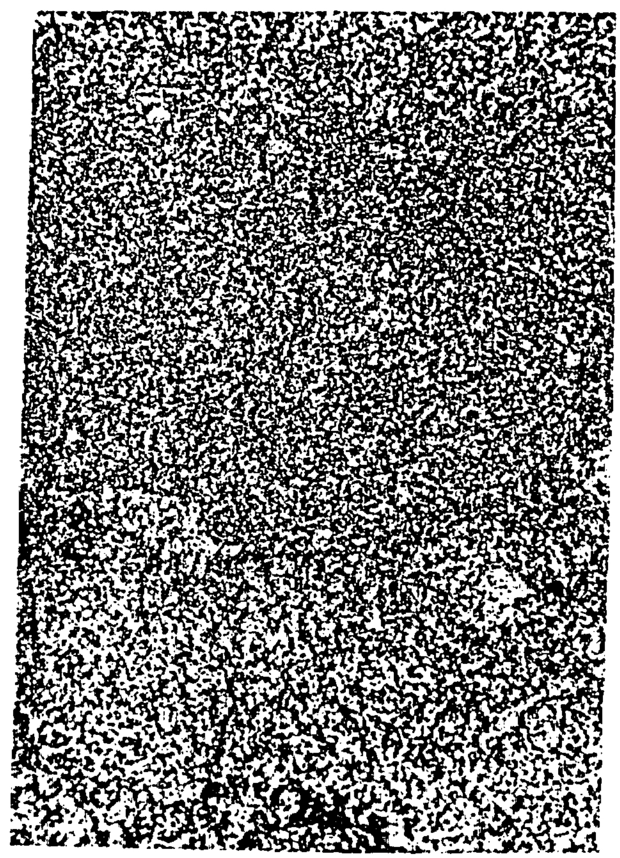

Figure 4 - Photomicrograph of fine-grained calcite-silica, Trench 14, showing the absence of a clastic silicate-grain framework. (B) Photomicrograph of framework-grain supported fabric with each grain coated by calcite, from a modern calcic (Bk) soil (pedogenic) horizon on a slope west of Busted Butte. Crossed polars (x 100). Photomicrographs: H. C. Monger.

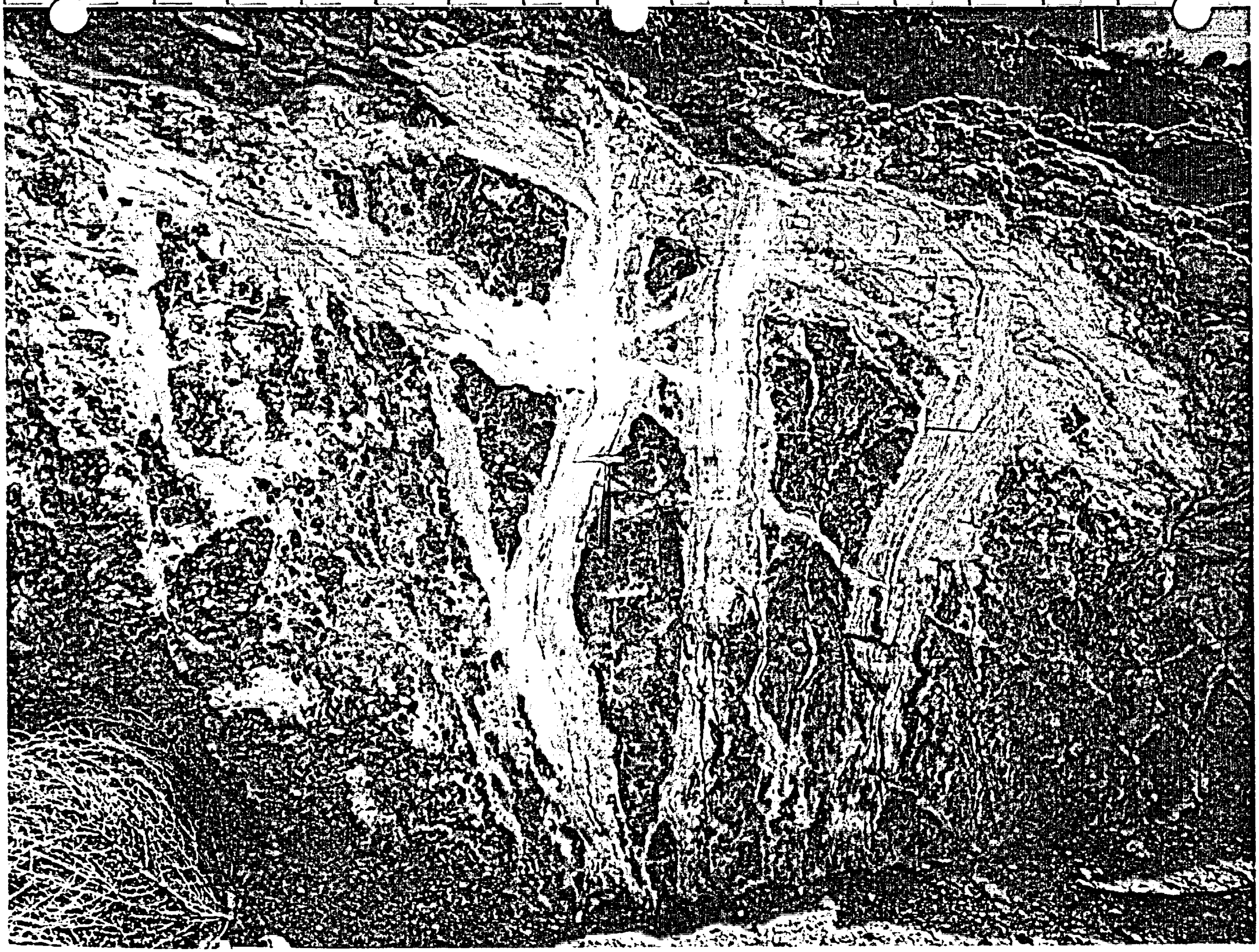

Figure 5- South wall of Trench 14 showing at least five episodes of crosscutting veins along the Bow Ridge fault. USDOE negative no. YM-284.

1.2. Mineralogy and Texture

The mineralogy and texture of the calcite-silica deposits at Trench 14 and Busted Butte is discussed in the DOE Report under Sections 2.2.2 and 2.3.2. Several examples of questionable interpretations of these data are given below.

Statement:

> *...the calcretes consist predominately of calcite with lesser amounts of opal-A and opal-CT, along with small portions of sepiolite... the mineralogic assemblage is the same as noted in the calcic horizon of arid region soils (p. viii).*

Comments:

This mineralogic assemblage of calcite/opal/sepiolite is correct; however, the deposits also contain minor quartz and trace amounts of pyrite/chalcopyrite (Hill, et al., 1994), minerals which are not typical of a pedogenic environment. Also, Hill (1993) pointed out that while some sepiolite in Nevadan soils is likely pedogenic in origin, most of the reported sepiolite in the Basin and Range seems to have formed as hydrothermal fault-infilling or vein deposits and that even "playa-formed" sepiolite in the Yucca Mountain area (Amargosa Valley) formed from fluids upwelling along fault zones. In addition, sepiolite is known to occur with calcite and opal in deeper parts of the Yucca Mountain vadose zone (Vaniman, 1993, p.1938) which fact also favors a non-pedogenic, hydrothermal origin of sepiolite.

Statement:

> *...it would be reasonable to expect differences in mineralogy between vein and slope deposits in the case of spring action, but not from pedogenic processes (p. 22).*

Comments:

Why it would be reasonable to expect "differences in mineralogy between vein and slope deposits" if both were precipitated from hypogene solutions containing dissolved silica, calcium, and carbon dioxide? Both calcite and opal should be deposited as vein and slope "travertine" material from such solutions as is consistent with what is observed in Trench 14 and at Busted Butte. What should be expected in such a system, and what in fact is observed, is the difference in stable isotope signatures (^{13}C and ^{18}O) between vein- and slope calcites due to on-going degassing and evaporation (see discussion in Section 1.4 of this report). The calcite-silica in the veins and travertine-like deposits do differ from "true" pedogenic deposits, however, the vein and travertine material consisting of an intimate mixture of calcite and opal, with carbonate ranging from ~20-75 % and silica from ~25-80 %, and with calcite/opal laminations/bands on the order of mm- to cm-thick. On the other hand, "true" pedogenic deposits contain mainly carbonate material with stringers of opal 50-100 µm thick.

Statements:

> *The vein fillings at Trench 14 are fine grained and poorly indurated in contrast to typically coarse grained calcite in feeder veins and at discharge points of spring deposits (p. 22)*

and:

> *...Figure 19 illustrates the considerable difference in texture between calcite at Devils Hole and the deposits in Trench 14. Devils Hole is typical of a spring deposits because it is near surface ground water deposit (p. 44)*

Comments:

The fact that the calcite-silica deposits are very fine grained (usually <5 µm; **Fig. 4A**) is not necessarily indicative of their being pedogenic. Instead, fine-grain size might simply indicate extremely quick cooling and/or degassing of hypogene solutions. Evidence against the fine-grain size of calcite being indicative of pedogenesis is that the size of calcite crystals in "true" pedogenic carbonate deposits range from ~1 µm to as much as millimeters (Hill et al., 1994).

The "typical spring-deposited vein at Devils Hole (Fig.19 of the DOE Report, caption) is not a vein: it is a mammilary speleothem (a underwater cave formation) which shows typical crystalline texture for this type of cave deposits (Hill and Forti, 1986). Thus, what is actually being compared in Fig 19 of the DOE Report are a cave deposit and controversial (hydrothermal or pedogenic) vein deposit.

Statement:

> *...detrital minerals are rare or absent in veins that feed spring mounds; in contrast, about 10-20 percent of the vein material at Trench 14 is detrital (p. 44).*

Comments:

In the first place, why should not some detrital material from the immediate vicinity or volcanic ash accumulate in the spring orifices by eolian and gravitational processes, especially in sand ramps such as those at Busted Butte? In the second place, much of the dense calcite-silica at Trench 14 is devoid of a clastic silicate-grain framework (**Fig. 4A**) in contrast to "true" pedogenic deposits which typically contain a detrital matrix (Fig. 4B).

Statement:

> *...overlying soils differ from the calcretes in their low abundance of calcite... this is expected relationship where calcrete forms pedogenically by accumulation of calcite leached from overlying soils (p. 48).*

Comments:

This is an incorrect interpretation because <u>all</u> of the soils at Yucca Mountain lack calcium. The "overlying soils" are devoid of calcite because they derive from calcium-poor volcanic rock (Livingston, 1993). This lack of adequate source of calcium for the controversial calcite-silica deposits has long been recognized as one of the most serious problems regarding the proposed *per descensum* origin of these deposits (see discussion of Hill et al., 1994).

Statement:

> *...ooids, pellets, and root casts are common in pedogenic deposits, but rare to absent in springs (p. 22).*

Comments:

This criterion is highly misleading. As all of these textural varieties supposedly reflect biological activity, the only unequivocal conclusion which may be drawn in this regard is that at a certain time the depositional site was colonized by vegetation. Such a situation is quite typical of many contemporary hot spring orifices in Nevada and elsewhere; e.g., Tecopa Springs, located about 90 km south of Yucca Mountain. Root-cast textures and sand cemented by silica can be found there in abundance (Dublyansky, 1994).

The list of equivocal statements and unwarranted interpretations may be continued, but those noted here should be sufficient to demonstrate the lack of a sound scientific basis for the conclusions reached by the DOE. The DOE's authors, themselves, admit that

> *...the characteristics noted here do not always provide unambiguous distinctions among spring, seep, and pedogenic deposits... (p. 22).*

Thus, the conclusion that

> *...the predominance of the evidence favors a pedogenic origin (p. 22)*

is, at least, unwarrented bsed on the evidence presented in the DOE report and flatly contradicted when data not included in the report is also considered.

1.3. Elemental abundance patterns

These data are discussed under Sections 2.2.3. and 2.3.3. "Quantitative Mineralogic and Chemical Analysis" of the DOE Report.

One general comment must be made before the discussion of specific topics covered in the DOE Report. Targeted geochemical studies (Hill, et al., 1994; Liu and Schmitt, 1994) of the controversial calcite-opal deposits, the local groundwater spring deposits as well as several occurrences for which a pedogenic origin may be suspected ("true" pedogenic deposits), have shown that these three types of deposits are virtually indistinguishable in terms of their elemental abundance profiles (**Fig. 6**). The majority of elements discussed in the DOE Report, such as lanthanides and Sc, reflect

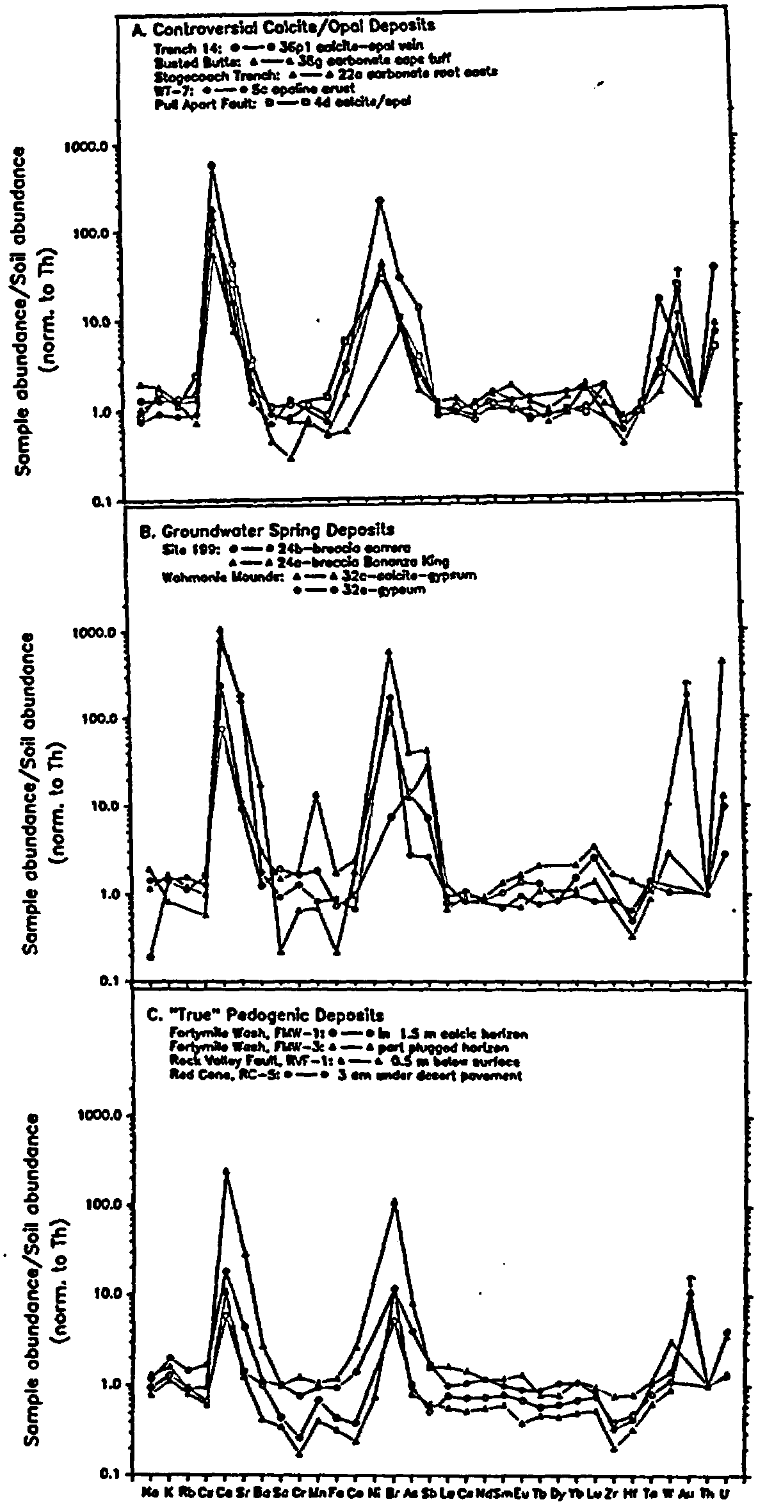

Figure 6 - Comparisons of element abundances in representative samples of the "controversial" calcite/opal deposits (A), groundwater spring deposits (B), and "true" pedogenic carbonate deposits (C) to the nearby A-horizon soils and normalized to Th in the samples and soils; i.e. $(X_i/X_S)/(Th_i/Th_S)$. In graphs A and C, we assumed that the WT-7, Pull Apart Fault, Fortymile Wash, and Rock Valley Fault A-horizon soil were similar to Trench 14 soils. ↑ indicate lower limits. Samples, rich in detritus like Fortymile Wash in C, mask potential enrichment and depletion processes.

primarily detrital contamination. This contamination, alone confirms that the controversial deposits were formed at or near the topographic surface. Such contamination may be expected in association with *per descensum* deposits as well as with *per ascensum* depositsand, thus, may not be used as an unequivocal genetic marker. The discussion below serves to illustrate this point.

Statements:

> *The great similarity of shape in the distribution curves for the lanthanide elements ... for vein calcretes to that in tuffs indicates a common component that determines the distribution. Clearly it must be the tuff itself... (p.22)*

and:

> *...the evidence indicates that the tuff detritus did not enter the calcretes by direct removal from the walls of a feeder conduit, as would be expected for a spring origin and particularly in veins where hydrothermal brecciation has occurred, but rather by first entering the soil where weathering led to an enrichment in Sc and then incorporation into the veins. This evidence favors a pedogenic origin as a result of providing information about the source of a component of the veins. (pp.22-23).*

Comments:

1. As the elemental patterns discussed above reflect detrital component, the DOE reasoning may be applied to any model which implies formation of calcretes at- and near the topographic surface. Upwelling waters discharging into the soil horizon would have the same detrital contamination and, thus, the same Fe/Sc signatures. So, <u>the evidence above favors a near-surface environment, but not necessarily a</u>

pedogenic process. The DOE conclusions with regard of implications of Sc and Fe abundances are not uniquely constrained and may not be regarded as necessarily valid.

2. The Fe(%)/Sc(ppm) signatures of Paleozoic carbonates in the Yucca Mountain region are 0,28±0,08 (Liu and Schmitt, 1994), that is not too different from 0,322±0,016 in calcretes. Short of misleading a reader, one cannot disregard this potential source of detritus and an upwelling mode of transport of this detritus.

Statement:

> *For a pedogenic origin ... a reasonable source* (of Ca) *would be from carbonate containing dust derived from Paleozoic carbonate rocks and playas in the vicinity and deposited in soils. (p. 25)*

Comment: This would be, indeed, a reasonable source, if a pedogenic origin for the discussed calcite veins and slope deposits at Yucca Mountain was known with certainty. However, within the context of a hypogene model, the same Paleozoic carbonates from underneath the mountain could have just as well served as a source of Ca.

Overall conclusion:

The reported geochemical data pertain to the detrital materials incorporated in the controversial Trench 14 and Busted Butte deposits. However, the presence of the surface derived detritus is of no assistance in discriminating between the competing (*per descensum vs. per ascensum*) origins. This is because contamination by the surficial detritus is expected in association with both of these origins.

1.4. Isotopic Analyses

Stable Isotopes

The data on stable isotopes are discussed under Sections 2.2.4. and 2.3.4. "Stable Isotope Data" of the DOE Report.

Statement:

> *Stable isotopic data can be used to gain insight into the source of oxygen and carbon incorporated into calcite in the calcretes...Two potential sources are considered here: soil water and gas (i.e. pedogenic sources), and local ground water from the saturated zone. (p.25)*

Comment : If the calcretes were formed by hypogene process, the waters and gases involved may have had nothing to do either with soil water/gas or with local (current) ground water. Such calcretes would have been formed from Ca-rich ground waters residing in the Paleozoic-Precambrian basement. Isotopically, these ground waters differ from shallow "ground water from the saturated zone". By limiting the analyses to the stated sources, the DOE Report discriminates between two competing models (*pedogene vs. hypogene*) by *a-priori* eliminating one of them from consideration. Such an approach to resolving the critical safety issues is misleading and evasive.

Statement:

> *The pedogenic case was evaluated by comparing numerous measurements of pedogenic carbonates (Quade et al., 1989) widely distributed in southern Nevada with calcites at Trench 14 and Busted Butte (see Fig. 10). (p. 25).*

and:

Carbon and oxygen isotopes ... in the vein carbonates at Trench 14 match those in pedogenic carbonate collected over a wide area of southern Nevada ... In detail, isotopic compositions imply pedogenic deposition of the Trench 14 calcites under conditions of a cooler climate with a mean temperature of about 15 °C (Quade and Cerling, 1990). Samples of soil carbonates and vein infilling from both Trench 14 and Busted Butte show that the isotopic composition of oxygen and carbon of most samples are virtually identical for the two locations and for the two types of deposits, soils and veins (Whelan and Stuckless, 1990). ... the variability in the data is small enough that all of the soil and vein carbonate can be explained by pedogenesis (p. 54).

Comments:

1. One may see from Fig. 10 of the DOE Report that calcretes from both Trench 14 and Busted Butte have $\delta^{18}O$ and $\delta^{13}C$ signatures of up to 4,5 permil lighter than pedogenic calcretes at the same altitude; so the statement that the samples are "virtually identical" is not true (Fig. 10 of the DOE Report is reproduced as **Fig. 7**).

2. It may also be observed, that there is a systematic shift for $\delta^{18}O$ and $\delta^{13}C$ in veins and slope calcretes at Busted Butte; both carbon and oxygen are lighter in veins and heavier in slope calcrete (**Fig. 8**; the data taken from Tables A-1 and A-2 of the DOE Report). Oxygen from Trench 14 displays the same behavior. Using the DOE's logic one must conclude that the veins at Busted Butte were formed at an altitude some 350m higher than the corresponding slope calcretes.

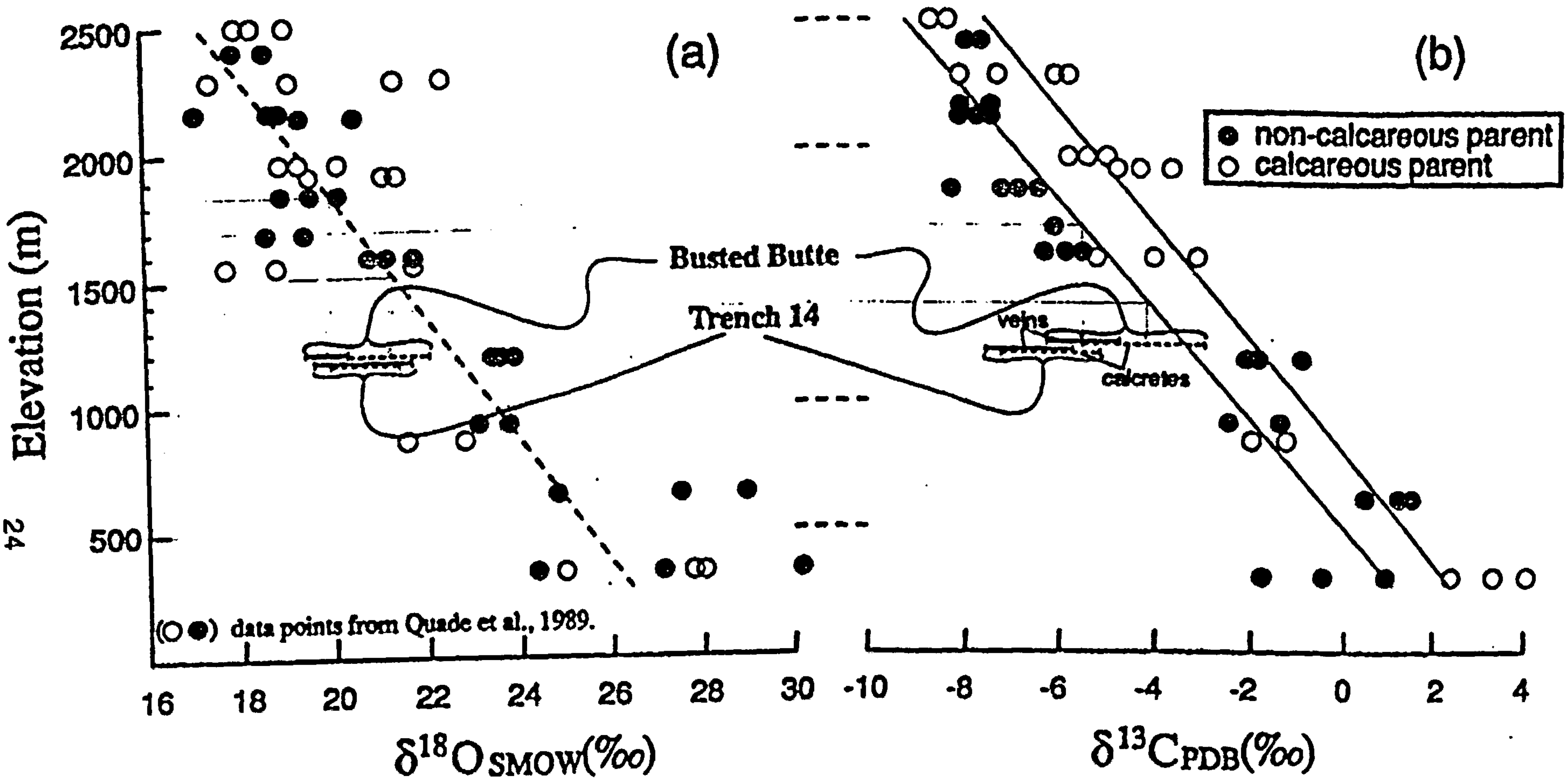

Figure 7 - The relationship between δ13O and δ18O for pedogenic carbonates and samples from the Trench 14 veins. From DOE, 1993.

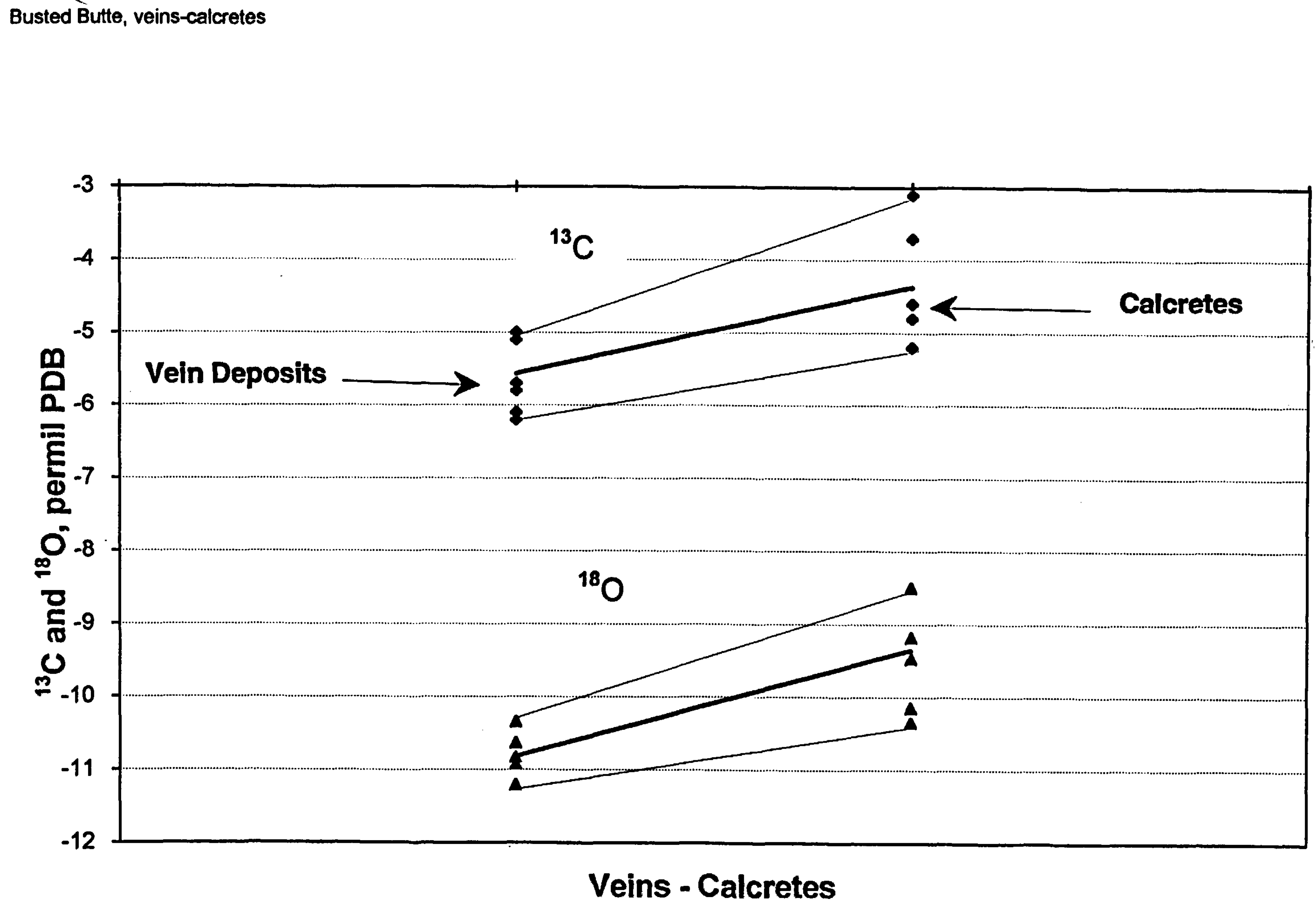

Figure 8 - Systematic change in ^{13}C and ^{18}O in veins and slope calcretes at Busted Butte.

The systematic $\delta^{18}O$ and $\delta^{13}C$ shift is not discussed in the DOE Report. Such a behavior, however, may well be expected for *per ascensum* deposits. During deposition of such deposits upwelling fluids (along fault zones and discharging on the topographic surface) loose dissolved CO_2 and evaporate. During both CO_2-degassing and evaporation the lighter isotopes ^{12}C and ^{16}O preferentially concentrate in the escaping gas phase and, thus, the carbonate-depositing fluids became progressively enriched in heavier isotopes (i.e., ^{13}C and ^{18}O). At Busted Butte, where sand ramps hosting the veins were truncated by erosion and the latter may be sampled to a significant depth from the topographic surface this trend is especially well pronounced. By contrast, in Trench 14 all the vein samples were taken at a depth of only 1-2 m below the topographic surface (see Plates 1-6 in Appendix Dof the DOE Report), so the difference between these two types of calcite is less clear.

3. Both the data obtained from cobble encrustations (and used as a reference standard for pedogenic calcretes; Quade et al., 1989) and the corresponding data from Trench 14 and Busted Butte may also be compared with $\delta^{13}C$ and $\delta^{18}O$ signatures from spring deposits of the Yucca Mountain area (Harmon, 1993; Hill and Schluter, 1994). The spring origin of the deposits considered here (specifically, Whamonie mound and southern Crater Flat) is fairly certain. For example, a USGS letter to the DOE describes the Whamonie mound as "...local surface deposits from recent warm springs" which indicate "...upward seepage of ground water, possibly from great depth." (USGS, 1980).

The results given in **Figs. 9** and **10** clearly show that stable isotope signatures of calcite deposited from spring water match signatures obtained from "pedogenic "carbonates. As a matter of fact, the match of $\delta^{13}C$ from spring calcite is much better than that of carbon from calcite at Trench 14 and Busted Butte (**Fig. 10**). One obvious conclusion which can be drawn from these data is that, at Yucca Mountain, both

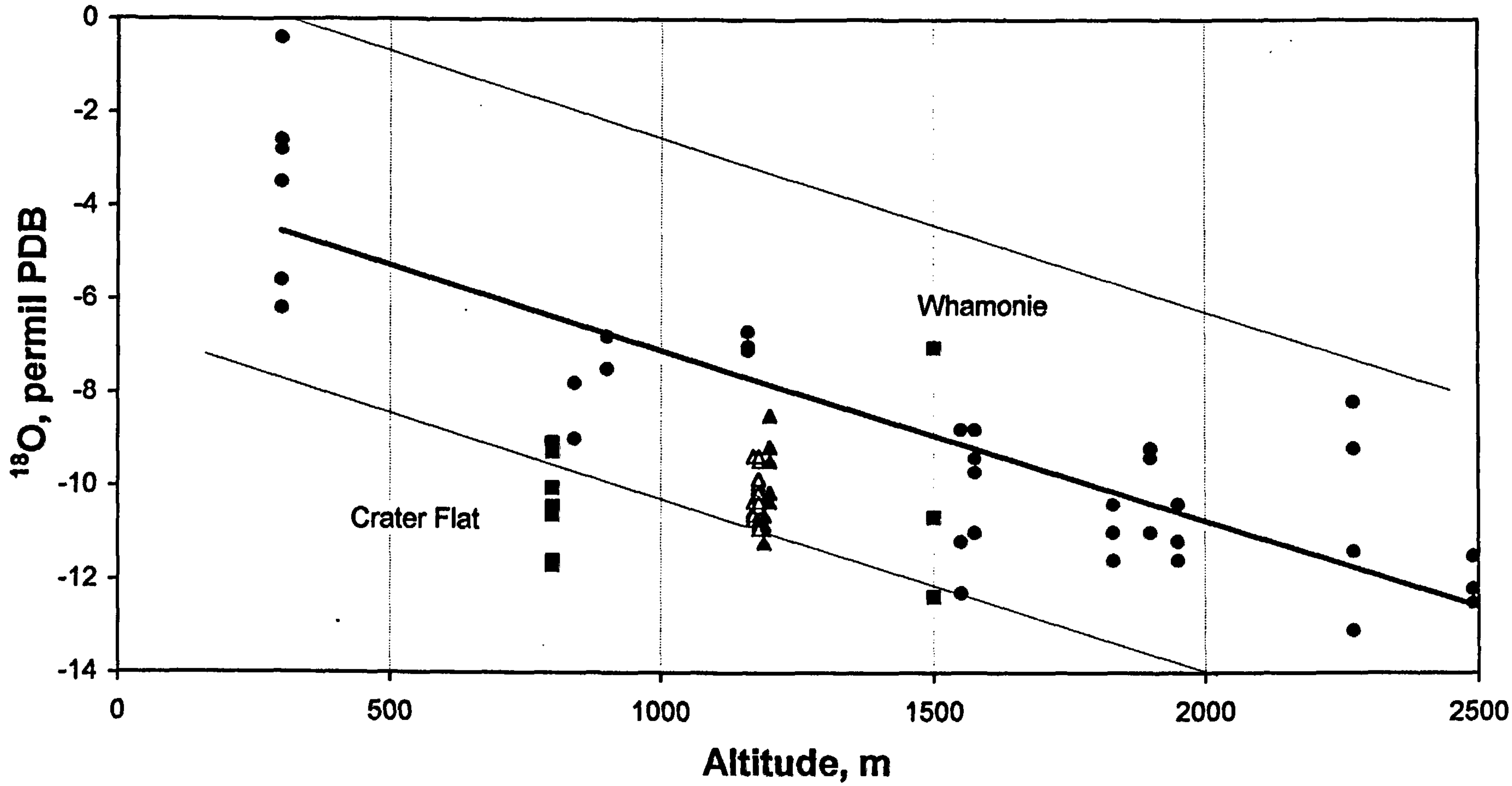

Figure 9 - ^{18}O in pedogenic carbonates (circles; by Quade et. al., 1988), spring deposits (squares; by Harmon, 1993, Hill and Schluter, 1994), Trench 14 and Busted Butte (triangles; by DOE, 1993). Thick solid line displays linear trend.

quade3.xls

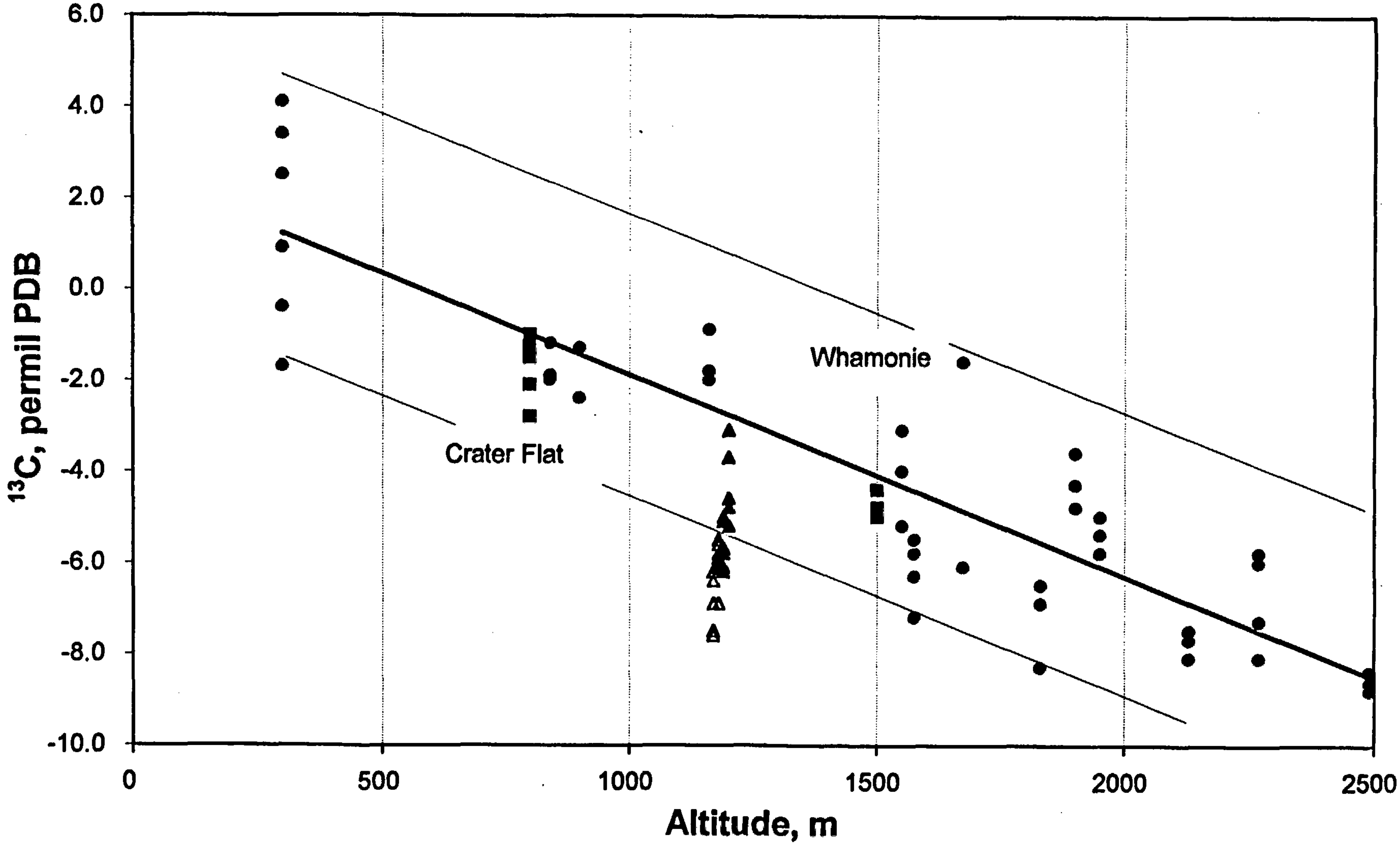

Figure 10 - ^{13}C in pedogenic carbonates (circles; by Quade et. al., 1988), spring deposits (squares; by Harmon, 1993, Hill and Schluter, 1994), Trench 14 and Busted Butte (triangles; by DOE, 1993). Thick solid line displays linear trend.

pedogenic process and ascending warm water would produce calcite with identical $\delta^{13}C$ and $\delta^{18}O$ signatures, and thus, these signatures can not be used to distinguish between the competing processes.

Statement:

The evaluation of potential origin of the calcretes from local ground water that may have risen to the surface...

was the second topic discussed.

For this purpose the data ... for several ground waters and the equilibrium constant ... for the measured temperature of the water were used to estimate the isotopic composition of calcite that would form at that temperature (for most of these ground waters the temperature was near 40 °C).

Comments:

There are several flaws in the methodology employed.

1. As it was already stated, the isotopic signatures of contemporary and shallow ground waters can hardly be used as a reference standard to evaluate the origin of calcite that was deposited several hundreds or tenths of thousands years ago and not necessarily from shallow ground water.

2. All calculations were made assuming deposition of calcite under conditions of isotopic equilibrium. This assumption would be reasonable for a large body of crystalline calcite, formed in a phreatic environment. For micritic calcite deposited at or close to the topographic surface, however, the assumption of equilibrium fractionation may not be valid. Fast crystallization would not allow the isotopic fractionation to attain

equilibrium, and other kinetic processes like CO_2-degassing and evaporation would further distort the isotopic signatures. Specifically, both degassing and evaporation would produce calcites with $\delta^{13}C$ and $\delta^{18}O$ signatures heavier than those produced under conditions of equilibrium fractionation. Consequently, calculations of depositional temperatures, as presented in Fig. 12 of the DOE Report, may lead to erroneous conclusions.

3. All calculations were made for a temperature of about 40 °C, while the actual formation temperature of calcites in Trench 14 and Busted Butte is unknown. Generally speaking, the increase in temperature causes decrease of $\delta^{18}O$ values by ~1,5 â per 10 °C.

Taking into consideration all of the above uncertainties, the reliability of the methodology employed and, as a consequence, the reliability of the DOE paleo reconstructions must be judged as very low.

4. On the other hand, a simple and logical approach would be to compare the stable isotope signatures of calcite from Trench 14 and Busted Butte with those of calcite of known spring origin **(Fig. 11)**. Two inferences can be drawn from the data shown in this figure. First, the $\delta^{13}C$ and $\delta^{18}O$ signatures of calcite from Busted Butte and Trench 14 overlap those of calcite from spring deposits. Second, in terms of carbon and oxygen isotopes these two types of calcite deposits are indistinguishable from "pedogenic" carbonates (the data for altitudes of 800 to 1700 m were taken from original Table by Quade et al.,1989). In light of these remarks, the approach employed by the DOE in performing analyses of stable isotope data must be regarded as scientifically invalid. Therefore, the conclusions resulting from these analyses are doubtful at best.

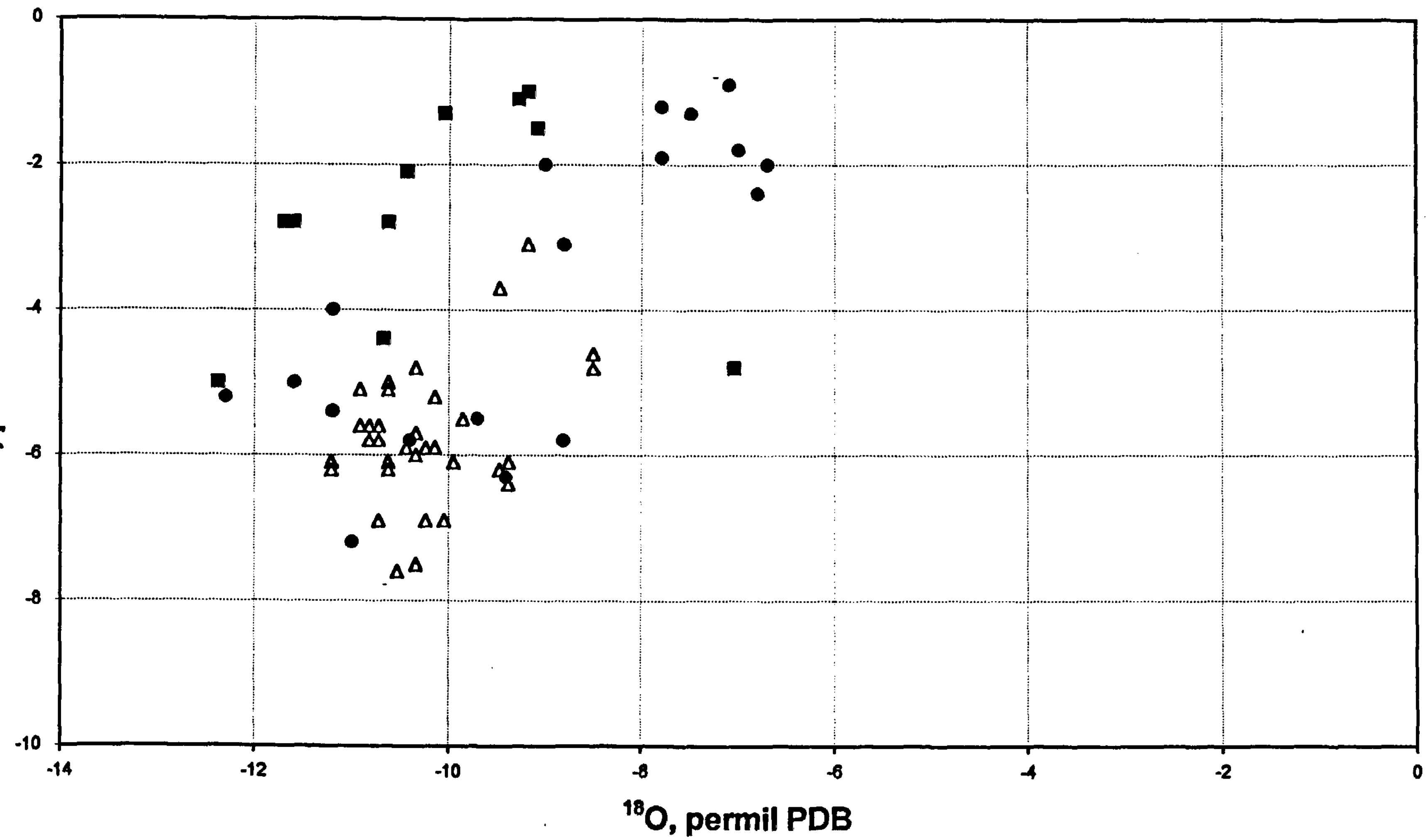

Figure 11 - Comparison of ^{13}C and ^{18}O signatures of vein and slope calcite from Trench 14 and Busted Butte (triangles) with those of calcite from spring deposits Whamonie mound and southern Crater Flat (squares) and "pedogenic" calcite (circles).

Radiogenic Isotopes

The data on radiogenic isotopes are discussed under Sections 2.2.5. and 2.3.5. "Radiogenic Tracer Isotope Data" of the DOE Report.

Strontium

1. In the DOE Report the discussion of strontium isotopes is restricted to the comparison of strontium isotope ratios measured in vein calcites with those of presumably (see comment below) pedogenic calcretes. However, if all the data available are considered **(Fig. 12)**, the obvious inference must be drawn that the controversial calcite-opal deposits, the ground water spring deposits and the "true" pedogenic deposits known at Yucca Mountain fall within the wide range of values characteristic of Paleozoic carbonates and hydrothermally altered Tertiary volcanic rocks, as well as of contemporary ground waters in the area. Thus, any combination of the local rocks and waters could have served as a source of Sr in calcites found at Yucca Mountain. Consequently, Sr by itself can not be used to establish unequivocally the source of calcium and strontium incorporated in the controversial Trench 14 and Busted Butte deposits.

2. Generally speaking, both the advocates of pedogenic origin of the Yucca Mountain controversial deposits (DOE position) and the opponents of this point of view agreed that the altered Paleozoic carbonates and the underlying Precambrian rocks of the area have served as an ultimate source of calcite and strontium incorporated in the controversial Trench 14 and Busted Butte deposits. However, even in the case of a deposit for which the source of incorporated calcium and strontium is beyond dispute,

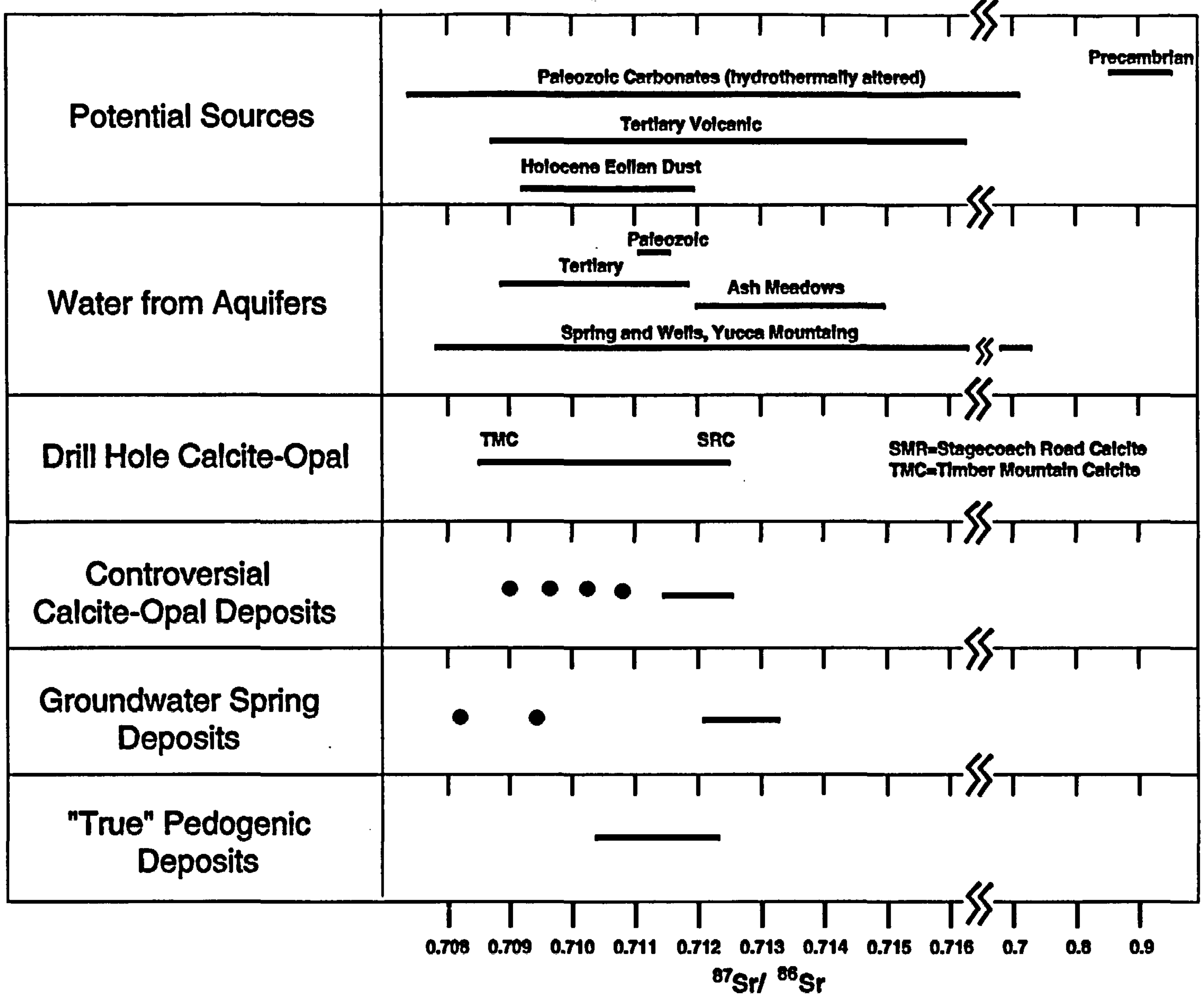

Figure 12 - Summary on Sr-isotopy at Yucca Mountain (data from Hill et al., 1994 and Hill and Schluter, 1994). Circles represent individual data points beyond the ±2σ interval of data distribution.

Number of measurements-

Rocks: Precambrian-3; Paleozoic-98; Tertiary-19; Holocene Eolian Dust-7; **Water from Aquifers:** Tertiary-15; (data for other aquifers are given as intervals of values); **Drill Hole Calcite-Opal-41; Controversial Calcite-Opal Deposits-104; Groundwater Spring Deposits-23; "True" Pedogenic Deposits-6.**

knowledge regarding the isotopic character of strontium is of no assistance in discriminating between hydrothermal deposits and pedogenic - *per descensum* deposits. This is because, in terms of the strontium isotopic ratio, calcium and strontium transported by airborne dust and rainwater are identical to those transported by upwelling water, <u>provided of course that the source of the transported elements is the same</u>. Thus, similarly as is the case with isotopes of carbon and oxygen, the isotopes of strontium can not be employed to determine unequivocally the origin of the controversial deposits from Trench 14 and Busted Butte.

3. Apart from the inappropriateness of Sr for genetic determinations (at least at Yucca Mountain), the line of reasoning employed in the DOE Report contains elements of circular logic. The slope calcretes, for which the origin is to be determined, were <u>presumed</u> to be of pedogenic origin and then used as a reference standard to judge the origin of the vein calcite. The unavoidable conclusion was that these two calcite facies represent the same genesis (that, in most instances, is pretty obvious just from the field relationships), and thus, the controversial vein calcites were concluded to be also of pedogenic origin.

> *Taking into account these three comments, the approach used by DOE must be regarded as scientifically (and, moreover, logically) invalid, and the conclusion drawn that:..the strontium isotopic data strongly favor a pedogenic origin for the calcretes, and argue against all the other proposed origins (p. 40)*

must be considered as misleading and groundless.

<u>Uranium and thorium</u>

Statements:

Uranium and thorium isotopes are also useful natural tracers for constraining the origin of calcite at Yucca Mountain (p. 58)

and:

Thus the veins and ground waters cannot be genetically related (p. 60).

Comments:

1. Both of these statements are grossly misleading and inappropriate. Justification for this opinion is provided in **Fig. 13**, which shows two important points. First, in the vicinity of Yucca Mountain deposits that are known to be "genetically related" to ground water carry values of $^{234}U/^{238}U$ activity ratio identical to those from the Trench 14 and Busted Butte deposits. Coarsely crystalline calcite veins from Amargosa Basin and from Furnace Creek Wash are examples of such deposits ($^{234}U/^{238}U$ activity ratios of less than 1,5; Szabo and O'Malley, 1985). Second, the low values of $^{234}U/^{238}U$ activity ratios (although most common) are not exclusively characteristic of the controversial Trench 14 and Busted Butte deposits. In this regard, new results from carefully-selected samples (to avoid undesirable open-system behavior) were reported by Harmon (1993) and are shown in **Fig. 13**. These new activity ratios are identical to those from the Devil's Hole vein, which is an undisputed ground water deposit. They are distinctly higher than those expected to be associated with *per descensum* pedogenic deposits and instead are consistent with precipitation from upwelling ground waters from great depth.

2. Uranium and thorium isotopes are, indeed, "useful natural tracers for constraining the origin of calcite", but only for a deposit behaving as a closed system. For a deposit submerged in a fluid saturated with respect to $CaCO_3$, the assumption of closed system behavior seems appropriate. In this setting vulnerable ^{234}U atoms, which are

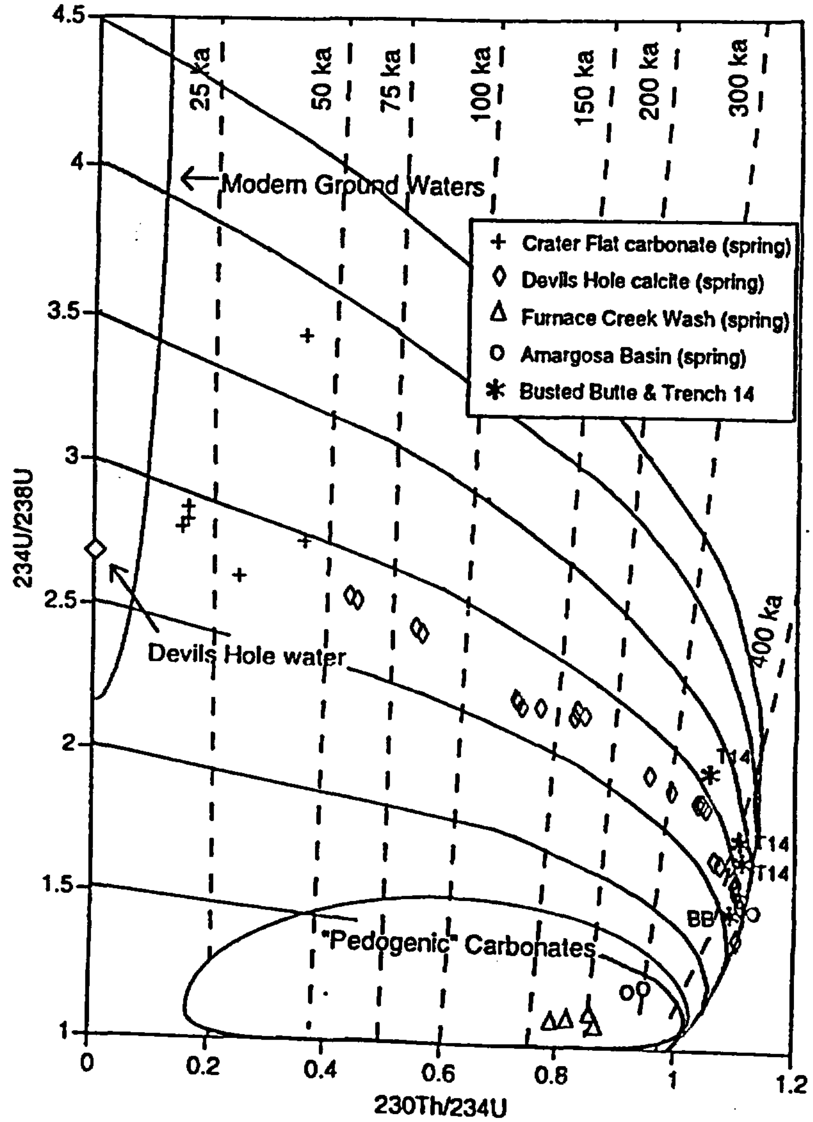

Figure 13 - Trench 14 and Busted Butte CCOD and Devils Hole, Amargosa Basin, Furnace Creek Wash, and Crater Flat GSD plotted on a U-series isochron diagram (36). "Pedogenic" carbonate field is from Paces et. al. (1994) but may be CCOD affected by open-system conditions rather than being representative of TPD. Asterisks (*) represent unleached (or relatively unleached) samples from Trench 14 and Busted Butte, Harmon (1993).

contained in a previously precipitated part of a travertine vein, are shielded by continuous precipitation of $CaCO_3$. In the vadose zone, however, the circumstances are markedly different. In this setting radiogenic ^{234}U atoms are not armored by ongoing deposition of calcium carbonate and are exposed to leaching by rainwater. Intermittent flushing by infiltrating rainwater may lead to preferential removal of some ^{234}U atoms, resulting in the lowering of the actual value of $^{234}U/^{238}U$ ratio. This may occur because, relative to parent ^{238}U atoms, radiogenic ^{234}U atoms are more vulnerable to leaching. This relative vulnerability is a consequence of the $^{238}U \rightarrow {}^{234}U$ decay, which involves alpha particle emission (Osmond and Cowart, 1982). The ejection of alpha particles has the effect of damaging the crystal lattice around the parent ^{238}U atom. The resulting daughter nuclide ^{234}U occupies the radiation-damaged site which, consequently, is more susceptible to chemical leaching. The measured value of $^{234}U/^{238}U$ ratio incorporated in a vadose zone calcite therefore reflects both $^{238}U \rightarrow {}^{234}U$ radioactive decay and selective removal of ^{234}U atoms by infiltrating rainwater. Consequently, the measured value of the $^{234}U/^{238}U$ ratio is a minimum value which, if corrected for radioactive decay assuming closed system behavior underestimates (by unknown amount) the isotopic ratio of the uranium dissolved in the parent fluid.

Even in the case of a deposit that demonstrates the desired closed system behavior, knowledge regarding the isotopic character of uranium dissolved in the parent fluid is still of questionable value. This is particularly true for low values of $^{234}U/^{238}U$, since low values may be characteristic of both supergene infiltrating fluids and upwelling hypogene fluids (see, e.g., Zukin et al., 1987).

Section 2. Reliance on the Biased NRC/NSA Report of 1992

In Section 2.2.9.2, entitled "Reports and Reviews", authors of the DOE Report attempt to gain a broad public and scientific acceptance of their demonstratively unwarranted conclusions. This attempt takes a form of demonstrating that these conclusions are similar to those drawn by the DOE sponsored NRC/NSA Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain. Unfortunately the overall conclusion by the Panel, as well as other interpretations throughout the NRC/NSA report, are not supported by available facts. In this regard, the Panel has ignored multiple lines of evidence, distorted and misrepresented the record, and did not provide adequate justification for the all-inclusive dismissal of hydrotectonic hazards at Yucca Mountain. More importantly, analytical data (e.g. radiometric ages, geothermometry and stable and radiogenic isotope abundances) not considered by the Panel, provide evidence for recurrent invasion of "the level of the proposed repository horizon" by hydrothermal fluids.

The report prepared by the NSA/NRC Panel, entitled "Ground Water at Yucca Mountain: How High Can It Rise?" has generated critical reviews by Sommerville et al., (1992) and by Archambeau (1992). These reviews were submitted to the National Research Council of the National Academy of Sciences. Rather than discuss the details of these reviews, they are enclosed as Appendices I and II, respectively.

Before attaching any significance to the fact that the DOE conclusions are similar to those expressed by the NRC/NSA Panel, interested readers are urged to review the material provided in the appendices. This material focuses on the specific data and observations that are at the heart of the controversy over both the origin of the Trench 14 and Busted Butte deposits and the suitability of the proposed Yucca Mountain repository. The appendices provide interested readers with facts which may enable them to contrast and assess the views of the opposing sides in this controversy. At the least, these appendices reveal the character of the debate, which may be enlightening to those unfamiliar with this controversy.

Section 3. Comments Regarding Origin of Silica Deposits and Breccias

This topic is discussed in Section 2.2.8 "Relationships of Silica Deposits and Breccias to Calcite-Silica Deposits" of the DOE Report. The four strong conclusions reached by DOE are given on p.39. Examined in detail, however, each of these conclusions appears to be either unwarranted, or purely speculative.

Conclusion 1:

> *Quartz and chalcedony in Trench 14 are of hydrothermal origin, but the deposits are at least 8 million years old.*

Comments:

This evaluation is based on two assertions, specifically that:

> *Comparable mineral deposits are not present in the younger pyroclastic units exposed in the trenches..., (p. 36)*

and:

> *Experimental ESR dating of one quartz sample from Trench 14 yielded an age of 8,7±2,6 million years... There are several unevaluated sources of error, all of which would increase the*

calculated age. At the upper limit of the calculated error, the quartz age approaches 12,7 million year age of Tiva Canyon Member (p.36).

First of these statements is misleading. The fact that "comparable deposits are not present in younger pyroclastic units exposed in trenches" does not necessarily mean that they are not present within young formations at other locations at Yucca Mountain (see additional information below). The second statement is based on one measurement which, in fact, gives an apparent age ranging from 6,1 to 12,7 Ma, so the stated age estimate is uncertain at best. If there are "several unevaluated sources of error", how one knows that all "would increase the calculated age"?

Conclusion 2:

AMC breccias in a gully at Busted Butte are cemented colluvium or slope-wash alluvium and are not related to either hydrothermal process or faulting.

Comments:

This assertive conclusion is based on the observations that: (1) the breccia fragments are not suspended in cement; (2) most of the clasts acquired coating of calcite and opal including plant root casts at some time, perhaps prior to incorporation in the existing deposits; (3) post depositional fracturing of the mostly rounded clasts has been very minor; and (4) cements show few signs of breakage and recementation. Then, an assertion is drawn that "The deposit may be a colluvial breccia or simple alluvium cemented by authigenic minerals" (p.37, emphasis added). Because all of the cited textural features may be produced by hydrothermal processes it is obvious, that the observations given above, descriptive by their nature, do not preclude a genetic relation of these breccias with low temperature hydrothermal process. The DOE conclusion, thus, is unwarranted.

Conclusion 3:

> *AMC breccias at Trench 14 were formed by movement along the Bow Ridge fault and have been variably modified by the same pedogenic processes responsible for the calcite-silica vein deposits.*

Comments:

This conclusion is based on the following observations: (1) grain-supported textures were identified microscopically; (2) the breccia cements are mineralogically the same as the cements in other AMC breccias and in laminated calcite-silica veins and calcretes; (3) contribution of hydraulic fracturing and mineral deposition by fluids from depths is not evident; (4) presence of root-casts; (5) lack of alteration in the tuff clasts. All of these observations (except 3) are equivocal, i.e., they do not preclude the competing model of breccia formation by upwelling waters. The observation 3 is highly speculative (why should hydraulic fracturing necessarily occur; what would be the evident indication of "mineral deposition by fluids from depth"; and why should such an indication be evident?). And finally, the conclusion contains another example of circular reasoning: the origin of calcite-silica veins is presumed to be pedogenic and, because of to similarity in mineralogy, the AMC breccia cement at Trench 14 is concluded to be pedogenic, as well.

Conclusion 4:

> *Fission track data for zircons in the AMC breccias are most compatible with input of surficial detrital material in the breccias.*

Comments:

The fission-track dating of zircons extracted from breccias at Trench 14 and Busted Butte gave ages ranging from 4,8±2,5 Ma to 59,7±12 Ma, that is, respectively, much younger and much older than the K-Ar age of the host tuff (13 Ma). In discussion on p.38 the authors of the DOE Report consider three possible interpretation of these data. The **first** possibility is that fluids which cemented the breccias brought zircons of different ages up from below the topographic surface. The zircons would have to have been heated sufficiently (up to 180 °C) prior to or during emplacement to cause some track annealing. The **second** possible interpretation is that the breccias were open to the surface and wind and surface water washed the zircons into the breccias. With respect to the possible source of these detrital zircons, the authors admit that "...no data are available at present to identify the possible source..." (p.38). The **third** possible interpretation represents a combination of the first two processes.

The authors of the DOE Report eliminate the first possibility by stating:

> *Deposition of zircons by ascending waters that were hotter than 180 °C when they reached the surface is not compatible with the high abundance of plant root casts throughout the breccia cement (p.38,* emphasis added*).*

This is a highly misleading statement, because, as it was initially considered by authors of the DOE Report, the zircons could have been "reset" by heating prior to the emplacement into the breccia cement, at a significant depth. The ascending waters, thus, may not necessarily have had the temperature of 180 °C at the surface. This consideration is consistent with paleo-temperature gradients of 170-180 °C/km inferred at some locales at Yucca Mountain (see Appendix III).

In light of the above considerations, it is appropriate to note that both models considered by DOE, i.e. transport of zircon by ascending hydrothermal fluids and transport by superficial agents such as wind and running water, are equally plausible. Therefore, in contrast to the DOE assertions, the currently available data do not allow for unequivocal resolution of the genesis of breccias at Yucca Mountain.

Overall conclusion and additional information

The whole discussion presented in Section 2.2.8 of the DOE Report and the conclusions drawn are speculative, and probably are not correct. While considering potential significance of both silica deposits and breccias from Trench 14 and Busted Butte, a reader should be aware of the following additional information:

1. Referring to the silica-cemented breccia in Trench 14, the panel convened by DOE in 1987 stated:

> *On the basis of field inspection it may reasonably be interpreted as a hydrothermal eruption breccia (Hanson et al., 1987).*

2. Breccias and silica deposits similar to those observed at Trench 14 and Busted Butte (except for the lithology of clasts) are present in numerous exposures of Paleozoic limestones around Yucca Mountain. This observation indicates that breccias are not necessarily syn-depositional with the host ignimbrites. Furthermore, because the silica deposits occur in Paleozoic limestones they are not necessarily

> *...most likely linked to hydrothermal processes engendered by infiltration of meteoric water into newly deposited and still-hot pyroclastic flows more than 10 million years ago (p.36).*

3. At numerous locations at Yucca Mountain the breccia clasts are silicified and altered (see, e.g., Appendix I, Figure 12).

4. Epigenetic (i.e., formed after coling of "pyroclastic flows more than 10 million years ago") silica mineralization is present in younger rocks and formations at Yucca Mountain. Specifically: (a) silica minerals are present in Rainier Mesa tuff; (b) needle-like quartz crystals are found in presumably "pedogenic" formations exposed in Trench

14 and in trenches excavated across the Stagecoach Road fault; (c) the age as young as <50 Ka and temperatures as high as 34 to 83 °C were obtained by ESR method from quartz extracted from two core samples (depth 280 to 450 m; Haskell and McKeever, 1994; see Appendix III).

In light of the above remarks it is evident that the origin and the age of formation of breccias and silica deposits at Yucca Mountainis still uncertain. However, objective and careful studies of these silica deposits and breccias may contribute significantly to understanding the hydrothermal history of Yucca Mountain. This history, in turn, lies at the heart of the controversy over both the origin of the Trench 14 and Busted Butte deposits and the suitability of Yucca Mountain to accommodate a high-level nuclear waste repository.

Section 4. Incomplete Data Information

Another problem with the DOE Report, other than wrongly interpreting some of the data, is that information given on the data is incomplete. In the DOE Report only general locations are given; or, if a specific location is given, the exact collection site and detailed description of the deposits at that location are not given. A specific example is on p. A-19, where uranium-series dates obtained on Busted Butte calcite-silica samples are listed. The reader is not given the location of the collection site (where the samples collected from vein or slope travertine, or if the A, B, C, and D represent collection from a number of different places or from a horizontal or vertical sampling suite in one place).

Another example is the ^{13}C and ^{18}O data for vein and slope calcite at Busted Butte. As it was shown in Section 1.4 (**Fig.** 8) of this report, these data reveal a trend that may be indicative of degassing and/or evaporation of fluids during deposition (that is very important for the purpose of determination of the origin of the controversial deposits). However, even the basic information about location sampling points is not available.

This incompleteness of information limits the usefulness of the data presented in the DOE Report.

Tracing down the source of data information from the DOE, such as is presented in the Report, is extremely difficult to downright impossible. In preparation of their data chart, Hill and Schluter (1994) contacted the DOE concerning information on the Busted Butte calcite-silica ages (and other data in this and other DOE reports), but the origin of these data, and the person or persons responsible for these data, could not be traced.

Section 5. Omission of Pertinent Data

By far a more serious problem with the DOE Report than incomplete data information is the omission of certain pertinent data. Data supplied by the DOE to the State of Nevada in 1992 (letters from R.Nelson, project manager of DOE to R.Loux, director of Agency for Nuclear Projects, State of Nevada) was not included in August, 1993 DOE Report. In particular, the following omissions favor a hypogene origin over a pedogenic origin.

1. **Carbon-14 ages on drill hole calcite.** Carbon-14 ages on calcite in drill holes G1, G2, GU3, and G4, at depths of 14 to 346 m, range from 20,910 to 45,260 yrs (11 out of 14 samples). These data suggest a young, hypogene origin for calcites in the shallow subsurface and imply that the calcite-silica deposits on the topographic surface at Trench 14 and Busted Butte could also be of hypogene origin.

2. **Fluid inclusion, carbon-oxygen, and ESR data on young drill-hole calcite.** Shallow calcites with young ages (both ^{14}C and U-series dates) can have high fluid-inclusion homogenization temperatures, again implying a hydrothermal, hypogene origin for the calcite-silica surface deposits at Yucca Mountain. In addition, some of these drill-hole calcites have carbon-oxygen isotope values characteristic of the calcite-silica deposits at Trench 14 and Busted Butte (Hill and Schluter, 1994), and this paragenetic association provides further support for a genetic connection between subsurface veins and the surface calcite-silica deposits. The geothermal environment at Yucca Mountain in Plio-Quaternary was evaluated on the basis of these data by Dublyansky (1994). Rather than discuss the details of this reconstruction here, it is presented in the attached Appendix III.

All these data imply that there was a late-stage, hydrothermal, hypogene episode at Yucca Mountain and that there is no reason why the calcite-silica deposits at Trench 14 and Busted Butte should not have been related to this episode. There is, however, another aspect of the overall problem. The main issue is not the origin of calcite-silica deposits in Trench 14 and at Busted Butte. Rather, the main issue is whether or not the Yucca Mountain vadose zone was inundated by thermal water in the relatively recent past, and thus, whether or not such inundation is possible in the future. Taking into account that currently available data from below the topographic surface argue persuasively in favor for the action of a hydrothermal system at Yucca Mountain during the Plio-Quaternary time span (see Appendix III), the origin of controversial deposits at

Trench 14 and Busted Butte, discussed in the DOE Report, is of purely academic interest.

Conclusions

A critical examination of the DOE Report, as presented in the preceding sections, leads to the following two conclusions. **First**, the DOE main conclusions, specifically that a).

> *...the calcite-silica deposits in Trench 14 originated from pedogenic processes and do not indicate presence of upwelling waters (p. 63)*

and b).

> *...studies of the silica deposits and breccias indicate that most were formed more than 10 million years ago (p. 64),*

were derived from incomplete and equivocal data, by ignoring equally valid alternative interpretations, and by ignoring elemental logic and falling into circular logic instead. With these shortcomings, the DOE conclusions must be regarded as unfounded and unsupportable under any rational test of uniqueness as to a casual mechanism.

Second, the fact that the DOE report was released in it's current form provides clear and convincing testimony with regard to a complete breakdown of the Yucca Mountain Project Quality Assurance Program. Evidently, the mandatory reviews are not conducted keeping in mind the ultimate objective of assuring a high degree of confidence in the conclusions drawn and in the soundness of the resulting management actions. Instead, the Quality Assurance Program seems to function with a sole objective of creating a perception of an undertaking where careful and objective scientific scrutinity prevails. However, in reality the QA program provides a cover for a process of discovery which is dominated by distortions, assertions, and lapses of elemental logic. In the context of developing a high-level nuclear waste repository, such a process is dangerous in the extreme.

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Appendix I

Review of the NAS/NRC Report: "Groundwater at Yucca Mountain: How High Can It Rise?"

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REVIEW OF THE NAS/NRC REPORT: "GROUNDWATER AT YUCCA MOUNTAIN: HOW HIGH CAN IT RISE?"

SPECIAL REPORT No. 1
CONTRACT No. 92/94.0004

SPECIAL REPORT Submitted to the
Nuclear Waste Project Office
State of Nevada

December, 1992

Authored by:

C. B. Archambeau

Review of the NAS/NRC Report: "Groundwater at Yucca Mountain: How High Can It Rise?"

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Review of the NAS/NRC Report:
"Groundwater at Yucca Mountain: How High Can It Rise?"

by

Charles B. Archambeau

There are three basic and serious problems that produce disagreement with the conclusions and recommendations of the Academy report. These are: *First, the report ignores a considerable body of critical data relating to the ages and nature of hydrothermal alterations at the site; second, many of the strong conclusions expressed in the report are not reasonably supported by the evidence presented and, in some cases, are inconsistent with data and results available to the committee but which are not cited or used by them; and finally, there are statements describing field relationships and data that are not consistent with the facts or are made in such a way as to be misleading.*

Zircon Age Data: Evidence for Hydrothermal Activity

An example of what can be regarded as a misleading characterization of data is given on page 44 of the report. The Academy Panel states:

> *"Fission - track dating of eroded fragments of (or detrital) zircons found in carbonate that cements AMC - type fault breccia at Trench 14 and at Busted Butte gives a spread of ages showing heterogeneity of source material, with some zircon ages older and some younger than the age of the bedrock in the immediate region (Levy and Naeser, in press). However, within the analytical uncertainty, most of the ages are about 10-12 Ma, or about the same as those of the dominant volcanic rocks in the region."*

However, the Levy and Naeser reference states (p. 17):

> *"The spread in ages from each sample indicates that there are zircons from multiple sources present. In both samples there are crystals <u>significantly</u> younger and <u>significantly</u> older than the age of the tuff."* (Emphasis added.)

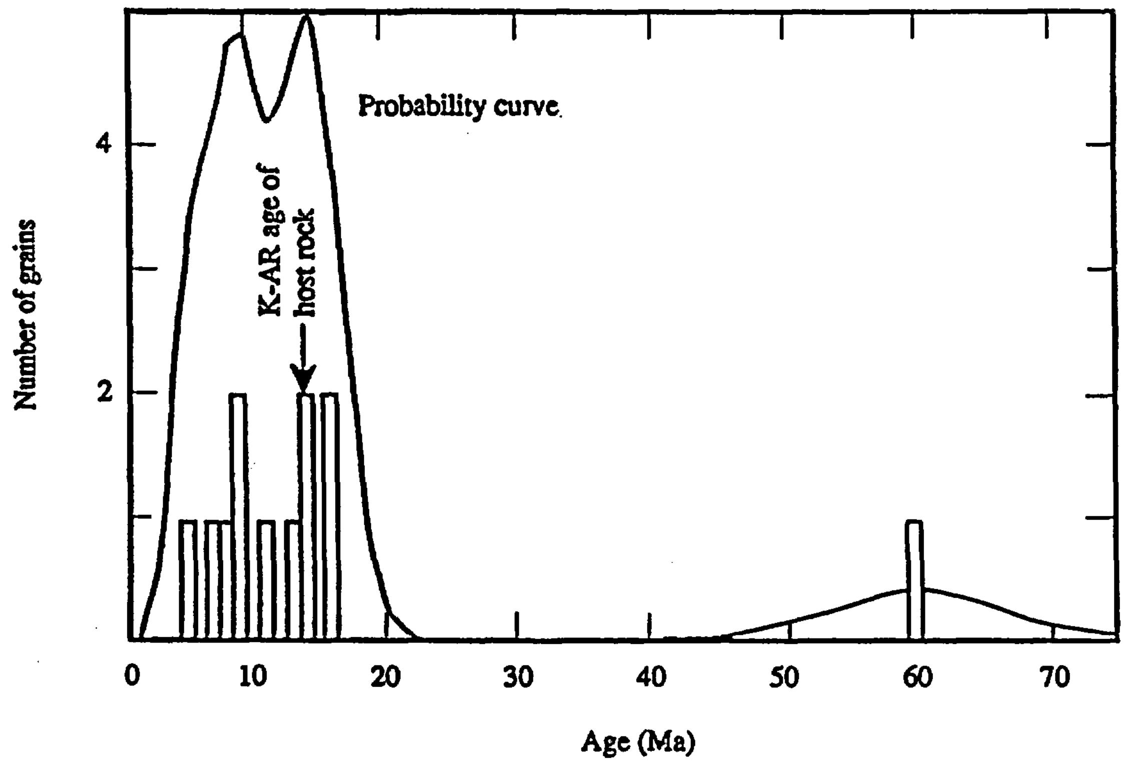
In the following paragraph Levy and Naeser go on to show plots of these data and state the basis for their confidence in the observed spread in zircon ages as follows (references quoted are omitted):

"One way to illustrate the spread in the ages is through the use of a probability density distribution plot. The probability density plot sums the normal distribution curves for all the grains in a sample. These curves are calculated from an age and its standard deviation. Figure 6 shows an example of a sample with a single age population; the Fish Canyon Tuff zircons are used as a primary age standard for most fission-track laboratories in the world and the probability curve exhibits a normal distribution. In contrast, samples HD-41-4 and HD-74-2 both show multiple age peaks (Figures 7 and 8). The ages of the individual grains are shown in the histogram beneath the probability curves for all three samples."

The data shown by Levy and Naeser in their Figures 7 and 8 are reproduced in the attached Figure 1. These data clearly show the multiple peaks identified by Levy and Naeser. *Contrary to what is stated by the Panel,* most of the zircon crystals analyzed from each sample show dates considerably less than the Potassium-Argon ages of the host tuff (13 Ma), rather than greater than the age of the tuff. Further, the Panel implies an age for the host tuff of 10-12 Ma, while it is clearly stated to be 13 Ma.

As seriously misrepresentative is the neglect of the Panel to indicate that the authors clearly use the term 'significant' in a technical sense. In fact, the Panel report does not even mention that the authors themselves attach significance to peaks in the distribution and that they do *not,* in any way, suggest that *"within the analytical uncertainty the ages are about the same as those of the dominant volcanic rocks in the region."* This is the Panel's statement, but they do not distinguish this assertion from the previous sentence referencing the paper by Levy and Naeser. They thereby induce the reader to assume that this statement is consistent with the results of the authors. In this way they do not have to explain why their characterization of these data is different from that given by the authors, or even mention that a difference exists.

An examination of the age data, as given in Figure 1, shows that there are ages 4.8 Ma, 6.2 Ma, 7.5 Ma, and 7.7 Ma among the crystals in these two samples. There are



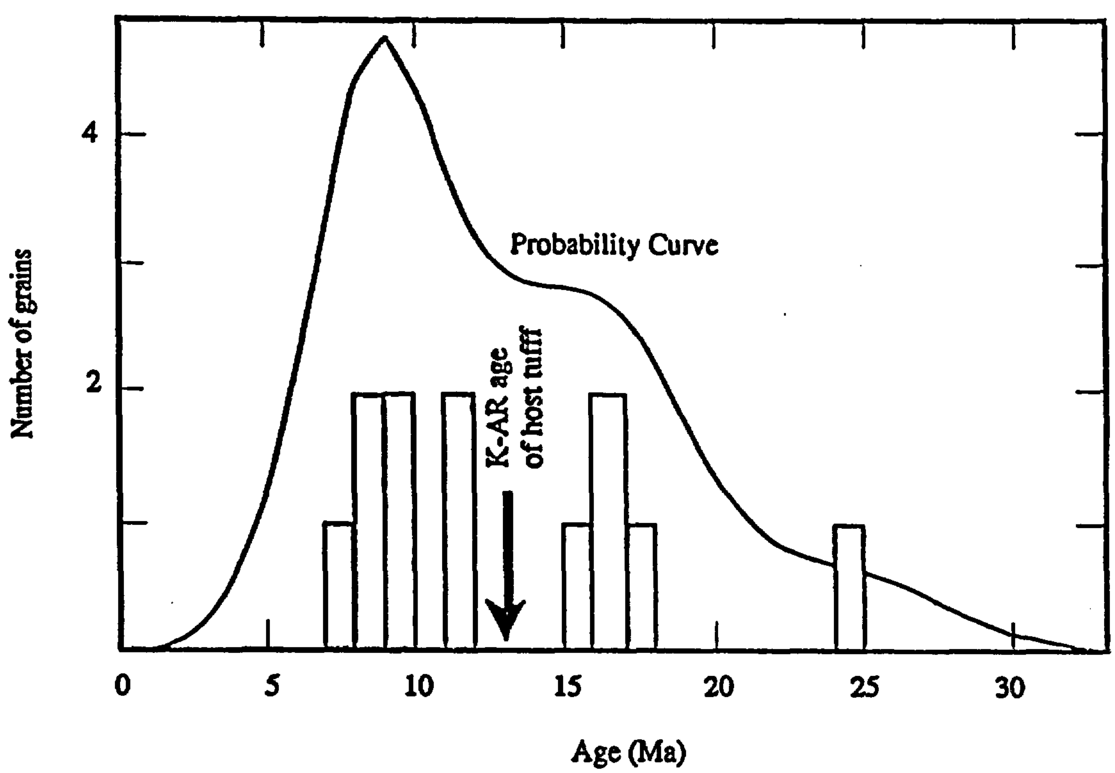


Figure 1. Fission track ages of zircons from breccias at Busted Butte (top) and Trench #14 (bottom). From Levy and Naeser, 1991.

several additional dates near 8.5 Ma. The two sigma interval attached to the youngest age, of 4.8 Ma, is 2.5. Thus, there is very high confidence (over 90%) that the age of heating of this crystal was between 2.3 Ma and 7.3 Ma, with the highest probability for a specific age being 4.8 Ma. The same interpretation of confidence intervals applies to the other ages given. Clearly, characterizing these age data as being within the age range 10-12 Ma, given "analytical uncertainty," is incorrect. It is on this inaccurate basis that the Panel states that (p. 3):

> *"The preponderance of features ascribed to ascending water clearly (1) were related to the much older (13-10 million years old (Ma)) volcanic eruptive process that produced the rocks (ash-flow tufts) in which the features appear,..."*

This conclusion is actually directly contradicted by the age data cited.

This issue is extremely important in that these are the only age data used in the NAS report to substantiate the claim that the last and final hydrothermal event occurred some 13 to 10 Ma ago. Age data from uranium series dating of calcites from veins at depth as well as potassium-argon dates from zeolites, which are commonly produced by hydrothermal alteration of volcanic glasses, were ignored by the Panel. However, as shown in Figure 2, many young ages are present in these data as well, some as young as 30 ka. In view of the preceding description of what is actually represented in the zircon age data, and in view of the zeolite and calcite vein age data, it is evident that high temperature annealing of fission tracks occurred at times much more recently than 10 Ma and that related hydrothermal alteration produced the observed young zeolites along with the recent calcite and opal veins throughout the mountain. Indeed, it is likely that analysis of additional zircon samples would show more recent ages, like the age data from the zeolites and calcites. Therefore, contrary to the Panel's statements, the age data actually support the occurrence of recent (post-Timber Mountain) hydrothermal activity rather than providing evidence against it.

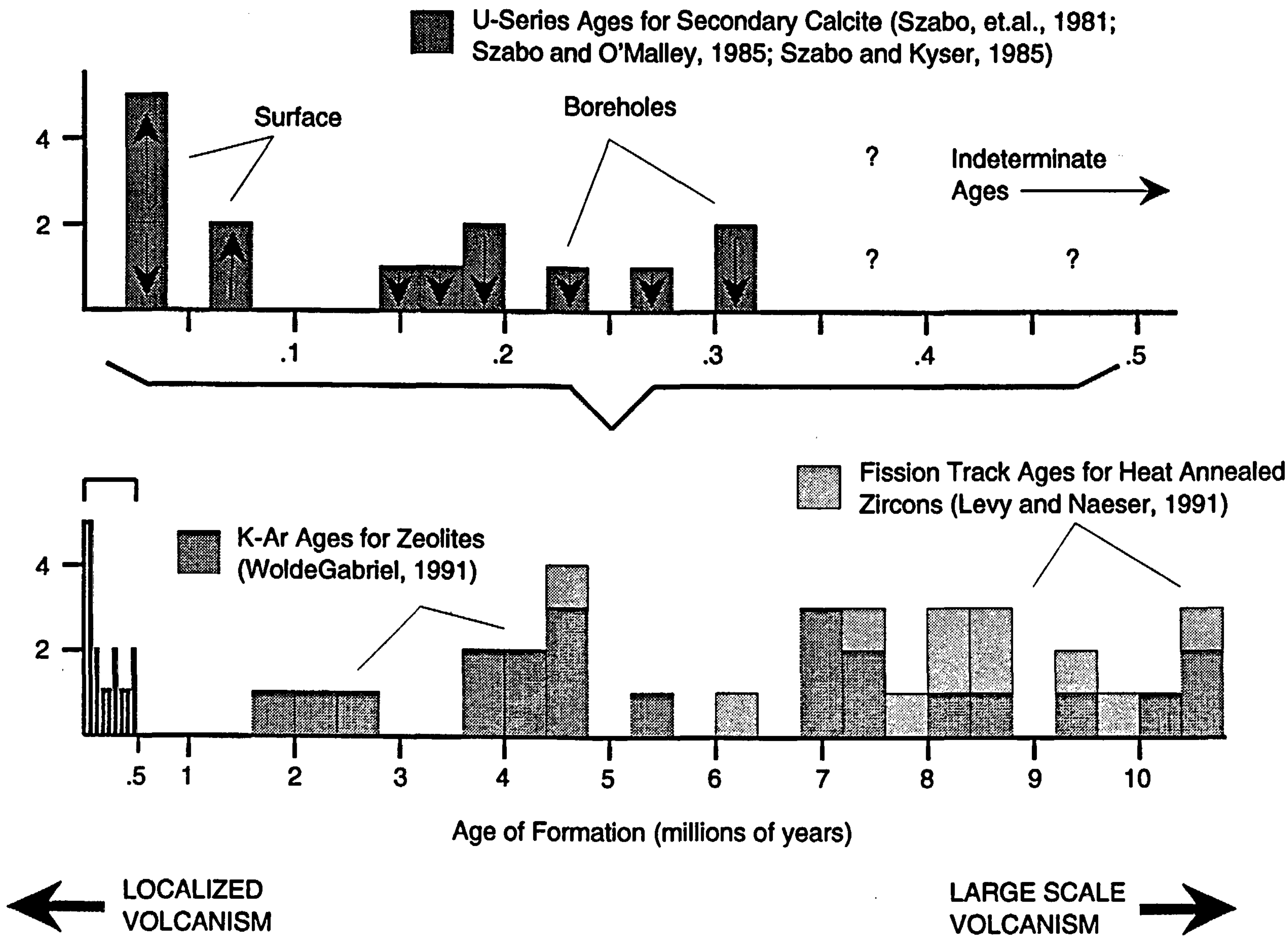


Figure 2. Ages of Fluid Alterations at Yucca Mountain

Field Observations: Spring Mounds, Faults and Surface Calcretes, Zeolites and Glass

Besides these misleading characterizations of important age data, the Panel has also characterized field observations inaccurately. One example is their statement that the Quaternary hydrothermal spring closest to Yucca Mountain is at Travertine Point, some 55 km away (p. 130). This statement is not correct: the hot springs at Oasis Valley just north of Beatty, Nevada, which were visited by the Panel, are only 25 km from the site. Further, they use the Travertine Point mound deposits to make the argument that springs at Yucca Mountain would also have to produce mounds, implying that all springs should produce mounds regardless of their topographic location or the chemical content of the water. However, the nearby springs at Oasis Valley do not now appear to be forming mounds. Likewise other springs in the region, at Boulder Dam and Dixie Valley, are not producing mounds. On the other hand, some of the many hot springs at Tecopa, CA (which is in the general area) are producing mounds, but others in this same area are not.

Consequently, the Panel has generalized from one example to establish a necessary criterion for ancient spring activity (the presence of mounds) and apparently presumed that the near proximity of the example to Yucca Mountain would provide the necessary justification. However, they are wrong on all counts: the example used is not the closest to Yucca Mountain, and mounds are sufficient but not necessary to establish spring activity. Indeed, water emerging from fault zones on a steep slope would not be expected to produce mineral mounds, but instead should produce slope parallel deposits, such as the calcrete deposits at Trench 14 and around Busted Butte.

Yet another example of importance is the Panels' statement (p. 33) in response to the idea that the observed calcretes at Busted Butte are produced by water flowing from up-slope fault zones. Here the Panel report rejects the idea on the basis of their own observation that there are no faults up-slope from these deposits. However, available geologic maps show at least one major fault zone at higher elevations at Busted Butte, contrary to this statement.

These two examples are important in that the Panel uses lines of argument built upon these statements to assert, in their overall conclusion statement, that:

> *"The preponderance of features ascribed to ascending water clearly... (2) contained contradictions or inconsistencies that made an upwelling ground - water origin geologically impossible or unreasonable,..."*

Another line of "evidence," considered by the Panel as contradictory or inconsistent with an upwelling water origin, is the zeolite and glass distribution with depth. Specifically citing the depth distribution of zeolites and glass as its evidence, the Panel states (p. 48):

> *"The boundary between the altered and vitric tuffs indicated that the water reached its highest levels and receded downward from 12.8-11.6 Ma, and that since that time the water level at central Yucca Mountain has probably not risen more than 60 m above its present position."*

However, it is not possible to find the support cited for this conclusion from the actual data, which are shown in Figure 3. In particular, the observations show that, in some drill holes, glass is present hundreds of meters below the present water table. Further, zeolites are also present hundreds of meters above the water table. Thus, the distributions of zeolite and glass do not produce a simple relationship with the water table, that is both glass and zeolite occur above and below the water table making it impossible to establish a boundary and an ancient receding level for the water table based on these data.

In regard to the latter, it is important to point out that the Panel did not mention that the K-Ar dates of the zeolites in question range from 2 to about 10 Ma, as shown in Figure 2, and are much younger than the host ignimbrites. Further, the youngest zeolites are near the surface and the oldest are at depths below the water table. If the water table reached its highest level at 12.8 - 11.6 Ma and receded downward from that

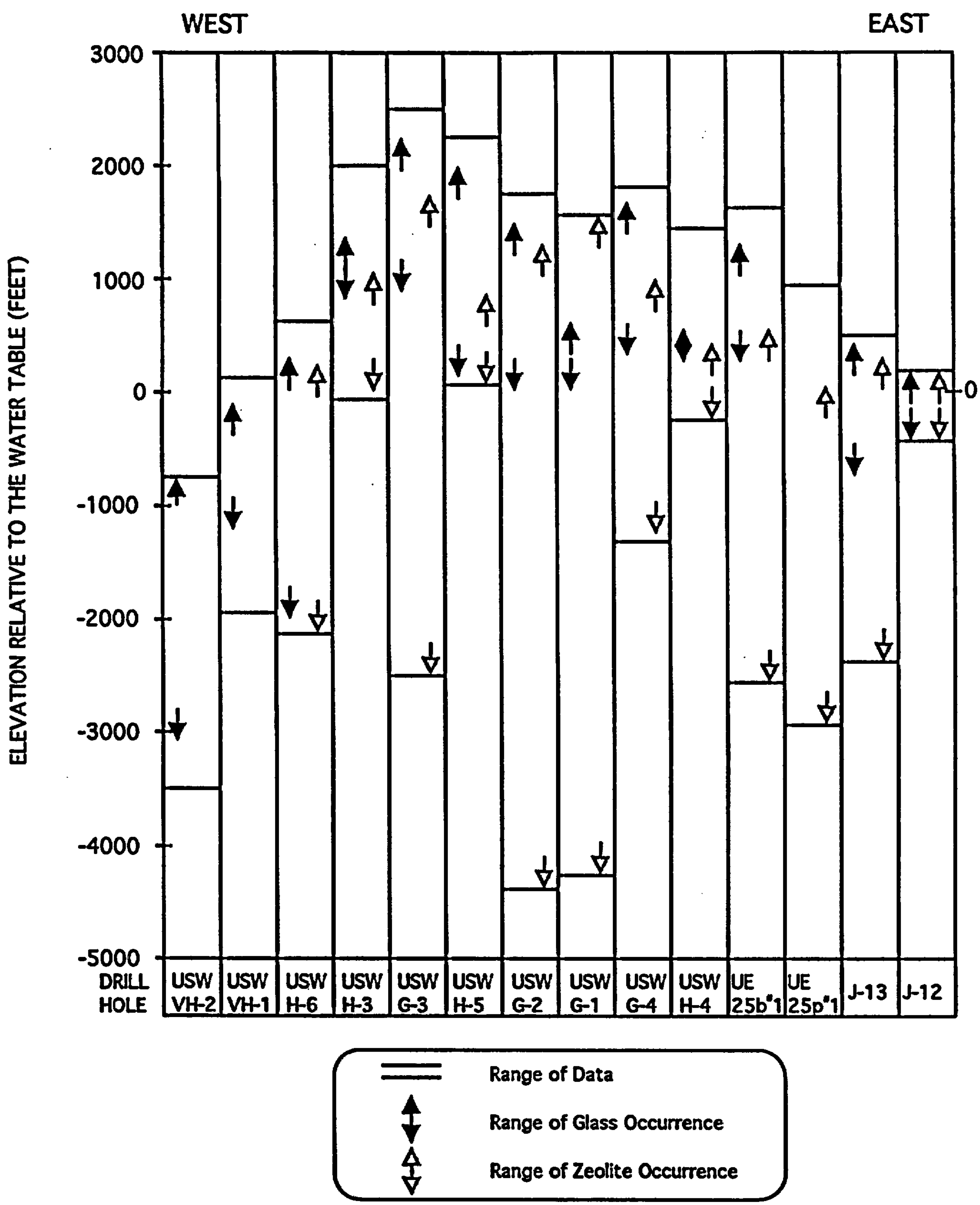


Figure 3. Distributions of glass and zeolite relative to the water table. Drill hole locations are distributed within and very near the proposed repository at Yucca Mountain with the exceptions of VH-2 and VH-1 in Crater Flat to the West and J-13 and J-12 in Jackass Flat to the East.

time to its present level, the opposite depth-age relationship for the post-10 Ma zeolites would be expected. Indeed, this depth-age relationship is what would be expected for an upwelling hydrothermal origin of the zeolites. Furthermore, this is the process generally accepted as being responsible for zeolitization in any case.

Isotopic Data: Comparisons Between Vein Calcites and Ground Water

A second major problem with the Panel report is that the strong conclusions produced by the Panel are either not reasonably supported by the evidence presented or are inconsistent with data and analysis results not cited in the report. This represents a class of problems differing from the previous cases, where the data cited are at least consistent with what is reported in the literature (though insufficient to support the conclusions drawn). However, the data cited are, nevertheless, not sufficient to support the conclusions drawn.

An example of this situation arises from the Panel's statements (*e.g.*, p. 52 & p. 148) that the isotopic ratios for strontium, uranium and thorium for the near-surface vein calcites at Trench 14 and Busted Butte do not match the measured ground water values and therefore that ground water cannot have been responsible for their deposition. Here they compare the isotopic ratios in the calcites to those characteristic of meteoric water at shallow depths below the water table level. At these depths the water resides in volcanic tuffs and does indeed have discordant isotope ratios relative to the surface calcites. However, what the Panel fails to mention is that the isotopic characteristics of the water change with depth, since its isotopic character depends on the host rock properties. Specifically, a strontium isotope ratio measurement from the only well that penetrated the Paleozoic limestones at Yucca Mountain gives a value significantly higher than those from the shallower water in the tuffs, and close to the moderately high values observed in the surface veins in question. Further, while values from yet deeper water, including that in the Precambrian below the limestones, have not yet been obtained at the site, the samples from older rocks at other sites, particularly in Precambrian rocks and Paleozoic shales, show very high strontium isotopic ratios in the range and higher than those observed in the Yucca Mountain and Busted Butte calcite veins, which average around .7125. The relationships of strontium ratios to rock types are illustrated by the data compiled in Table 1, where rhyolites and tuffs have low ratios around .707, limestones have ratios near .709 while Precambrian rocks have high ratios near .717.

Consequently, it is very likely that if water were convected upward from depths of the order of 3 km or deeper at Yucca Mountain it would have high strontium isotopic ratios and when mixed with the shallower water, which has lower strontium ratios, would produce the moderately high strontium isotopic ratio values observed in the near surface vein calcites. A similar argument applies to the other isotopes, although in the case of uranium series isotopes it is more complex (Archambeau and Price, 1991).

It is significant that the Panel offered no discussion of why the strontium ratios at Trench 14 and elsewhere at Yucca Mountain are so high, relative to observed limestone values. Certainly if these vein and associated calcrete deposits are simply due to the evaporation of rainwater carrying calcium and strontium picked up in solution from wind blown dust from (rather distant) limestone outcrops, as is asserted by the Panel, then one would expect to see strontium ratios near the limestone values of .709 rather than the much higher values that average .7125. Surely one could make the argument that there is no apparent support for such a pedogenic origin based on the isotopic data. Indeed there is every reason to doubt this hypothesis in view of the very discordant values observed in the strontium ratios of the surface calcites at Yucca Mountain relative to the values to be expected from the available sources of wind-transported calcite near Yucca Mountain.

Thus, the Panel has ignored important consequences of a "pedogenic origin" for the calcites and have also ignored the possibility of upwelling from greater crustal depths, where it is known that the isotopic ratios of the water would be different from those

Location	Rock	$^{87}Sr/^{86}Sr$	Source	Note
Unaltered Ignimbrites				
Long Valley Caldera	Inyo Domes Rhyolites	0.70630	Goff et al. (1990)	mean of 3 samples
do	do	0.70606	do	mean of 7 samples
do	Mafic and Intermediate	0.70630	do	mean of 3 samples
do	Moat Rhyolites	0.70601	do	mean of 6 samples
do	Early Rhyolites	0.70665	do	mean of 2 samples
do	do	0.70716	do	hydrothermally alt
do	do	0.70742	do	do
do	Bishop Tuff	0.7070	do	mean of 2 samples
do	do	0.70713	do	mean of 6 samples
do	do	0.70645	do	sanidine seperates
do	do	0.70745	do	hydrothermally alt
do	Pre-caldera Volcanic	0.70610	do	mean of 3 samples
representative mean value: 0.70667				
Paleozoic Carbonates				
Spring Mountains	Limestone	0.70913	Peterman (1990)	outcrop
do	do	0.70823	do	do
do	do	0.70837	do	do
Ash Meadows	do	0.70990	do	do
Rock Valley	do	0.70934	do	do
representative mean value: 0.70899				
The Precambrian Basement				
Round Vly. Peak, CA	Schist	0.71656	Goff et al. (1990)	PC-derivative
do	Hornfels	0.72201	do	do
do	Sandstone	0.71126	do	do
Dish Hill, CA	Granodiorite	0.7177	Peterman et al (1970)	xenolith
representative mean value: 0.71688				

Table 1. Strontium isotopic ratios of unaltered ignimbrites, paleozoic carbonates and Precambrian rocks of the western Basin and Range Province. The high strontium isotopic ratio (> 0.71) of Yucca Mountain alteration products and calcite veins is indicative of a deep crustal source.

in the shallow water. Further, it is known, or can be inferred, that the ratios from the deep sources of water would be close to those observed in the vein calcites. Instead, they have implicitly assumed that either convection from such large depths does not happen or simply ignored the evidence of the changing isotopic character of the water with depth and formed the conclusion that ground water in general cannot be responsible for the calcite vein deposits at the site. Since Wood and King (1992) show that the volumes of outflow at the surface (approximately .5 km^3) in the vicinity of the Borah Peak (Idaho) and Hebgen Lake (Montana) earthquakes can be explained as upward water flow ("seismic pumping") along fracture zones from depths at least as great as 5 km, it is clear that the possibility of upwelling of water from the Paleozoic and Precambrian should have been addressed by the Panel. Since they neither take note of the upwelling evidence given by Wood and King nor consider the changing isotopic ratios in the water with depth, their conclusion appears inappropriate and, in fact, might clearly be reversed when all the pertinent data are considered.

Indeed, even the limited data used by the Panel to support their conclusions can be interpreted quite differently. Specifically, the shallow water near the top of the water table should be representative of infiltrating rain water in areas at and near Yucca Mountain where there is no upwelling of convected water from depth. Such "sink areas" are extensive at Yucca Mountain and the water at depth should be representative of infiltrating rain water. If this water does not have isotopic characteristics matching the vein calcites, which it does not since the strontium ratio for such water is .7105, then the logical conclusion is that infiltrating meteoric water (which would have taken any available calcium and strontium from wind-blown dust into solution) does not have isotopic characteristics that are compatible with the observed vein calcites. This observation, as well as those given previously, contradict the Panel's general conclusion that these vein calcites are *"classic examples of arid soil characteristics recognized world-wide."* Further, rather than showing that the isotopic character of the vein minerals versus that of the shallow ground water rules out upwelling ground water as a source of the calcite-opal veins observed, the lack of agreement between the isotopic characteristics of the vein calcites and the shallow water at Yucca Mountain can be interpreted to mean that pedogenic hypothesis advanced is not supported by the pertinent isotopic data.

Water Level Changes at Devils Hole

Another example of a conclusion that is not reasonably supported by the evidence and data cited is the water level data at nearby Devils Hole. The Panel cites evidence (pp. 35, 55) that the ground water level exposed in the open cavern at this location has not fluctuated by more than 10 meters in the last 45 ka. In addition the Panel cites evidence from other studies that imply that the water level has been below the land level, which is 16 meters above the ground water level, for the last several hundred thousand years. However, the Panel fails to mention, or take account of the fact, that the Devils Hole Cavern occurs in an isolated outcrop with its opening elevated above the surrounding area and that within this nearby area there are many active springs. Thus, any rise in the water table would result in greater surface outflow from the active springs and so prevent any rise in the Devils Hole water level above about 10 meters. Consequently, the water level data in the Devils Hole Cavern does not reflect upward rises in the water table, although declines in the level should be correlated with declines in the water table in the area. In this regard, there is some evidence that the water level in the cavern may have been lower in the past than at present. In any case however, the Panel's argument that the water table has probably been stable for a long period of time, based on lack of evidence for any rise in the water level at Devils Hole greater than 10 meters, is not correct.

Age Data, Low Grade Metamorphic Alteration and Temperature Data

The final area of major concern with the Panel's report is the neglect of the very large body of data relating to the ages and character of hydrothermal alterations at the site. The Panel uses very limited data, and principally the zircon age data previously discussed, to argue that the last hydrothermal event occurred about 10-12 Ma ago. However, in addition to the zircon age data, which actually implies much more recent activity, there is an additional body of data that also indicates that there has been on-going hydrothermal activity.

This data involves the age data shown in Figure 2 in combination with paleogeotherm estimates inferred from oxygen isotopes, rock alteration temperatures from zeolitization and illitization processes in rocks at Yucca Mountain, vein formation temperatures from fluid inclusions, and finally, zircon annealing temperatures from the samples at Trench 14 and Busted Butte. All of this inferred temperature data, shown in Figure 4, indicate high temperatures and high geothermal gradients existent at Yucca Mountain in the past. Since the age data shown in Figure 2 are from samples in close proximity to the locations sampled for the temperature estimates, and in the case of the zircons are the same samples used to estimate annealing temperatures, there is little doubt that the high temperatures and gradients are associated with very recent hydrothermal activity at Yucca Mountain. In particular, the K-Ar and uranium-series dates for zeolites and calcium carbonate vein material, respectively, indicate episodic and moderate to high temperature hydrothermal activity that has continued from 13 Ma to essentially the present. In addition, the zircon ages and annealing temperatures also indicate post-Timber Mountain hydrothermal activity involving quite high temperatures for the fluids involved. Finally, all the geothermal gradients inferred from heat flow and oxygen isotope data are sufficient to produce convection and are therefore consistent with a history of hydrothermal activity.

The fact that the Panel did not consider any of the data pertaining to paleo-temperatures and ignored all the age data, except that for the zircon ages which they misrepresented, has resulted in a description of the recent geologic and hydrologic history of the site that is almost certainly incorrect. Indeed, the only uncertainty that might still be entertained is whether the youngest ages, of less than 500 ka, are correlated with the high temperatures indicated in Figure 4. This can be cleared up

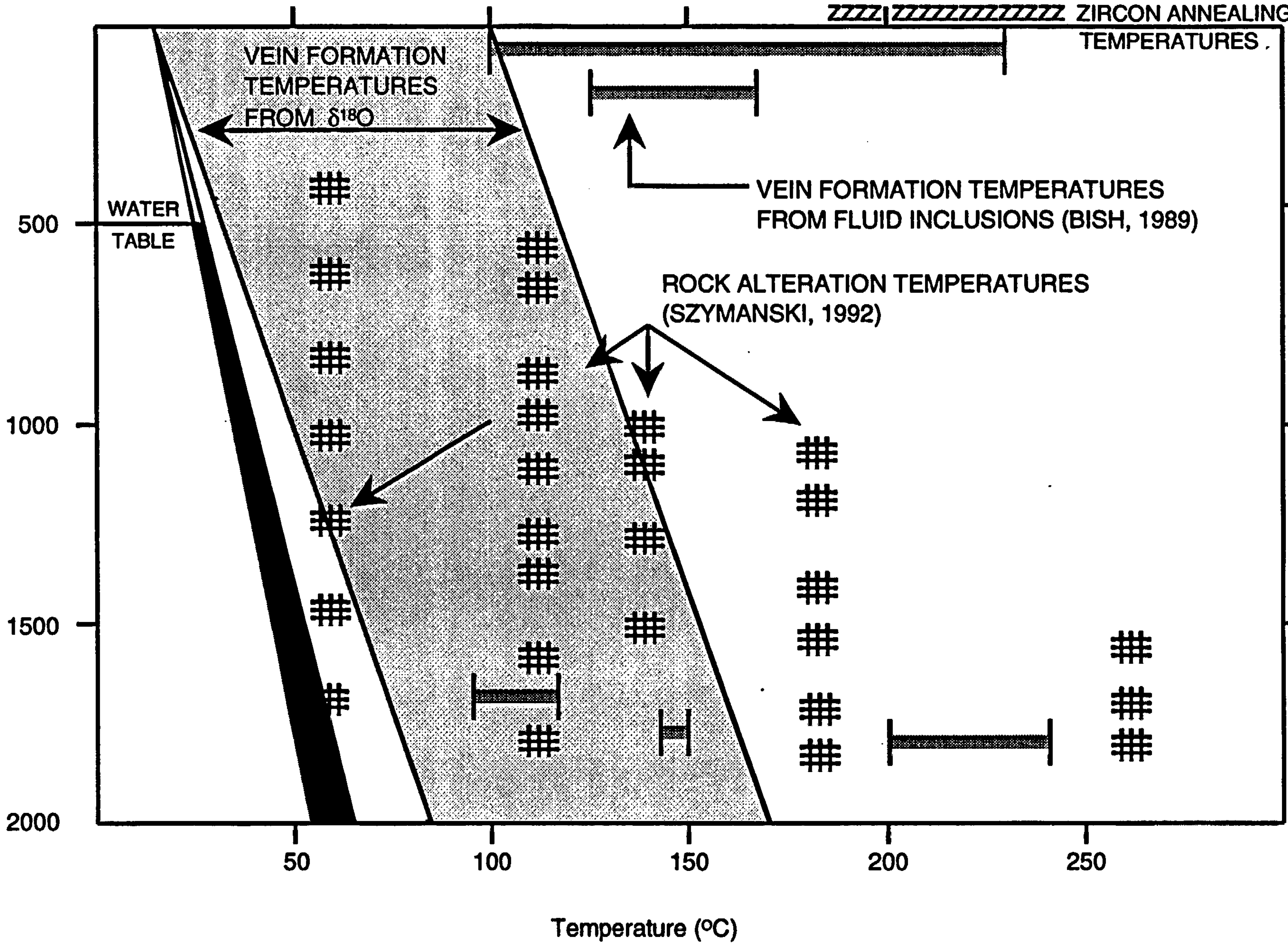


Figure 4. Borehole samples from Yucca Mountain reveal alteration products formed at high temperatures, indicating that the site has been invaded by high temperature fluids.

by additional sampling of course, but in any case there is no reasonable doubt that hydrothermal alteration and deposition occurred well after the time of 10 to 12 million years ago claimed by the Panel. Once this Panel conclusion is recognized as unsupportable in the face of the available quantitative age and paleo-temperature data, it only becomes a question of how frequently and how recently the episodic hydrothermal activity has occurred. The available data shown in Figures 2 and 4 clearly suggest that it has been frequent enough and recent enough to justify the belief that it will most likely continue and that it could occur at any time in the future.

In addition to ignoring age and paleo-temperature data, the Panel did not address the significance of the reported mineral enrichment of interstitial fluids extracted from pores within the tuffs above the water table (Smith, 1991). Relative to local fluids within fractures in the tuffs, the interstitial fluids are strongly enriched not only in alkali-earth elements, but also in transition, base and noble metals and rare earth elements (REE) which at least suggest, if not require, a hydrothermal origin. Table 2 indicates the observed enrichment of several elements found in this trapped water, expressed as a ratio of abundances relative to the element content in nearby well water. Clearly, the presence of noble and base metals is indicative of a hydrothermal fluid. Further, in addition to an overall enrichment of REE, there is an unusual enrichment of heavy REE relative to light REE that is not shared by the host ignimbrites. This enrichment is illustrated in Figure 5 where the normalized REE abundances versus increasing REE atomic weight are shown for the interstitial fluids (a) and local ignimbrites (b). Clearly the abundance trend versus atomic weight is quite different for the ignimbrites compared to the interstitial water. Specifically, the relative enrichment of heavy REE in the interstitial water is conspicuous and since it is also observed elsewhere for hydrothermal solutions that are concentrated in CO_2 (Michard and Albarede, 1986; Michard et al., 1987), it is certainly likely that these fluids are remnants of late hydrothermal fluids.

Table 2

Mineral Enrichment of Vadose-Zone Interstitial Fluids

ELEMENT	ENRICHMENT Ratio *
Magnesium	10
Calcium	8
Nickel	1000
Copper	50
Zinc	45
Rubidium	2
Strontium	30
Yttrium	100
Molybdenum	300
Iodine	20
Tungsten	300
Platinum	**
Gold	**
Titanium	20

*Data are from borehole UZ#4 (interstitial fluids) normalized by J-12 and J-13 well waters (Smith, 1991).

**Well waters contained no measured gold and platinum. Interstitial fluids contained .2 ppb for both metals.

Table 2. Mineral enrichment of vadose-zone interstitial fluids relative to well waters residing in ignimbrite fractures.

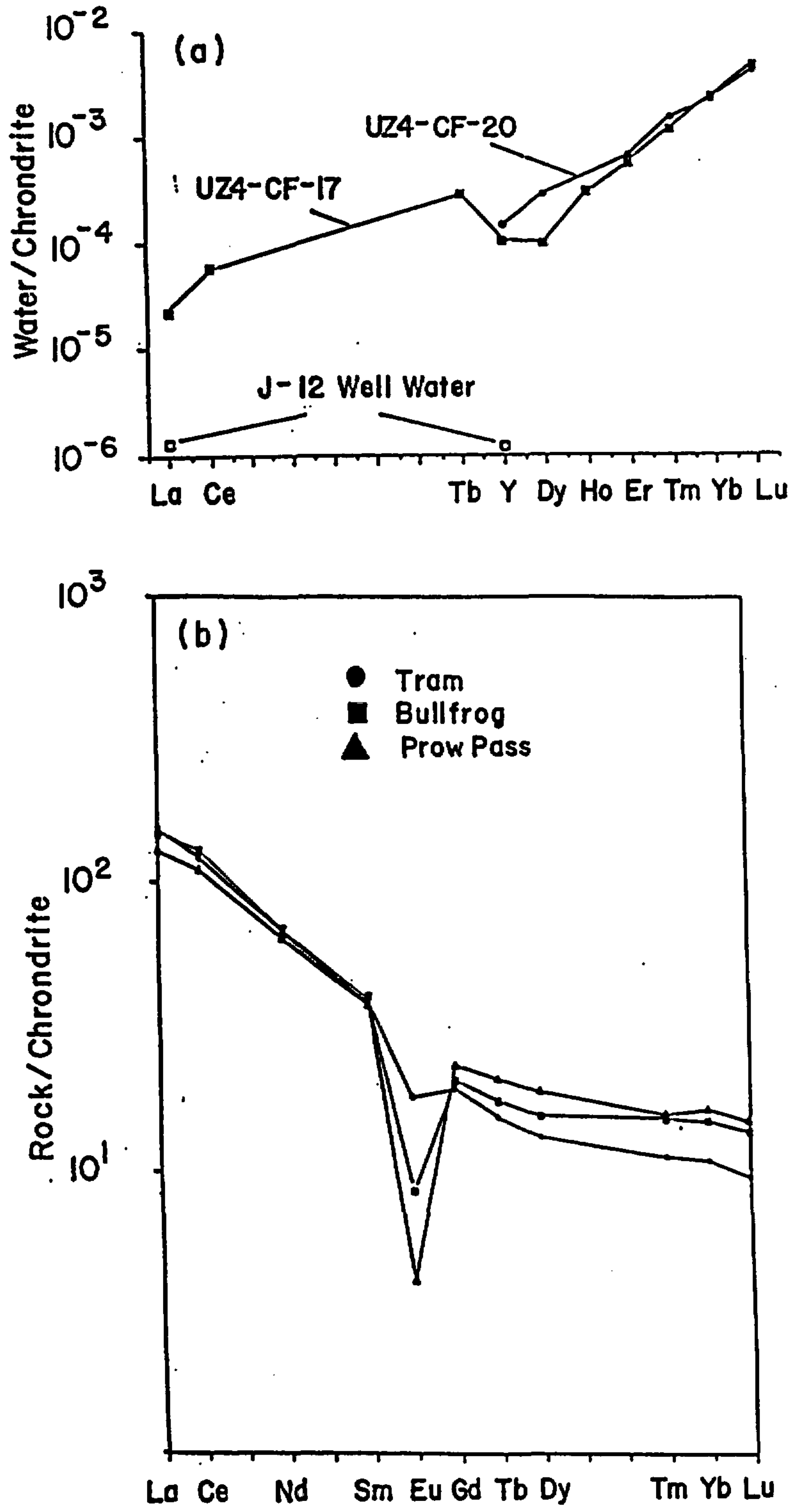


Figure 5. Chondrite-normalized REE abundance patterns. a.) Interstitial fluids and well water residing in ignimbrite fractures: data from Smith (1991). b.) Crater Flat ignimbrites: data from Scott and Castellanos (1984). Heavy REE enrichment for interstitial fluids is due to high CO_2 pressure.

The inference of a high CO_2 content for these remnant hydrothermal fluids is important in that a high gas content would be consistent with an interpretation of gas assisted fragmentation and brecciation during hydrothermal fluid intrusion and account for observed intense brecciations of the country rock associated with late carbonatization at many sites at Yucca Mountain. This inference, while not conclusive in itself, does certainly bring into question the Panel's conclusion that (p. 46):

> *"...there is no need for, or good evidence in support of, upwelling of deep hot waters to account for the brecciation (of near-surface country rocks) or silica - carbonate cementation."*

If the Panel had presented the fluid inclusion data along with the temperature and age data in their report, it seems unlikely that they could have made such a statement or, if made, have made it sound plausible in the face of the evidence.

A related Panel statement involves the fault breccia cement at Trench 14. The Panel conclusion states (p. 44):

> *"...that the fault breccia cement at Trench 14 and Busted Butte is of pedogenic or surficial origin, based on the presence of older detrital zircons, grain size and structure characteristics, and is not of hydrothermal origin."*

As noted earlier, the zircons are not as old as indicated by the Panel and in any case do not provide an age estimate for low to moderate temperature hydrothermal deposition (see the temperature range for zircon fission track annealing indicated in Figure 4), while the small grain size of the calcite cement could be expected to occur as a consequence of rapid release of CO_2 from a hydrothermal fluid near or at the surface (Archambeau and Price, 1991). Further, the "structure characteristics" referred to by the Panel are precisely those interpreted by others, such as Hansen et al. (1987), as being characteristic of hydrothermal brecciation.

Thus, the strong conclusion drawn by the Panel is certainly not warranted by the observations they cite, in that other interpretations are at least as plausible if not preferable. But beyond these alternative interpretations, it is once again evident that the

Panel should have used additional available data to infer the origins of the silica-carbonate breccia cements and veins at Yucca Mountain. In this regard Table 3 provides a clear indication of the unusual enrichment of the breccia cement in base and noble metals relative to the stratigraphically equivalent background values for the tuffs at Trench 14. The results in the third column are the median values for 25 analyses of nine breccia samples while the fourth column indicates the significant enrichment of the most strongly mineralized specimen. The fifth column shows that the degree of enrichment of the interstitial fluids (discussed earlier) is comparable with that of the more strongly mineralized breccia samples. Such enrichment contradicts the hypothesis of a pedogenic origin for the breccia cements and combined with the previously mentioned age and temperature data is strong evidence for a hydrothermal origin of the breccia, which is of post-Timber Mountain age.

Beyond the omissions of the data and results already mentioned, the Panel does not address several other topics and related data of considerable importance. In this regard, in situ stress measurements, such as those by Healy et. al. (1984) and Stock et. al. (1984, 1986), are clearly critical to an assessment of geodynamic stability of the site. These observations were not considered by the Panel. However, contrary to the Panel's assessment that the Yucca Mountain area is not likely to experience a large earthquake in the near future, the results from Healy et al. and Stock et. al. imply the opposite. Indeed, the recent 5.6 magnitude earthquake at Little Skull Mountain, 15 km southeast of Yucca Mountain, also indicates that an unstable stress state, rather than a quasi-stable state, actually prevails.

Consequently, at least in part because of their lack of consideration of a large body of the most quantitative and unequivocal data, the Panel reached many conclusions that are not supported by the complete body of data that exists.

Table 3
Mineral Enrichment of Breccia Cement

ELEMENT	ENRICHMENT			
	TIVA CANYON LITHOPHYSAL TUFF FROM EXILE HILL *	MEDIAN, TRENCH #14 BRECCIA CEMENT *	MAXIMUM, TRENCH #14 BRECCIA CEMENT *	INTERSTITIAL FLUIDS **
Ag	2	2	16	
As	1	3.6	36	
Au	<1	2	5	
Cu	.25	1	4	50
Mo	7	18	650	300
Pb	14	65	610	1-5
Sb	<1	25	100	
Zn	44	90	33	45
Bi	<1	<1	<1	

*Data from Weiss (1990); the maximum values of enrichment are for a single sample (3SW195B) with the highest overall mineral evrichment relative to average concentrations for the Yucca Mountain area (Castor et al., 1989).

**Data from Smith (1991); enrichment relative to well water.

Table 3. Mineral enrichment of breccia cement: results for lithophysal tuff and interstitial fluids are shown for comparison.

General Comments on the Panel Report

In addition to a general disregard of important quantitative data and a rather cavalier approach to elementary logic, the Panel not only distorted some of the data and interpretations reported in the literature (such as the zircon age data) but also misrepresented the concepts described by Szymanski in his 1989 report on hydro-tectonic activity at the Yucca Mountain site. To make matters worse, the Panel also misrepresented the information given to them during a presentation by the minority members of the DOE External Review Panel (Archambeau and Price). Specifically, the NAS/NRC Panel states, on page 129 of their report:

> *"It should be noted that the charge to the panel included an evaluation of the particular concepts described in the report by Szymanski (1989). Those concepts involved seismic pumping as the primary mechanism for driving the deep ground water to the surface in a cyclic progression of crustal stress changes. The panel evaluated the geologic evidence presented for this process and found both the evidence and the seismic pumping model inadequate to support the consequences attributed to them. As the panel was concluding its studies, the "minority" members of the 5 member external review panel selected by DOE and Szymanski to review his report informed the NAS panel that both the interpretation of some of the evidence and the model itself had changed: that Szymanski no longer believed that seismic pumping alone could drive the water up as high as he had stated in his report, and that he now had a new concept involving a thermally driven hydrotectonic cycle. This information was presented at the NAS panel's last meeting. Although there was no time left for the NAS panel to give consideration to a new thesis, nor was there a written document that could be evaluated, the cyclical concept as presented to the NAS panel appeared to have little validity, given that the panel is convinced that the geologic evidence refutes the assertion that ground water has risen repeatedly 100 meters or more in the recent geologic past. Because an essential part of the "cycle" has not yet happened, there is no basis for postulating a cyclical process whatever the proposed mechanisms involved."*

In referring to the minority members' report, the Panel alleges that they were informed that "both the interpretation of some of the evidence and the model itself had changed" and then go on to elaborate that Szymanski now "had a *new* concept involving a thermally driven hydrotectonic cycle." Both of these statements are false.

Specifically, these statements were not made by the minority members. Indeed the material distributed to the NAS Panel by the minority members describes, in very specific terms, the full concept advanced by Szymanski in his 1989 report which includes the concept of a hydrotectonic cycle involving *both* seismic pumping and thermally driven convection of the ground water following a tectonic event, such as an earthquake. This combined response to changes in the hydrologic system was considered to be the cause of upwelling water and associated mineral deposition at Yucca Mountain. Only if the minority members had contradicted their own written summary of Szymanski's 1989 report could they have made the statements attributed to them and that is simply not what occurred, nor realistically is it credible. Furthermore, the minority members presented a summary of their report to the NAS Panel in May of 1991 and submitted their complete report to the DOE in November of 1991. This final report reproduces the material made available to the NAS Panel. Therefore, it is a matter of record that the Panel had ample time to refer to the relevant material, long before they submitted their report in July of 1992, and in addition shows that they misquoted the minority members.

Beyond this distortion of the facts, the Panel misrepresented the content of Szymanski's 1989 report since they assert that he had changed his original concept of seismic pumping as the primary cause of water level changes and introduced a new concept involving thermally driven processes at a time well after writing his report. If the Panel had actually read Szymanski's report they would have found that this latter concept is discussed in considerable detail and was thought to be the principal mechanism for deposition of calcite throughout the mountain.

Therefore, one can only conclude that the Panel did not actually read Szymanski's report, or if they did read it they chose to misrepresent it. In either case this is hardly what would be expected from a NAS panel that is charged with the responsibility of evaluating a report. On this basis alone there would be reasonable grounds to seriously question the Panel's findings as it suggests an inclination to distort and misrepresent the record.

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Appendix II

Critical Review of the National Research Council Report: "Groundwater at Yucca Mountain: How High Can It Rise?"

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CRITICAL REVIEW OF THE NATIONAL RESEARCH COUNCIL REPORT: "GROUNDWATER AT YUCCA MOUNTAIN: HOW HIGH CAN IT RISE?"

REPORT No. 2
CONTRACT No. 92/94.0004

QUARTERLY REPORT Submitted to the
Nuclear Waste Project Office
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August, 1992

Authored by:

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TABLE OF CONTENTS

I. Introduction: Background of the Controversy about Hydrotectonic Conditions at Yucca Mountain

Controversy has developed over the issue of whether or not the 500-m thick vadose zone at Yucca Mountain has been recurrently invaded by hypogene fluids. Geologic formations at the site contain abundant signs which indicate that fluids have altered the original ignimbrites and deposited the controversial calcite-opal-sepiolite veins. Radiometric ages from samples of alteration minerals from above the contemporary water table, are nearly uniformly distributed over the past 13 million years (e.g., WoldeGabriel,1991; Figure 2). In addition, the reported ages from samples of the calcite-opal-sepiolite veins range from about 25,000 to over 400,000 years B.P. (e.g., Szabo et al., 1981; Szabo and O'Malley, 1985; Szabo and Kyser, 1985). Thus, there is abundant evidence that geologic formations comprising the Yucca Mountain vadose zone have been altered by subsurface fluids during the relatively recent geologic past. The disputable scientific issue involves the origin of these fluids. Specifically, the appropriate question is: **Do the observed alteration and mineralization represent supergene/pedogenic processes or, conversely, are they representative of epigenetic/hypogene processes?**

Hazardous conditions at the site would arise from processes that could spread radionuclides into the biosphere, and subsurface fluids represent the most likely means for transport. Upwelling fluids of the type interpreted from the geologic record (Smith, 1991; Szymanski, 1992) could flush through the repository, corrode waste packages and transport dissolved radionuclides to the biosphere.

Spring deposits were identified at and adjacent to Yucca Mountain in the early stages of site investigations (e.g., Hoover, et al., 1981; Knauss, 1981; Szabo, et al., 1981), but serious technical concerns regarding repository performance were first documented by former DOE scientist, J.S. Szymanski. After repeated attempts from 1984 to 1987 to refocus site investigations, and to resolve critical questions about upwelling fluids, he reported (1987, 1989) interpretations that the local hydrologic system is controlled by tectonic factors and, as a result, recurrently undergoes major changes.

In response to Szymanski's 1989 report, the DOE initiated two external reviews: one to report directly to the DOE and one to report to the National Academy of Science's National Research Council (NAS/NRC). The DOE Panel, composed of five experts, reported two divergent views: three of the experts (Powers, et al, 1991) judged Szymanski's interpretations to be inappropriate; and two of the experts (Archambeau and Price, 1991) judged Szymanski's interpretations and model to be appropriate. In view of the remaining and unresolved controversy, however, investigations remained defocussed and ill-suited for rapid recognition of potential hazardous conditions (e.g., GAO, 1992; SAIC, 1992).

The NAS/NRC Panel has recently released their findings in the report Groundwater at Yucca Mountain: How High Can It Rise? which appears to offer good news for those advocating suitability of the site to accommodate a high level nuclear waste repository. In particular, the Panel reported:

> *The panel's overall conclusion was that none of the evidence cited as proof of groundwater upwelling in and around Yucca Mountain could be reasonably attributed to that process.* (p. 3)

Unfortunately the overall conclusion, as well as other interpretations throughout the report, are not supported by currently available facts. In this regard, the Panel has ignored multiple lines of evidence and does not justify the all-inclusive dismissal of hydrotectonic hazards at Yucca Mountain. More importantly, analytical data (e.g., radiometric ages, geothermometry and mineral and isotope abundances) not considered by the Panel provide evidence for recurrent invasions of the Yucca Mountain vadose zone by hydrothermal fluids.

II. Summary of the Technical Disagreement with the NAS/NRC Report

The topic addressed by the Panel arose from interpretations that the hydraulic conductivity structure could be controlled in part by tectonic stress, and that a hydrothermal circulation system is present at Yucca Mountain (Szymanski, 1989). These interpretations, in turn, point to the likelihood of erratic hydrologic disturbances which could explain the presence of youthful calcite-opal-sepiolite veins that are common throughout Yucca Mountain. Concerns about hydrologic stability have thereby exacerbated the controversy surrounding the genesis of the calcite-opal-sepiolite mineral assemblage occurring in the form of breccia cements, veins, calcretes and silcretes. In brief, the question is: **Were these minerals precipitated from supergene fluids (rainwater) or from hypogene fluids (hydrothermal solutions)?**

The NAS/NRC Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems finds that **there is no unequivocal field evidence for hypogene fluids having risen to the surface over the past 100 thousand years.** In support of their interpretation, the Panel draws a series of deductions which we regard to be at odds with mineralogic, geochemical, isotopic and geochronological data. The foundation of the conclusions reached by the Panel is the belief that the water table has not risen more than 60 meters above its present position over the past 11.6 million years, based on the depth distributions of glass and zeolites. This belief, if appropriate, would eliminate the possibility of any hydrothermal circulation within the vadose zone since the end of the hydrothermal stages of activity of the Timber Mountain Caldera, more than 10 million years ago. Dismissing the possibility of hydrothermal circulations, the Panel argues that the only fluid, other than infiltrating rainwater, that could have by some means (climate change, volcanic intrusion or earthquake) invaded the vadose zone and precipitated the controversial minerals would be of the same chemistry as the contemporary fluids residing in the ignimbrites. Because the latter fluids are known to be isotopically discordant with the parent fluids of the calcitic-opal-sepiolite veins, the Panel argues that the resulting minerals could not have precipitated from *"analyzed"* ground water, and therefore concludes that the minerals must have precipitated from infiltrating rainwater. The possibility that the minerals precipitated from the kind of fluids residing in Paleozoic carbonates and discharging at nearby thermal springs was not considered by the Panel. However, in this review we illustrate how the mineralogic, geochemical, isotopic and geochronologic data are much more readily explained in terms of hypogene paragenesis rather than in terms of supergene paragenesis.

The belief that zeolites found above the water table were produced in response to supergene/diagenetic processes is an essential part of the Panel's case. Yet the chemical composition of the zeolites, relative to the parent glasses, is inexplicable within the *supergene/diagenetic context. A more straightforward and less problematic* interpretation of the genesis of the zeolites is the traditional view that they are products of propylitic alteration. This interpretation is consistent with the fact that the Yucca Mountain ignimbrites, both above and below the water table, contain literally billions of tons of metasomatic elements (calcium, magnesium, and strontium) that were not present at the time the ignimbrites were metamorphosed during the hydrothermal stages of activity of the Timber Mountain Caldera. Potassium/argon ages of the zeolites obtained to date are as young as 2 million years B. P., and the high ratios of strontium isotopes (^{87}Sr / ^{86}Sr) are consistent with a deep source, possibly in the Precambrian basement, not rainwater. Samples of fluids enriched in alkali-earth elements have been extracted from pore space in shallow (<100 meters) ignimbrites, and these exhibit substantial enrichment in base and noble metals and rare earth elements (REE), indicative of a hydrothermal origin. Mosaic breccia cements are similarly mineralized in a manner that is not explicable in the context of the supergene/pedogenic hypothesis. On these bases we bring into question many of the conclusions of the NAS/NRC Panel Report.

The only analytical data used in the Panel report to substantiate the claim that the last and final hydrothermal event occurred some 13 to 10 million years B. P. are fission track ages of zircons embedded in the mosaic breccia cements. The Panel characterized these data by stating that:

> *...within the analytical uncertainty, most of the ages are about 10-12 Ma, or about the same as those of the dominant volcanic rocks in the region.* (p. 44)

However, the authors of the work stated that:

> *...there are zircons from multiple sources present. In both samples there are crystals significantly younger and significantly older than the age of the tuff.* (Levy and Naeser, 1992)

Indeed, examination of the fission track data shows a multiply peaked distribution of ages in each sample and that the youngest age is 4.8 million years B. P. In addition, the ninety percent confidence interval for this age is from 2.3 to 7.3 million years B. P. Finally, the majority of the twenty-four most probable ages are actually significantly younger than the age of the host ignimbrites, which is given by K/Ar dating as 13 million years B. P. Therefore, contrary to the Panel's description of the fission track data, most of the ages are much younger than the host ignimbrites and provide evidence that hydrothermal activity has occurred at much more recent times than considered by the Panel.

We refrain from discussion of field exposures in this review, because written descriptions do not lend themselves readily to the task. Instead, we focus on analytical results that are more amenable to a written discussion. In particular, we focus on a large quantity of geochemical and mineralogic data that were not considered by the Panel. Their section on "Geochemical and Mineralogic Considerations" is less than a page in length (p. 47), and yet leads the Panel to the crucial conclusion that the water table has been essentially static for the past 11.6 million years. This conclusion was, in turn, used to justify the dismissal of hydrothermal processes as a potential means for raising the water table. The lack of consideration of geochemical and mineralogic evidence by the Panel was a flaw in the execution of their assignment, which is stated as follows:

> *The panel regarded their task as not only evaluating the staff scientist's thesis, but also assessing the likelihood that the ground water level could rise to the height of the repository by any plausible geological process, or that such a rise had occurred in the past.* (p. 2)

By dismissing hydrothermal processes as a factor, the Panel obtains *"no"* as the answer to the question: *"Has it happened?"* For reasons outlined briefly below and discussed subsequently, the correct answer might well be "yes," in which case the answer to the question *"Can it happen?"* may also be "yes" instead of "no" as the Panel concluded.

A very large set of geochemical and mineralogic data was not considered by the Panel . Specimens of vadose-zone interstitial fluids, fluids residing in ignimbrites and carbonates, glasses and alteration products, and epigenetic veins have been analyzed by project scientists. The results provide a spatial and temporal image of the post-Miocene alteration and mineralization experienced by the Yucca Mountain ignimbrites (Szymanski, 1992).

The earliest hydrothermal episode produced weak alkali-earth metasomatism (Ca + Mg ~10-25 mole % of the exchangeable cations, cf. ~3% for glass) which is pervasive in the lower part of the stratigraphic section. Associated altemation minerals include clinoptilolites with K/Ar ages ranging from 9.5 to 10.5 million years B. P., contemporaneous with the late stages of activity of the Timber Mountain Caldera. Both the strontium isotopic ratio (^{87}Sr / ^{86}Sr ~ .709) of whole-rock samples and spatially correlative calcites, and the carbon isotopic ratio ($\delta^{13}C$ from -2 to 4.5 per mil wrt PDB) of the calcites are indicative of parent fluids having resided in the underlying Paleozoic carbonates.

Hydrothermal activity subsequent to the Timber Mountain hydrothermal episode differed spatially, chemically, isotopically, and in duration. The more recent metasomatism observed higher in the stratigraphic section is less pervasive, and appears to be confined to aureoles typically associated with faults and fractures. The whole-rock Ca + Mg substitution is greater than that associated with the Timber Mountain hydrothermal episode, and may be as high as 50% of the exchangable cations. Clinoptilolites have (mixed) K/Ar ages ranging from 2 to 8.5 million years B. P. The strontium isotopic ratio (~ .712) of whole-rock samples and spatially correlative calcites, and the carbon isotopic ratio (δ^{13} C from -10 to -3) of the calcites are both suggestive of parent fluids from deep-seated sources, specifically from the Precambrian basement and mantle igneous CO_2, respectively. In contrast to the prolonged (1 million year) Timber Mountain metamorphism, hydrothermal alterations over the past 8.5 million years have been intermittent, have spanned a much greater depth range, and have been primarily associated with faults and fractures.

Remnants of late hydrothermal fluids have been separated from cores in two shallow boreholes (Smith, 1992). Relative to the local ignimbrite-based fluids, these interstitial fluids are strongly enriched not only in alkali-earth elements, but also in transition, base and noble metals and rare earth elements (REE), suggestive of a hydrothermal origin (Szymanski, 1992). In addition to the overall enrichment of REE, there is an unusual enrichment of heavy REE relative to light REE that is not shared by the host ignimbrites. It is significant that relative enrichment of heavy REE is observed elsewhere for hydrothemal solutions that are concentrated and rich in CO_2, where carbonate anion complexing is the mechanism believed responsible (Michard and

Albarede, 1986; Michard et al., 1987).

The mineral enrichment in the trace elements of the interstitial fluids is comparable with that of the mosaic breccia cements. Similar solutions have evidently caused fragmentation of bedrock associated with the late carbonatization, in addition to late alkali-earth metasomatism and calcic zeolitization.

High temperatures of formation of shallow subsurface veins are documented by fluid inclusion temperatures well in excess of 100°C, and by elevated paleogeotherms determined from oxygen isotopic ratios. Within 30 meters of the fluid inclusion samples there are calcites with uranium series ages younger than 100 thousand years. If, as is expected, the dated calcites are representative of the ages of the nearby samples of calcite used in obtaining the inclusion temperatures, then the high temperatures obtained provide direct evidence for recent hydrothermal activity at shallow depths in Yucca Mountain and clearly contradicts the reported conclusions regarding recency of hydrothermal activity.

Consequently, these observations taken together strongly suggest that, over the last several hundred thousand years, episodes of calcite emplacement contemporaneous with local mafic volcanism have occurred at intervals that are not long in comparison with the isolation time required for a HLRW repository. Yet, evaluations by the Panel fail to even consider the great wealth of geochemical data that reveal distinct patterns of hydrothermal evolution extending throughout the Plio-Quarternary time span.

III. Hydrothermal Alteration of the Vadose Zone Ignimbrites

One of the main conclusions reached by the Panel was that the water table at Yucca Mountain had been essentially static in the post-Timber Mountain time. Citing the results of Levy (1991), the Panel stated:

> *The boundary between the altered and vitric tuffs indicated that the water reached its highest levels and receded downward from 12.8-11.6 Ma, and that since that time the water level at central Yucca Mountain has probably not risen more than 60 m above its present position.* (p. 48)

We could not to find support for this conclusion from the relevant data (Figure 1). The data show minimum and maximum elevations of the occurrence of glass and zeolites, relative to the water table, as reported by Bish and Chipera (1989), Carlos et al. (1990), Sheppard et al. (1988), Carr (1982), and Carr and Parrish (1985) at the drill sites shown in Figure 2. Levy noted:

> *...the downward transition from vitric to zeolitized tuffs is a gross feature common to all Yucca Mountain drill holes.* (Levy, 1991)

However, the inference that the water table has not risen more than about 60 m in the past 12.8-11.6 million years B. P. is not self-evident. In some drill holes, glass is present hundreds of meters below the water table. Further, zeolites (clinoptilolite, stellerite, mordenite, analcime) are present hundreds of meters above the water table in some drill holes. In the vadose zone, both vitrophyres of the Topopah Spring Member exhibit fracture-based devitrification. The distributions of zeolites and glass do not bear simple relationships with the water table, i.e. glass above and zeolites below the water table.

This casts doubt on the viewpoint that the vadose zone zeolites were formed in response to supergene/diagenetic processes. A very significant fact that is not considered by the Panel is that the zeolites have radiometric ages considerably younger than the host ignimbrites (Figure 3).

Relationships between the occurrences of zeolites and glass are clarified (Szymanski, 1992) by plotting K/Ar ages of clinoptilolites (WoldeGabriel, 1991) against depth below the deepest occurrence of glass (Figure 4). The results suggest that an upward progression of zeolitization occurred as glass became less abundant at depth. This feature is consistent with a progressive hydrothermal zeolitization.

Significant depth trends are also apparent in the chemical composition (Figure 5) of the alteration products (zeolites and whole-rock ignimbrites) and the strontium content and isotopic ratios (Figure 6) of the whole-rock ignimbrites. The deepest clinoptilolites have ages of about 10 million years B. P. and are essentially alkali (K + Na) rather than alkali-earth elements (Ca + Mg) in chemical composition. Younger, shallower clinoptilolites have alkali-earths ranging above 50% of the exchangeable cations. The strontium content of the whole-rock samples (30 to 700 ppm) is also generally much higher than for glass (19 ± 6 ppm: Peterman et al., 1991). These vast quantities of alkali-earth elements could not possibly be present if the zeolitization were of a diagenetic/supergene origin, as claimed by Levy (1991) and WoldeGabriel (1991). In regard to repository performance, it is particularly disturbing that the most strongly metasomatic zeolites containing high concentrations of total strontium and strontium-87 are also the shallowest and youngest.

A satisfactory alternative to the hypothesis of the diagenetic (supergene) paragenesis is the traditional view that zeolites are alteration products formed in response to hydrothermal metamorphism (Sheppard et al., 1988; Steiner, 1955; Coombs, 1970; Meyer and Hemley, 1961). As stated by Weiss:

> *The presence of extensive and pervasive propylitic alteration, ± fluorite, in otherwise fresh tuffs of Miocene age clearly implies the existence of a large fossil hydrothermal system in Yucca Mountain, and supports our earlier contention that zeolitic alteration may not be entirely of a diagenetic or deuteric origin as is commonly believed.* (Weiss, 1990)

A hydrothermal origin has been inferred for illite/smectite alteration at depths between approximately 1070 and 1525 meters in drill holes USW G-1 and USW G-2 (Bish and Aronson, 1992). K/Ar dates for these minerals average 10.4 million years B. P., suggesting that they were formed in response to a hydrothermal episode associated with the Timber Mountain Caldera, some 10 km north of the proposed repository. Clinoptilolites below a depth of about 1000 meters are of about the same age as the clay minerals, and were also presumably formed by fluids associated with the Timber Mountain hydrothermal episode. However, the younger clinoptilolites must have been formed by subsequent hydrothermal solutions much richer in alkali-earth elements. Relative to the Timber Mountain hydrothermal fluids, these solutions were also abnormally enriched in strontium-87 and depleted in carbon-13. Taken together, these isotopic characteristics were likely acquired in a deep substratum, probably the Precambrian basement. The following has been observed:

Importantly, at Yucca Mountain, the parent fluids for both the strontium-87 enriched calcites and the carbon-13 depleted calcites were also involved in (1) whole-rock strontium metasomatism, and (2) calcic zeolitization. It follows then that by proposing a supergene-pedogenic origin for the carbon-13 depleted and strontium-87 enriched calcites, the USGS investigators are in fact proposing that the supergene-pedogenic processes, in addition to being capable of (1) producing veins some 300 meters below the water table, and (2) causing a factor of 1.5 increase in the geothermal gradient, are also fully capable of causing the observed space-differential calcium, magnesium, and strontium metasomatism in large volumes of initially homogeneous ignimbrites. Such a proposition, however, is in accord neither with established geological principles nor with common sense. (Szymanski, 1992)

In summary, contrary to the opinions adopted by the Panel, the maximum and minimum elevations respectively of altered and vitric tuffs can not be taken as meaningful indicators of the range of water table changes over the past 11.6 million years. Further, the age trends of the zeolites, and their chemistry and isotopic characteristics, support the view that these are hydrothermal alteration products, rather than diagenetic or deuteric, as suggested by the Panel.

IV. Hydrothermal Processes

The lack of consideration of hydrothermal processes is, perhaps, the major scientific deficiency of the Panel's report, which stated:

> *Inasmuch as the only deposits associated with hydrothermal processes in close proximity to Yucca Mountain were formed more than 10 Ma during formation of the tuffs, and the only Quaternary evidence for warm springs observed by the panel was more than 55 km from Yucca Mountain, at Travertine Point (from the earliest Quaternary (2 Ma - 700 ka), the panel discounted hydrothermal systems as a potential mechanism for raising the water table level in the Yucca Mountain area.* (p. 130)

The first point seems to rely on the Panel's inference regarding the stability of the water table, discussed above, and on the inferences concerning the paragenesis of surficial calcites, which are discussed subsequently. The second point, concerning the proximity of hydrothermal springs visited by the Panel, is factually incorrect. Notably, the majority of the Panel visited active hot springs in Oasis Valley, a few miles north of Beaty, that are located about 25 km from Yucca Mountain.

Thermal springs are not hard to find in the Yucca Mountain region. For example, Hill (1992) cited several examples, among them the following:

> *There is evidence of hydrothermal activity throughout the area, both past and present. This can be seen at Devil's Hole, the discharge point for much of the watershed of the Yucca Mountain site, where the temperature of the water measures 34°C (Hoffman, 1988).*
>
> *Oxygen isotope analyses of calcite mammillary crusts in Devil's Hole range between about 14 to 17 (PDB), indicating that such low-temperature hydrothermal activity has been going on at least throughout the last 250,000 years or so* (Winograd et al., 1988).

Hydrothermal activity is also indicated by the occurrence of the sepiolite mine near Yucca Mountain. Ehlman et al. (1962) described the occurrence of sepiolite in Utah and Nevada and believed these were formed by low temperature hydrothermal solutions associated with quartz, opal, and sulfide mineralization and with nearby acidic intrusive rocks and magnesium-rich carbonate rocks. (Hill, 1992)

Similarly, referring to the Wahmonie gypsum-sepiolite mound (situated about 15 km northeast of Yucca Mountain), the United States Geological Survey advised the DOE as follows:

Concurrent with drilling at Calico Hills, geophysical studies conducted at Wahmonie indicated that the granite, which occurs at the surface, would be only marginally large enough for a repository at the depth needed. These studies, plus surface mapping, also suggest that the granite within reasonable depth was probably altered by hydrothermal solution. In addition to the altered granite, local surface deposits from recent warm springs indicate upward seepage of groundwater possibly from great depth. (DOE, 1985)

In sharp contrast to the Panel viewpoints, we believe that even a casual researcher of the Yucca Mountain area can be reasonably certain about one important point. This point is: the post-Timber Mountain hydrothermal activity cannot be discounted without ignoring a large quantity of mineralogic, geochemical, isotopic, geochronological and geophysical data.

In this regard, in the following sections we will focus on the large body of quantitative data and results related to the question of post-Timber Mountain hydrothermal activity. These data and results pertain to: a) whole rock alterations, b) epigenetic mineralization of the vadose zone rocks, c) paleogeothermal gradients, d) homogenization temperatures of fluid inclusions, e) spatial distribution of the metamorphic facies, and f) interstitial fluid from the vadose zone.

Whole-Rock Alterations

The view that alteration of the Yucca Mountain ignimbrites is essentially deuteric and/or supergene/diagenetic is at odds with the fact that vast quantities (literally billions of tons) of metasomatic elements now reside in these rocks. Livingston has compiled data from Broxton et al. (1986) on the extent of whole-rock alteration, relative to glass, of ignimbrites from both above and below the water table (Figure 7), and concluded:

1. *A substantial portion of the altered rocks are 4 to 10 percent lower in silica than is glass.*
2. *Most altered rocks are 0.1 to 0.5 percent richer in titania than is glass.*
3. *Most altered rocks are richer in alumina by at least 0.5 percent than is glass, and a substantial portion is richer by 2 to 5 percent.*
4. *Most altered rocks are richer by 0.5 to 4.5 percent in iron oxide than is glass.*
5. *Most altered rocks are richer by 0.25 to 1.75 percent in magnesia than is glass.*
6. *Almost all altered rocks are 0.5 to 5 percent richer in lime than is glass.*
7. *Most altered rocks are 0.5 to 2.5 percent lower in soda than is glass, although a few are enriched by 2.5 percent.*
8. *Most altered rocks are lower in potash by 0.5 to 3.0 percent than is glass, although a few are richer by 2.5 percent.* (Livingston, 1992)

A conclusion that can be drawn from this data is that: Because metasomatic alteration is present well above the water table, and because all age-dated zeolites from the vadose zone postdate hydrothermal stages of activity of the Timber Mountain Caldera, it is inappropriate for the Panel to have discounted hydrothermal systems as a potential mechanism for raising the water table level

in the Yucca Mountain area.

Epigenetic Mineralization of the Vadose Zone Rocks

The results of electron microscope examinations of specimens of the Topopah Spring Member of the Paintbrush Tuff were reported by Carlos et al. (1990). Fracture-coating minerals were also analysed by X-ray diffraction. From these studies both deuteric mineralization and subsequent epigenetic mineralization are apparent. The deuteric mineralization, developed in lithophysal cavities and along cooling cracks, is represented by tridymite (sometimes transformed to cristobalite or quartz), hematite, and fine-grained manganese oxides and zeolites. Subsequent epigenetic mineralization is represented by drusy quartz, fluorite, smectite, coarse-grained zeolites and calcite. In borehole USW GU-3, drusy quartz occurs over tridymite and its pseudomorphs, and fluorite is interpreted to have been formed after tridymite and quartz. In several boreholes, coarse-grained zeolites were formed after manganese oxides and fine-grained zeolites. Many of the epigenetic zeolites are euhedral, neither crushed nor slickensided, and in a few instances are developed over slickensided fractures. Calcite appears to be the latest mineral formed, and in borehole USW G-2 calcite was observed to occur as two distinct generations separated by the deposition of heulandite. The latter observation represents strong evidence for recurrent invasion of the vadose zone by hydrothermal fluids, a possibility that was discounted by the Panel.

The epigenetic character of some of the vadose-zone mineral species was also recognized by Weiss, who reported hand-lens and binocular microscope examinations of some 1850 meters of rock core. Among his observations were:

> *Fluorite is present as veins and fracture fillings and as irregular drusy coatings lining lithophysal and (or) relict pumice cavities and is not confined to great depths, or the northernmost part of Yucca Mountain, but was observed in fractures at depths as shallow as 318m and 362m in drill hole USW GU-3.* (Weiss, 1990)

> *The presence of extensive and pervasive propylitic alteration, +/- fluorite, in otherwise fresh tuffs of Miocene age clearly implies the existence of a large fossil hydrothermal system in Yucca Mountain, and supports our earlier contention that zeolitic alteration may not be entirely of diagenetic or deuteric origin as is commonly believed.* (Weiss, 1990)

These observations are again at odds with the Panel's dismissal of *"...hydrothermal systems as a potential mechanism for raising the water table level in the Yucca Mountain area."* Moreover, when considered in conjunction with the ages of zeolites, these data indicate post-Timber Mountain hydrothermal activity.

Paleogeothermal Gradients

Paleogeothermal gradients have been reconstructed by Whelan and Stuckless (1992) from the vertical distribution of oxygen isotopic ratios from samples of calcites and opals extracted in drill cores (Figure 8). The paleogeotherms, from 34 to 140° C/km, are much higher than the contemporary geothermal gradients, from 18 to 24° C/km, measured in the corresponding drill holes (Sass et al., 1987). The high paleogeotherms by themselves indicate that the subsurface calcites and opals are of a hydrothermal origin, a possibility that was not considered by the Panel.

The existence of contemporary geothermal gradients that are low by Great Basin standards is explained as follows:

> *Heat flow is likely to vary between about 30 and 70 mWm^{-2} (.75 to 1.7 HFU) within the very small area. This in turn suggests very shallow (in the range of 2.5 to 5 km) heat sources and sinks as the cause of the variation. The most likely sources and sinks would be hydrologic... From the present series of measurements; it seems clear that various fluids are moving about in the unsaturated zone, that water is moving in a very complicated manner within the saturated zone to depths on the order of 1 km, and that in the Paleozoic rocks beneath the tuffs there is also a complex hydrothermal circulation system.* (Sass et al., 1983)

The area mentioned in the first sentence of this quote is shown by the dashed rectangle in Figure 2, and the reference to hydrothermal circulation in the Paleozoic carbonates pertains to well UE 25 p#1.

In an earlier study, it was noted that:

> *The nearly threefold variation in conductive heat flow over a lateral distance of only 25 km suggests the presence of a more deeply seated hydrothermal convective system with a net upward flow beneath Calico Hills and a net downward flow beneath Yucca Mountain.* (Sass et al., 1980)

As far as conductive heat flow (unperturbed by convective circulation) is concerned Sass and Lachenbruch, 1982, conclude:

> *The regional heat flow from beneath the zone of hydrologic disturbance may be the same as that characteristic of the Great Basin in general (80mW/m^2 or 2 HFU), or it could be as high as 100 mW/m^2, or 2.5 HFU.* (Sass and Lachenbruch, 1982)

It is evident that, in the Yucca Mountain area, there are strong indications of geothermal circulations of crustal fluids. The evidence for gangue mineralization and the young ages of zeolites are both consistent with recurring post-Timber Mountain flows of this type. Therefore the Panel's conclusion that there is no evidence for post-Timber Mountain hydrothermal activity and that renewed hydrothermal circulations are not likely is not well founded. On the contrary, there is considerable evidence supporting the opposite conclusion.

Homogenization Temperatures of Fluid Inclusions

Bish (1989) has reported homogenization temperatures of fluid inclusions in calcites from drill cores. The shallowest samples, from drill hole USW GU-3, had homogenization temperatures ranging from 101° to 227° C, at a depth of 31 meters, and from 125° to 170° C, at a depth of 131 meters. These temperatures are shown as a function of depth in Figure 9, along with other geothermal data. The ages of the calcites are not known, but U-series ages have been determined by Szabo and Kyser (1985) for nearby calcites from the same drill hole. The ages, in thousands of years B.P., are 227 ± 20 (19 meters), 26 ± 2 (40 meters), >400 (97 meters) and 30 ±4 (100 meters).

The calcites with high homogenization temperatures were located within 30 meters of samples with ages considerably younger than 100 thousand years B.P. If the ages of the calcite samples (used to obtain fluid inclusion homogenization temperatures) span the same range as those of nearby calcites for which ages are available, and there is little or no reason to expect that they wouldn't, then the temperatures obtained are a direct indication of very recent hydrothermal activity in the Yucca Mountain vadose zone. This directly contradicts the Panel's conclusion that there is no evidence for post-Timber Mountain hydrothermal activity and that renewed hydrothermal circulation is very unlikely.

Curiously, the Panel makes no mention of the fluid inclusion data, but recommends the acquisition of such data:

> *In order to avoid circular reasoning, independent estimates of the temperatures of paleo-ground waters should be made. Calcite veins intersected in drill cores should be searched for fluid inclusions. Microthermometry of the fluid inclusions will provide independent estimates of calcite precipitation temperatures.* (p. 168)

The subsequent quotation, however, reveals a new complexion of the Panel's recommendation:

> *Further efforts should refocus away from the descending/ascending water controversy.* (p. 134)

In summary, the currently available fluid inclusion data may be regarded as strong evidence for the post-Timber Mountain hydrothermal activity at Yucca Mountain. It seems to us that these data cannot be discounted and ignored and that, at the least, further inquiry is necessary.

Spatial Distribution of the Metamorphic Facies

Szymanski (1992) has constructed paleogeotherms from the observed zonation of zeolitization and illitization. The gradational sequences used for this purpose are the clinoptilolite-analcime-albite facies and the allevardite-kalkberg clay-illite facies, respectively.

The alteration temperatures are shown in Figure 9, along with fluid inclusion data (Bish, 1989) and present-day temperatures in the drill holes from which calcite samples were analysed for their $\delta^{18}O$ content to determine paleogeotherms (Whelan and Stuckless, 1992). The position of the minimum paleogeotherm (34° C/km) on the temperature axis is indeterminate, and arbitrary surface temperatures (ambient temperature and 100°C) are used to illustrate the paleogeothermal gradient.

All of this evidence points to invasion of the vadose zone by hydrothermal fluids. Szymanski (1992) has demonstrated that some of this activity is: a) intermittently recurring and b) significantly younger than the hydrothermal stages of activity of the Timber Mountain Caldera. This interpretation directly contradicts the Panel's conclusions regarding past and possible future hydrothermal activity at Yucca Mountain.

Interstitial Fluids from the Vadose Zone

Samples of fluids residing in pore space have been separated from ignimbrite cores from two shallow (~100 m) dry-drilled boreholes. Chemical analyses of these fluids, and of fluids from below the water table, have been reported by Smith (1991). Mineral enrichment of the interstitial fluids (relative to fluids from below the water table) is illustrated in Figure 10. The alkali-earth affinity of the interstitial fluids is indicated by a tenfold enrichment of calcium and magnesium and a thirty-fold enrichment of strontium. The enrichment in trace elements, including rare earth elements (REE) and base and noble metals, is consistent with a hydrothermal source. This fluid cannot reasonably be regarded as either deuteric or diagenetic, and its alkali earth character shows a kinship with the late zeolitization and carbonatization (Szymanski, 1992).

In addition to the overall enrichment in REE, there is an unusual enrichment of heavy REE relative to light REE (Figure 11). In contrast, the host ignimbrites have the usual enrichment of light REE. Enrichment of heavy REE is attributable to carbonate anion complexing and is observed elsewhere (France, Bulgaria: Michard et al., 1987; Michard and Albarede, 1986) for hydrothermal solutions that are rich in carbon dioxide.

The chemical data for interstitial fluids are of assistance in interpreting the paragenesis of surficial calcites and breccia cements, which are discussed later.

The chemical data for shallow interstitial fluids at Yucca Mountain indicate a hydrothermal origin, probably involving fluids high in CO_2. Because these interstitial fluids are also high in the alkali-earth elements, in distinction to the alkali ignimbrites, they can be reasonably associated with the alkali-earth zeolites which carry radiometric ages that are as young as 2 million years.

In summary, the chemical data from samples of the interstitial fluids, in combination with the radiometric ages, indicate post-Timber Mountain hydrothermal activity occurring in the Yucca Mountain vadose zone. These data provide a strong basis for disagreement with the Panel's conclusion that: "*there is no evidence for post-Timber Mountain hydrothermal activity and that hydrothermal systems have essentially no potential to raise the water table at Yucca Mountain.*"

V. Mosaic Breccias

The Panel distinguished four types of breccias at Yucca Mountain and concluded that:

> *None of these can be attributed unequivocally to upwelling pressurized ground water; on the contrary, evidence strongly supports a surface process origin for some.* (p. 49)

This opinion differs from that of an earlier review panel convened by the DOE. Referring to the silica-cemented breccia cut by the calcite-opal-sepiolite veins in Trench #14, this panel stated:

> *On the basis of field inspection it may reasonably be interpreted as a **hydrothermal eruption breccia.*** (Hanson et al., 1987)

Leaving aside contentious differences of perception of field exposures, mineral assays of Trench #14 breccia reported by Weiss (1990) provide unmistakable evidence of a hydrothermal origin. The results are shown in Figure 12. Enrichment of the rock samples is computed relative to the stratigraphically equivalent background (Castor et al., 1989). Results for lithopysal ignimbrites (in the first column of Figure 12) are indicative of the extent of deuteric enrichment of these rocks. Results in the second column are for the median of seven breccia specimens. Significant enrichment is evident for the most strongly mineralized specimens, as shown in the third column. The variation in degree of mineralization may be regarded as evidence for polygenetic formation of the breccia. Finally, the fourth column shows that the degree of enrichment of the intersititial fluids (discussed previously) is comparable with that of the more strongly mineralized breccia specimens. The interstitial fluid enrichment, however, is unlike the deuteric mineralization exhibited by the lithophysal tuff.

In summary, the mineralization of the mosaic breccia, although disappointing from the perspective of mineral resources, is nonetheless unmistakably hydrothermal.

This conclusion is further supported by a number of independent lines of evidence. Among these are: a) occurrences of equivalent breccias in the Paleozoic carbonates, b) isotopic characteristics of the breccia cements, c) relative concentration of carbon-13, and d) fission track ages of the breccia enclosed zircons. These lines of evidence were developed by Szymanski (1992) and are summarized below.

Breccias in Paleozoic Carbonates

At localities where Paleozoic carbonates crop out near Yucca Mountain (e.g., Bare Mountain, and just north of Highway 95 some 10 km southeast of Yucca Mountain), authigenic-mineral-cemented (AMC) breccias are commonly found. These resemble the disputed AMC breccias at Yucca Mountain in every way except that the clasts are carbonate, not ignimbrite.

The Panel's postulate of syn-depositional brecciation, or brecciation caused by the deposition of younger ignimbrites, fails to explain the paragenesis of the

carbonate breccias. The postulate fails the most elementary uniqueness test.

Isotopic Characteristics of Mosaic Breccia Cements

The mineral assemblage comprised of calcite, opal A, opal CT, and sepiolite is common to mosaic breccia cements, veins, and calcretes. These three facies share the same $\delta^{18}O$ vs. $\delta^{13}C$ field, and are texturally equivalent. Both of these observations may be taken as indicating that all facies were precipitated from common solutions but with a varying degree of topographic exposure. The $\delta^{18}O$ vs. lithofacies gradient may be regarded as reflecting the combined effects of evaporative enrichment and temperature-dependent fractionation, while the $\delta^{13}C$ vs. lithofacies gradient may be regarded as reflecting the diffusional enrichment in carbon-13. For an upwelling solution, oxygen-18 enrichment would be lowest for the parent solutions of the breccia cements, higher for the parent solutions of the bedrock veins, and highest for the percent solution of the calcretes. The observed isotopic gradients (Figure 13) are just as would be expected for the precipitates of hydrothermal solutions as they rise, cool, and discharge at the topographic surface. A supergene/pedogenic mode of deposition would not produce the observed isotopic gradients.

Characteristics shared by fluids that precipitated the calcite-opal-sepiolite veins and fluids that produced the late metasomatism of the Topopah Spring Member are alkali-earth bulk composition and abnormal enrichment in strontium-87 (Szymanski, 1992). As noted by the Panel (p. 50), $^{87}Sr/^{86}Sr$ ratios for Trench #14 and Busted

Butte calcites are high, in the range 0.7119 to 0.7127. Strontium isotopic ratios for the metasomatically altered ignimbrites are also high, in excess of 0.7119 (Peterman et al., 1991). Because shallow ground waters have lower ratios, from 0.7100 to 0.7115, the Panel reached the conclusion:

> *It is concluded that vein calcites from Trench 14 and Busted Butte did not precipitate from analyzed ground waters.* (p. 165)

What is missing from this statement is that the analyzed fluid samples are exclusively sodic-potassic in bulk composition. The host rock for these fluids consists of ignimbrites. An altogether different picture emerges if one considers the alkali-earth fluids from well (UE 25P#1) that penetrates the underlying Paleozoic carbonates. In this case, the strontium isotopic ratio is 0.7118 (Stuckless, 1990). The Panel's conclusion is therefore only applicable to the shallow sodic-potassic fluids, not to the deeper alkali-earth solutions.

In consideration of the above discussions, we observe that: Using an incomplete process of elimination, the Panel reasons that if the vein calcites could not have precipitated from fluids residing in the ignimbrites, they must have precipitated from infiltrating rainwater. A much more satisfactory alternative is that the parent fluids for the controversial calcites had resided in the Paleozoic carbonates and/or in the underlying Precambrian basement, which is the most plausible source of strontium-87.

Relative Concentrations of Carbon-13

The isotopic signature of carbon in the breccia cement (-7 to -8 per mil with respect to PDB) is similar to that present in fluid inclusions in hydrothermal calcites and that in calcites of unquestioned hydrothermal origin (Faure, 1986; Hoefs, 1987; White et al., 1990). The carbon-13 content is greater than is expected for carbonate solutions produced by known supergene/pedogenic processes (Szymanski, 1992).

We believe that the carbon isotopic ratios from the breccia cements are not consistent with the postulated supergene/pedogenic origin of these cements. We also conclude that these ratios indicate that the carbon content of the breccia cements did not originate from inorganic reservoirs such as Paleozoic carbonates. The carbon isotopic ratios, however, are consistent with the hypothesis that the carbon originated from an igneous source. This conclusion is further supported by the fact that, for the last million years, all five of the locally recognized magmatic events were accompanied by contemporaneous episodes of carbon-13 depleted carbonatization (Szymanski, 1992).

Fission Track Ages of the Breccia Enclosed Zircons

Fission track ages of zircons contained in the AMC breccia cement establish an upper bound on the age of the breccia, which dates the most recent annealing of fission tracks (at temperatures above about 200^{o}C). Levy and Naeser reported ages for twelve zircon crystals in each of two samples, one from Trench #14 and the other from Busted

Butte. They reported as follows:

> *The spread of ages from each sample indicates that there are zircons from multiple sources present. In both samples there are crystals significantly younger and significantly older than the age of the tuff.* (Levy and Naeser, 1991)

The Panel described these results differently:

> *However, within the analytic uncertainty, most of the ages are about 10-12 Ma, or about the same as those of the dominant volcanic rocks in the region.* (p. 44)

This statement contradicts Levy and Naeser (1991), who attach statistical significance to the multiple age peaks exhibited for both specimens (Figure 14). Furthermore, contrary to the statements by the Panel, the K/Ar age of the host tuff is 13 million years B.P. and not 10-12 million years B.P. as implied by the Panel and secondly, most of the ages from the zircons are significantly younger than the host rock, the youngest being 4.8 million years B.P. Like the younger zircons, the metasomatic zeolites in the vadose zone also carry radiometric ages significantly younger than the age of the host ignimbrites (Figure 4).

In summary, the most recent annealing of fission tracks in zircons may have been caused by hydrothermal solutions that produced the alkali-earth zeolitization and were involved in deposition of the carbon-13 depleted and strontium-87 enriched veins. In view of this possibility, it is difficult to understand why the Panel *"...discounted hydrothermal systems as a potential mechanism for raising the water table level in the Yucca Mountain area."* (p. 130) On the contrary, it seems necessary to invoke post-Timber Mountain hydrothermal activity to explain the observed data.

VI. Calcite Paragenesis and Isotopic Data

Concerning the Panel's interpretations of isotopic data, their report is flawed by inconsistencies and invalid conclusions. According to the Panel:

> *The hypothesis of rising ground water as the origin of the calcites in the Yucca Mountain area has failed the tests of isotope geochemistry and is, in fact, contradicted by the available data.* (p. 167)

This statement is not only incorrect, but also is contradicted by the Panel's own statements. Specifically, the Panel stated that:

> *In the discussion that follows, it will be demonstrated that known surface calcite deposits at Yucca Mountain did not precipitate from analyzed present-day ground waters. Whether or not the calcites could have precipitated from ancient ground waters cannot be proven because critical data on paleo-ground waters are lacking.* (p. 150-151)

That the disputed veins did not precipitate from the present-day sodic-potassic fluids (host rock consists of alkali ignimbrites) is undisputed and is beside the point. The issue is whether these veins could have precipitated from alkali-earth fluids resembling the vadose zone interstitial fluids discussed previously. The latter fluids are enriched in base and noble metals and have REE enrichments, suggestive of a hydrothermal origin. Solutions of this kind most likely have been responsible for the observed post-Timber Mountain metasomatic zeolitization, and have probably formed the trace-element enriched breccia cement in Trench #14. The issue is whether such solutions could have also precipitated the carbon-13 depleted and strontium-87 enriched veins.

Strong evidence for a hydrothermal origin of the disputed veins is provided by the high paleogeothermal gradients obtained from oxygen isotopic ratios and by the high homogenization temperatures obtained from shallow calcites.

Further support for this interpretation is provided by two additional lines of evidence: a) isotopic comparative analysis, and b) strontium isotopic ratios. Both of these lines of evidence are considered below.

Isotopic Comparative Analysis

The NRC/NAS report stated:

Isotopic evidence shows that none of the surficial calcite deposits analyzed to date could have precipitated from known ground waters. (pp. 55-56)

The panel concludes that to date the preponderance of evidence supports the view that the calcretes and other secondary carbonates in veins of the area formed from meteoric water and surface processes. (p. 56)

In view of the fact that, at Yucca Mountain, the isotopic compositions of paleo-ground waters, the conditions of carbonate precipitation, and the post-depositional isotopic modifications are not constrained by available data, it is appropriate to consider alternative avenues of investigation. One such avenue is isotopic comparison of the Yucca Mountain veins with local and regional calcites of unquestioned hydrothermal origin.

Figure 15 shows that, in terms of $^{234}U/^{238}U$ isotopic ratio, the Yucca Mountain calcretes, surficial veins, and subsurface veins are indistinguishable from the Furnace Creek and Amargosa Basin travertines. In contrast to the Devil's Hole veins, which are submerged, these travertines are appropriate analogs because they occur above the water table, where the leaching environment is similar to that of the Yucca Mountain vadose zone (Szymanski, 1992)

Figure 16 shows that the Yucca Mountain calcretes, surficial veins, and subsurface veins have a range of carbon isotopic ratios similar to that of Long Valley Caldera travertines and hydrothermal veins (data from White et al., 1990). An even wider range of carbon isotopic ratios is exhibited by the worldwide data compiled by Hoefs (1987) for carbonate gangue associated with various hydrothermal ore deposits. Hoefs (1987) has explained the wide range of carbon isotopic ratios observed in magmatically active regions as a consequence of dual carbon sources. Hydrothermal fluids deriving their dissolved carbon from marine limestones are relatively enriched in carbon-13 and have $\delta^{13}C$ ratios of 0 ± 2 per mil PDB. At other times, hydrothermal fluids may acquire carbon through dissolution of igneous CO_2. Typically, such fluids are depleted in carbon-13 and have values of $\delta^{13}C$ ranging from -3 to as low as -10 per mil PDB (Faure, 1986).

Figure 17 shows that, in terms of oxygen isotopic ratios, the Yucca Mountain calcites are indistinguishable from hydrothermal carbonates elsewhere in the western Great Basin. Carbonate gangue in the Carlin disseminated gold deposits has a wider range of isotopic ratios than the Yucca Mountain calcites. The Cortez carbonate gangue and the Amargosa Basin spring-marsh deposits also have wider ranges of oxygen isotopic ratios.

Figure 18 shows that, in terms of strontium isotopic ratios, the Yucca Mountain calcites are indistinguishable from the Devil's Hole veins, which are of undisputed hypogene origin.

Collectively, as noted above and in Figures 15-18, the similarities of the U, C, O, and Sr isotopic ratios from the Yucca Mountain veins to those from known hydrothermal deposits support the notion that the former could likewise be of hydrothermal origin.

In summary, we conclude that the Panel has elected to either dismiss or ignore the broader body of isotopic data reported in the literature. These data support the viewpoint that the disputed veins could have formed from geothermal fluids.

Origin of the Disputed Veins Based on the Strontium Isotopic Ratios

Flawed deduction of paragenesis by the Panel is exemplified readily in the case of strontium isotopic ratios. Strontium isotopic ratios of carbonates are not appreciably altered by fractionation and post-depositional modifications that affect the other isotopic ratios. The Panel correctly observed (p. 50) that the strontium isotopic ratios of calcites

(0.7119 to 0.7127) are discordant with those of analyzed sodic-potassic fluids (0.7100 to 0.7115). However, this does not mean that the disputed veins precipitated from infiltrating rainwater. With isotopic concordance as the criterion, the Panel could have considered the affinity between the Yucca Mountain calcites and present-day thermal fluids discharging at Devil's Hole. These fluids reside in Paleozoic carbonates and exhibit a strontium isotopic ratio of 0.7123 (p. 49). A similar affinity is apparent with fluids from Paleozoic carbonates in drill hole UE 25 p#1. Samples of these fluids yielded the strontium isotopic ratio of 0.7118 (Stuckless, 1990). These strontium isotopic affinities indicate that the disputed veins could be of a hypogene origin.

Similar conclusions can be drawn by asking the following two questions: (1) why are the strontium isotopic ratios so high for both the disputed veins and the metasomatically altered ignimbrites, and (2) why is the strontium content so high for the metasomatically altered ignimbrites? Strontium enrichment is evident both for altered ignimbrite relative to glass (Figure 6) and for vadose-zone interstitial fluid relative to the contemporary sodic-potassic fluids (Figure 10). A clue to the origin of the strontium is provided by its isotopic ratio. Unfortunately, no data has been reported for two of the Yucca Mountain lithostratigraphic complexes (the pristine ignimbrites and the Paleozioc carbonates), and again we have to rely on indirect data (Figure 19). Representative ratios are 0.707 for young (unaltered) ignimbrites, 0.709 for marine limestones of Paleozoic age, and 0.717 for the Precambrian basement. The metasomatic zeolitization and the latest carbonatization are associated with strontium isotopic ratios significantly higher than those expected for fluids which have acquired their strontium content from either carbonates or ignimbrites. This is also reflected in the relatively high strontium isotopic ratios of present-day ground waters. An obvious inference is that the Precambrian basement is the most plausible source of strontium. This possibility was not considered by the Panel so that, in effect, it was dismissed without argument.

In summary, we observe that the Panel has elected not to consider all of the available strontium isotopic data. These data, in fact, support the contention that the disputed veins could have formed from geothermal fluids.

VII. Geodynamics of the Yucca Mountain Area

Considering the present state of geodynamic instability of the crust and upper mantle at and around Yucca Mountain, the Panel's discounting of *"hydrothermal systems as a potential mechanism for raising the water level"* is particularly difficult to understand. An unstable geodynamic configuration is indicated by several independent lines of evidence. Among these are: a) the results of seismic tomography studies (Monfort and Evans, 1982; Evans and Smith, 1992), b) the results of a seismic reflection survey (Brocker et al., 1989), c) considerations of local magmatic activity during the Plio-Quarternary time span (Noble et al., 1991; Szymanski, 1989 and 1992), and d) the results of in situ stress measurements (Healy et al., 1984; Szymanski, 1989).

With reference to the contemporary geodynamic configuration of the Yucca Mountain region, perhaps the most illuminating are the results of seismic tomography studies. These studies were performed initially by Monfort and Evans (1982), and later by Evans and Smith (1992), and are summarized in Figures 20 through 22. From these figures, it may be inferred that, locally, the lower crust and uppermost mantle are in a state of incipient/partial melt. In this regard, Figure 21 indicates that the upper mantle to the east-southeast of Yucca Mountain has anomalously low velocities. The absolute values of the velocities are not specified and the variation percentages reflect changes relative to the horizontally averaged means. The mean values for P-wave velocities in the upper mantle of the Basin and Range are known to be low relative to stable continental areas (e.g., Archambeau et al., 1969), so that 3% decreases are significant.

Such low velocities have typically been interpreted as being indicative of incipient/partial melting, with the amount of decrease in the velocity being proportional to the degree of melting.

The same considerations regarding the occurrence and manifestation of partial/incipient melt apply to the crust. In this regard, higher velocity variations for the crust are shown in Figure 22. Here, the lower-than-average velocities imply some degree of melting in the lower crust. From the results shown in the figure, it is evident that an anomalously low velocity zone exists beneath both Crater Flat and over the entire width of Yucca Mountain. The most extreme decrease in P-wave velocity is directly beneath Yucca Mountain, while the low velocities beneath Crater Flat are at mid-crustal depths and not as extreme. However, the Panel report commented on these results in the following terms:

> *Analysis of far-traveled earthquake waves (P-waves) passing nearly vertically through the crust and upper mantle beneath Yucca Mountain and surrounding regions (Evans and Smith, 1992) shows no evidence of a low velocity feature that would suggest a volume of molten rock (or magma chamber) beneath Yucca Mountain.* (p. 98)

While evidence of a magma chamber is not evident, this is not by any means the whole issue. For the Yucca Mountain region, partial/incipient melting is the most likely source of recent volcanism. Indeed, it is just such a zone in the upper mantle that appears to be responsible for the recent volcanism in Crater Flat.

The observed distribution of seismic velocities suggests both elevated temperatures and high lateral temperature gradients in the middle/lower crust. Under these circumstances, convective circulations of intracrustal fluids constitute a thermodynamic necessity. These rather obvious conditions were not addressed by the Panel, instead the focus was entirely on whether or not a magma chamber might be present. This addresses an extreme case scenario and avoids confronting the issue of whether the observed crustal velocities indicate an unstable situation that could result in hydrotectonic disturbances at Yucca Mountain.

Other measurements that are important to an assessment of the geodynamic stability of the site are the in situ stress measurements, such as those obtained by Healy et al., (1984). These observations, while critical to an assessment of suitability of the Yucca Mountain site to accommodate a high level repository, were not considered by the Panel. Contrary to the Panel's assessment that the Yucca Mountain area is not likely to experience a large earthquake in the near future, the stress measurements imply the opposite. The recent earthquake activity near Yucca Mountain appears to indicate that an unstable stress state, rather than a quasi-stable state, actually prevails.

We find that these geodynamic data are of paramount importance in considering the suitability of Yucca Mountain to accommodate a high level nuclear repository. Consideration of these data by Szymanski (1989 and 1992) leads to the overall conclusion that the local hydrologic system is profoundly influenced by tectonic factors. The abnormal geothermal conditions at depth create a situation whereby Rayleigh-Bernard instabilities are intrinsic elements of

the local hydrologic regime. Evidence that the local rocks are deforming leads to another important conclusion, specifically that the hydraulic conductivity structure is controlled by in situ stress and is subject to significant temporal changes. With both of these factors present (i.e., convective boundary conditions and in situ stress dependence of hydraulic conductivity) the Yucca Mountain hydrologic system must be regarded as susceptible to episodic changes. This possibility has not been considered by the Panel, and in our view, by itself invalidates major conclusions reached by the Panel.

VIII. Hydrologic Behavior Inferred from Modeling Studies

The NAS/NRC Panel purports to examine the extent of hydrologic disturbance that might be produced by a local igneous intrusion and/or by a local earthquake without regard for interactive processes affecting crustal fluids. Furthermore, the resulting estimates of hydrotectonic effects are flawed on two counts: (1) observed behavior at other tectonically active regions is either ignored or misinterpreted, and (2) numerical models employed by the Panel fail to account for first-order processes that govern coupled hydrotectonic interactions.

Analyses of the type presented in the Panel report might be useful for some purposes, but are grossly inadequate for use as the basis for the Panel's strong conclusion that:

> *...stress/strain changes resulting from an earthquake are inadequate to cause more than a few tens of meters rise in the water table based on the convergence of the results of a variety of models and assumptions, especially if the deep carbonate aquifer is as incompressible as the limited data suggest.* (p. 116)

The Panel's analysis of the effects of a volcanic intrusion is even less representative, yet the Panel's opinion of benign behavior is more strongly depicted. In this regard, the Panel stated:

> *...a 25 m rise in water table is clearly a conservative upper bound estimate for the expected form of intrusion in the Yucca Mountain region.* (p. 101)

The essential deficiency is that numerical models are applied to predict behavior of the system without first demonstrating some capabilities for simulating actual hydrotectonic behavior. Furthermore, the numerical models used as the basis for Panel interpretations fail to account for even first-order processes.

Some of the more serious problems in their representations are: First, that fluid flow is wrongly assumed to take place exclusively through interstices, even though the Panel acknowledges elsewhere in the report (p. 174) that this form of diffusive flow is unimportant compared with channeled flow through networks of fractures. After concluding that an earthquake can only cause small changes in the water table, the Panel noted that if the fractured system were more accurately modeled:

> *It may then be possible to determine if physically reasonable conditions consistent with an hypothesis of seismically-driven flooding of the repository horizon would develop at the site.* (p. 118)

These are clearly inconsistent statements and the Panel's conclusions regarding small changes are unjustified. Second, that flow properties are erroneously assumed to remain invariant when subjected to tectonically induced changes in stress and strain. Given the importance of fracture flow, such tectonically induced changes can reasonably be expected to fundamentally restructure the flow system. Third, that thermal convection of fluids is inappropriately assumed to occur in isolation from flow that is induced by rock deformation. For the case of an earthquake-induced flow, the effects of thermal convection are simply ignored; whereas, for the case of an igneous intrusion, the two first-order flow-inducing effects are treated as independent noninteractive processes. Fourth, that the magmatic environment of the Yucca Mountain area has not been considered in evaluations of hydrotectonic processes and interactions. For example, deep seated fluids can absorb large quantities of CO_2 that are introduced in association with local magmatic processes. As fluid pressures reduce in response to local strains or to seismically induced flow, CO_2 can be expected to come out of solution and form gas bubbles. The accompanying reduction in fluid density introduces substantial buoyancy forces which promote fluid migration and further emergence of CO_2 in a positive feedback mode, accelerating the process to potentially explosive proportions. Such a mechanism could account for hydrothermal eruption breccias identified at Yucca Mountain (e.g., Hansen et al., 1987; Szymanski, 1989, 1992; Archambeau and Price, 1991). Fifth, that dissolved minerals also influence flow paths, as evidenced by the abundant networks of veins found throughout Yucca Mountain. The lesson is that fracture conduits, that once provided flow paths for mineralized fluids, have since become plugged. However such phenomena are again not considered in the reported evaluations of hydrotectonic interactions.

Given the inadequate formulations used by the Panel, the modeling results can hardly be expected to accurately predict or bound hydrotectonic interactions at Yucca Mountain. Whereas hydrothermal processes are commonly associated with igneous activity, the Panel report did not consider such associations, and fails to provide a single example in which active volcanism has had benign effects on the hydrologic system of the type interpreted for Yucca Mountain. Hence, conclusions about how a tectonic event might influence the hydrologic system are substantively without merit. Neither the amplitude of changes in water table nor the dimensions of the zone of influence are based on observational data or representative analysis. This leaves the Panel's conclusions without justification and, hence, are unwarranted.

Some observational data are cited for earthquake-induced effects on ground water at other sites where conditions differ in important respects from those at Yucca Mountain. For example, most of the cited earthquakes did not occur in response to tectonic extension where normal faulting tends to relieve extensional strain and generally compresses the effected rock. In contrast, earthquakes responding to tectonic compression (e.g., reverse faulting earthquakes) tend to release subhorizontal compression and dilate the effected rock, so that a rise in the water would not be expected

Two earthquakes studied carefully for post-seismic changes in surface outflow of water, namely the 1959 Hebgan Lake (M=7.3) and the 1983 Borah Peak (M=7.0) earthquakes, however, occurred under conditions of crustal extension similar to those at Yucca Mountain. For these two events little is known about resulting long term changes in the water table. In particular, most of the observed hydrologic effects pertain to volumes of mobilized groundwater. In this regard, however, increased stream flows within several tens of kilometers from the surface ruptures indicate that large quantities of water, ranging from .2 to .8 km^3 (Wood and King, 1991), were mobilized during a period of about one year after the respective earthquakes. By modeling amplitudes and spatial distributions of recorded outflows, Wood and King deduced that fluids appear to have been mobilized from depths of at least 5 km in both cases. If comparable volumes (i.e., a significant fraction of a km^3) were to be mobilized in response to an earthquake at Yucca Mountain, there would be ample fluid volume to flood the vadose zone over an extended area and still produce large volumes of surface runoff. To illustrate by example, we note that 0.3 km^3 of mobilized fluids would suffice to fill fractures that occupy 10^{-4} of the total volume of the medium. In a 0.5 km thick vadose zone extending over an area the size of the Nevada Test Site (about 3,000 km^2), half of the mobilized fluid (0.15 km^3) would still overflow to and discharge at the land surface. Furthermore, the resulting increase in hydraulic head that would accompany a 0.5 km rise in the water table elevation is within the range of average changes in stress (i.e., tens of bars) interpreted from historical earthquakes (e.g., Kanamori and Anderson, 1978).

In summary, while observational data are not available for direct interpretation of earthquake effects on a deep water table of the type found at Yucca Mountain, reasonable extrapolations of available data, by Wood and King (1992) in particular, strongly imply that the deep water table could well rise hundreds of meters in response to a local earthquake. The Panel failed to consider relevant evidence. Clearly the answer to their question *"Can it happen?"* would have to be, on the basis of these observations alone: "Very likely."

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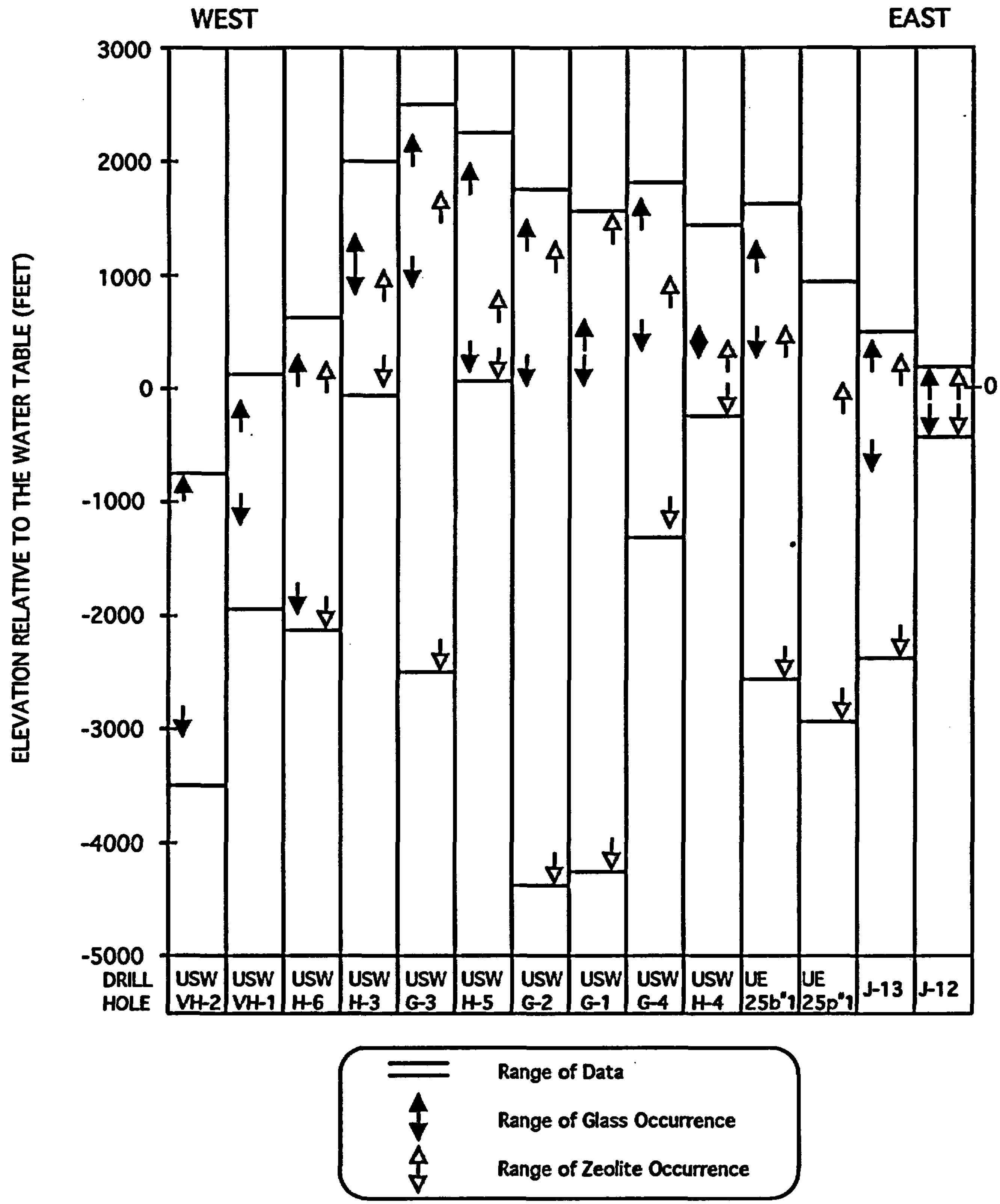


Figure 1. Distributions of glass and zeolite relative to the water table. Drill hole locations are illustrated in Figure 2.

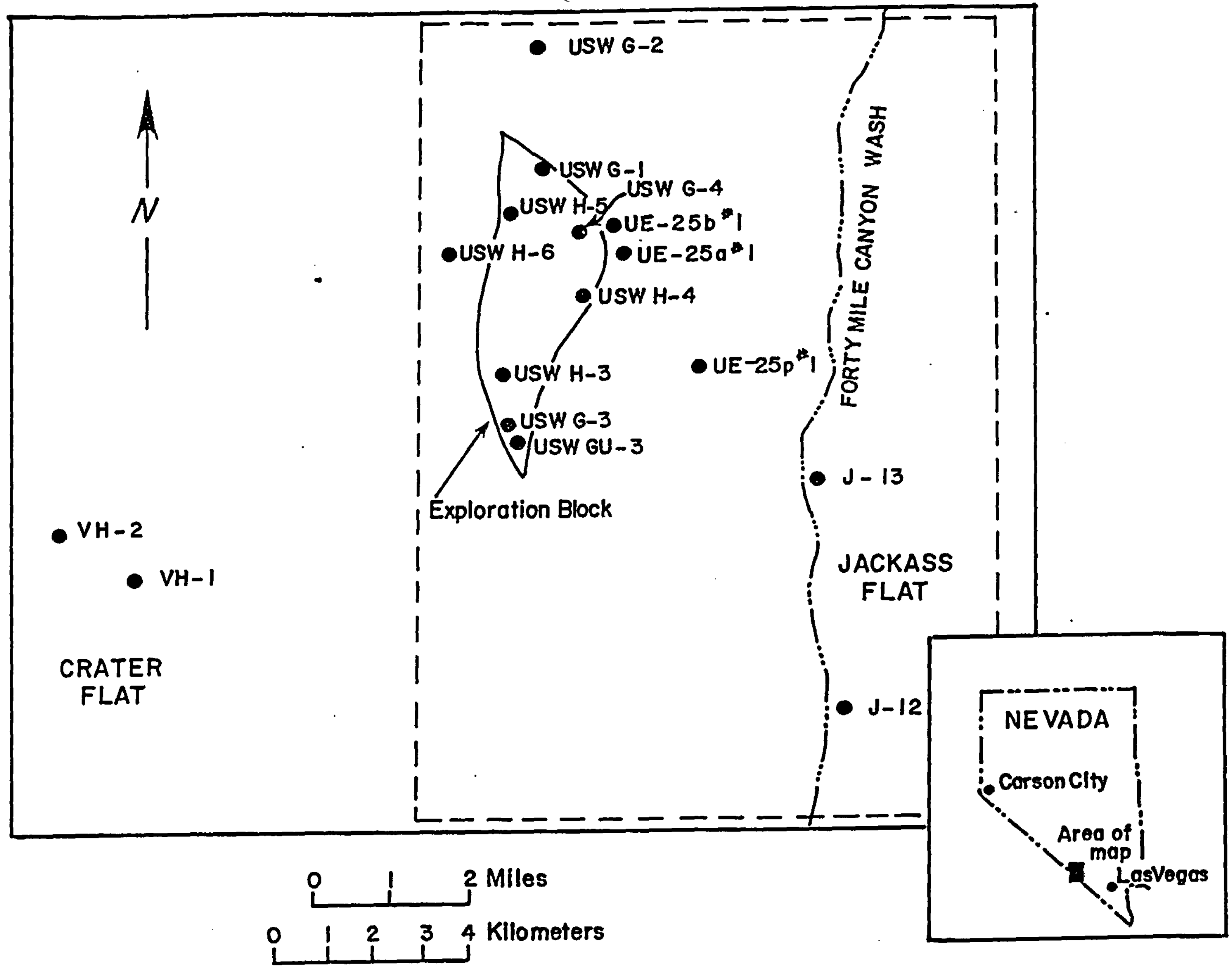


Figure 2. Location of drill holes discussed in text. Modified from Levy (1991) and Sass et al. (1981).

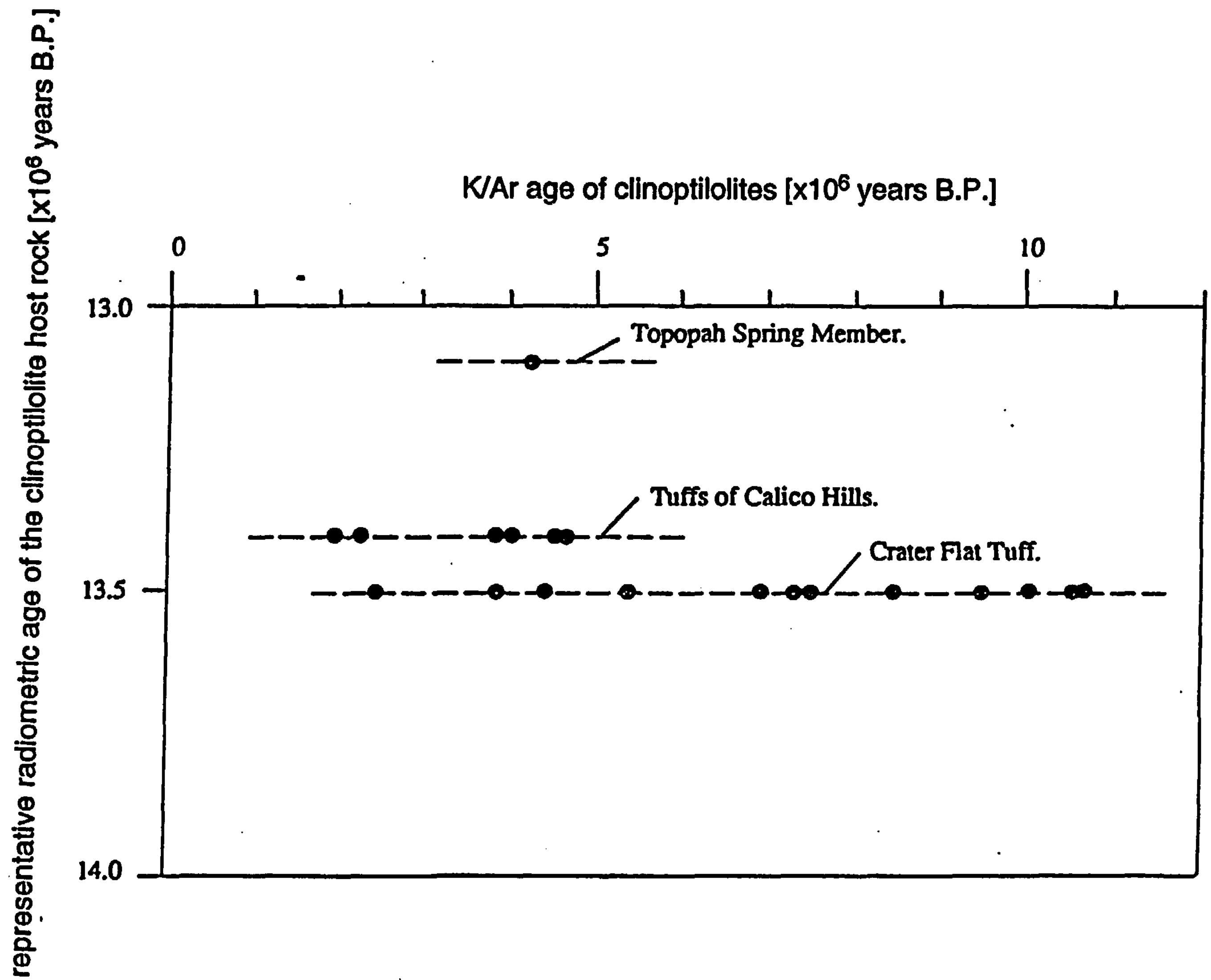
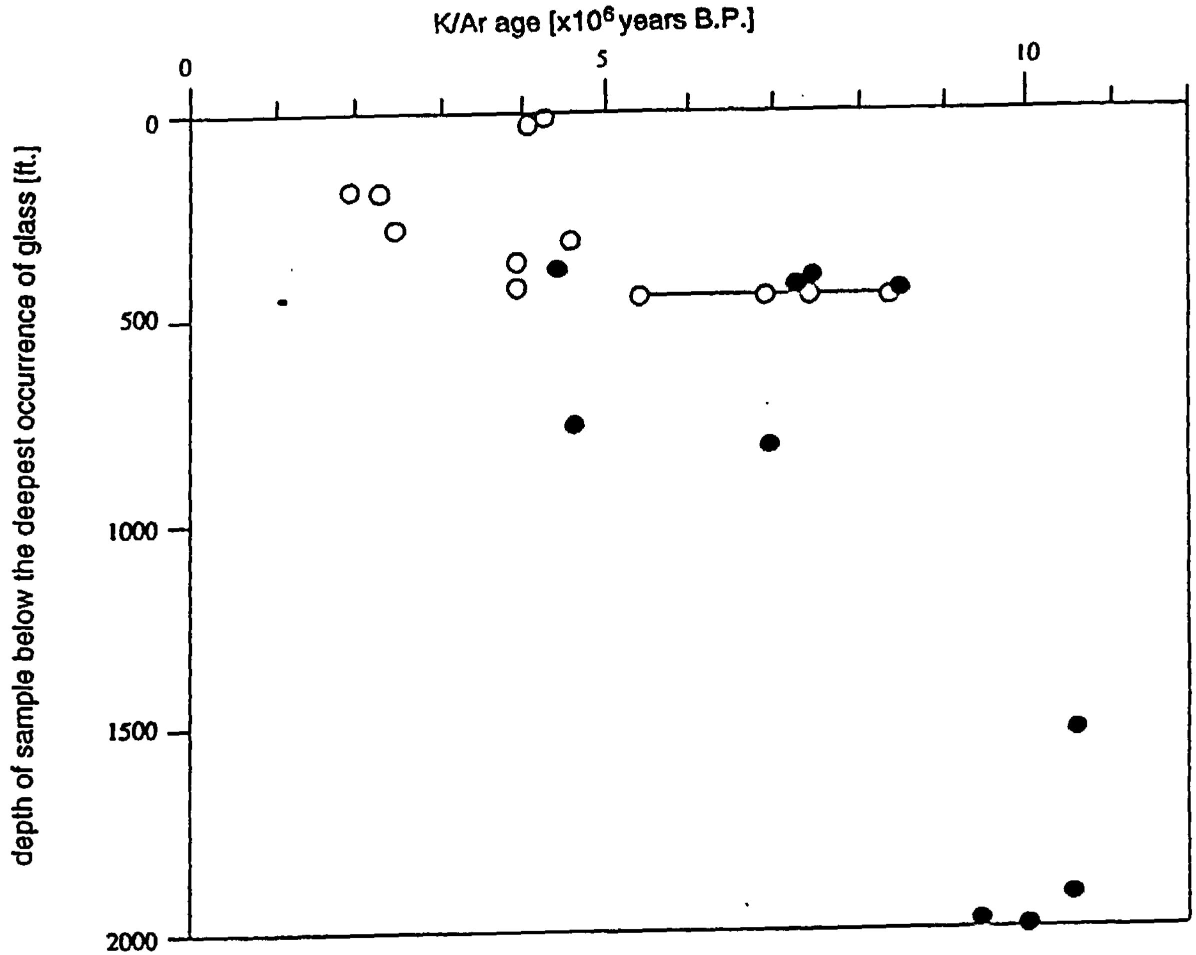


Figure 3. Relationship between the K/Ar ages of clinoptilolites and ages of host rocks. From Szymanski (1992); data are from WoldeGabriel (1991).

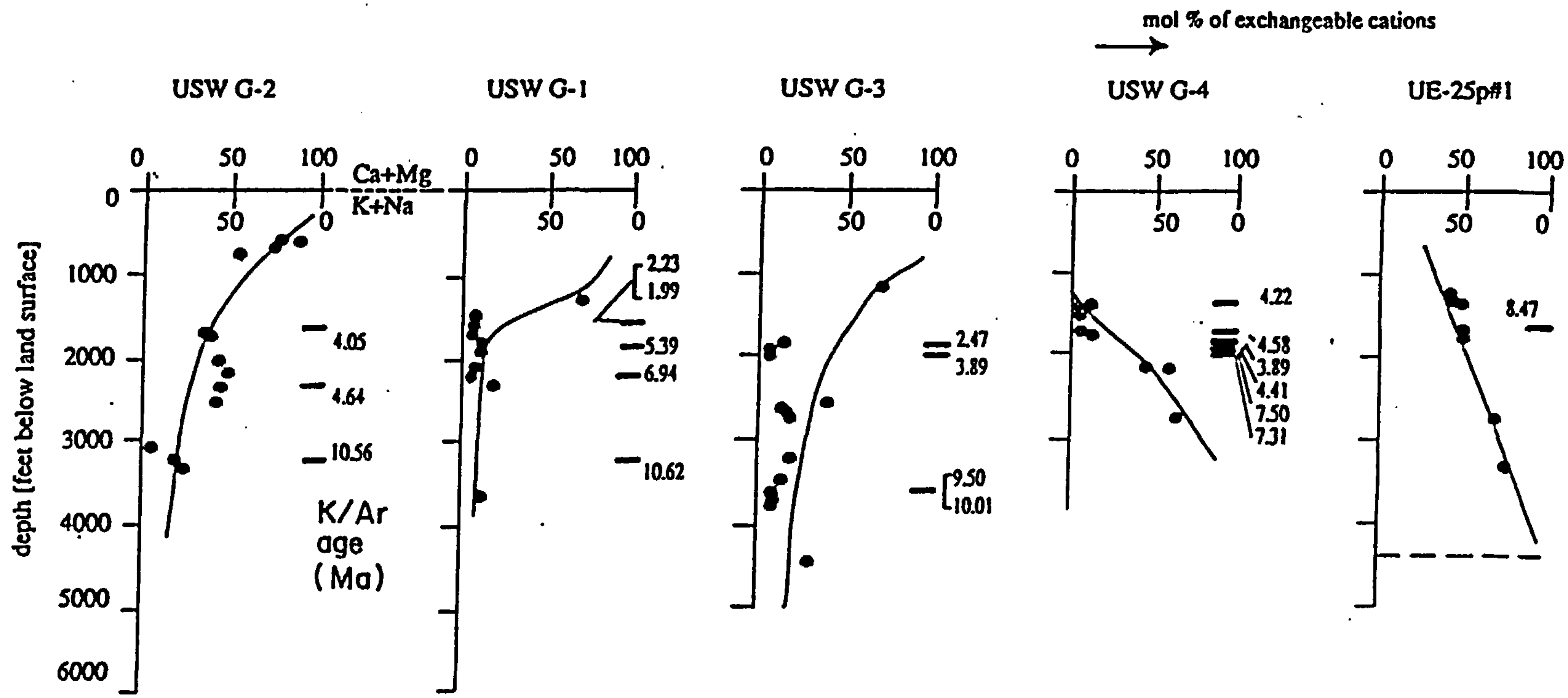


Key:

○ - clinoptilolite sample from the vadose zone

● - clinoptilolite sample from below the water table

Figure 4. K/Ar ages of Yucca Mountain clinoptilolites as a function of availability of vitric material (Szymanski, 1992).

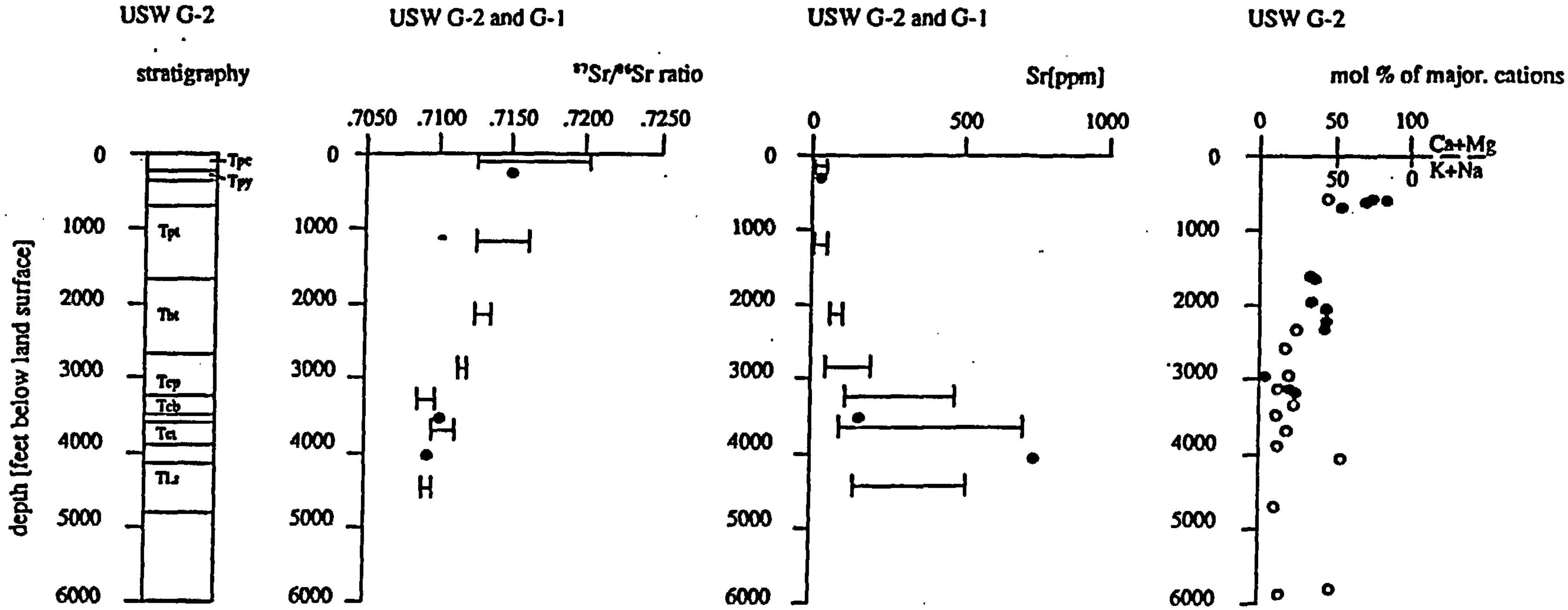


Note:

a) mol % of exchangeable cations are from Broxton et. al., (1986)

b) K/Ar ages are from WoldeGabriel (1990)

Figure 5. K/Ar ages of the Yucca Mountain clinoptilolites, as a function of depth for individual boreholes, and mol % of exchangeable cations. From Szymanski (1992).



Explanation:

- ● - major cation content of clinoptilolite samples
- o - major cation content of whole-rock samples

bar indicates range of values for either $^{87}Sr/^{86}Sr$ ratio or concentrations of Sr (whole-rock samples)
Tpc - the Tiva Canyon Member, **Tpy** - the Yucca Mountain Member, **Tpt** - the Topopah Spring Member, **Tht** - the Tuffs of Calico Hills, **Tcp** - the Prow Pass Member, **Tcb** - the Bullfrog member, **Tct** - the Tram Member, and **Tlr** - the Lithic Ridge Tuff.

<u>Figure 6.</u> Depth comparison - $^{87}Sr/^{86}Sr$ ratios, Sr concentrations, and major cation concentrations of alteration products (whole-rock cores and clinoptilolites).

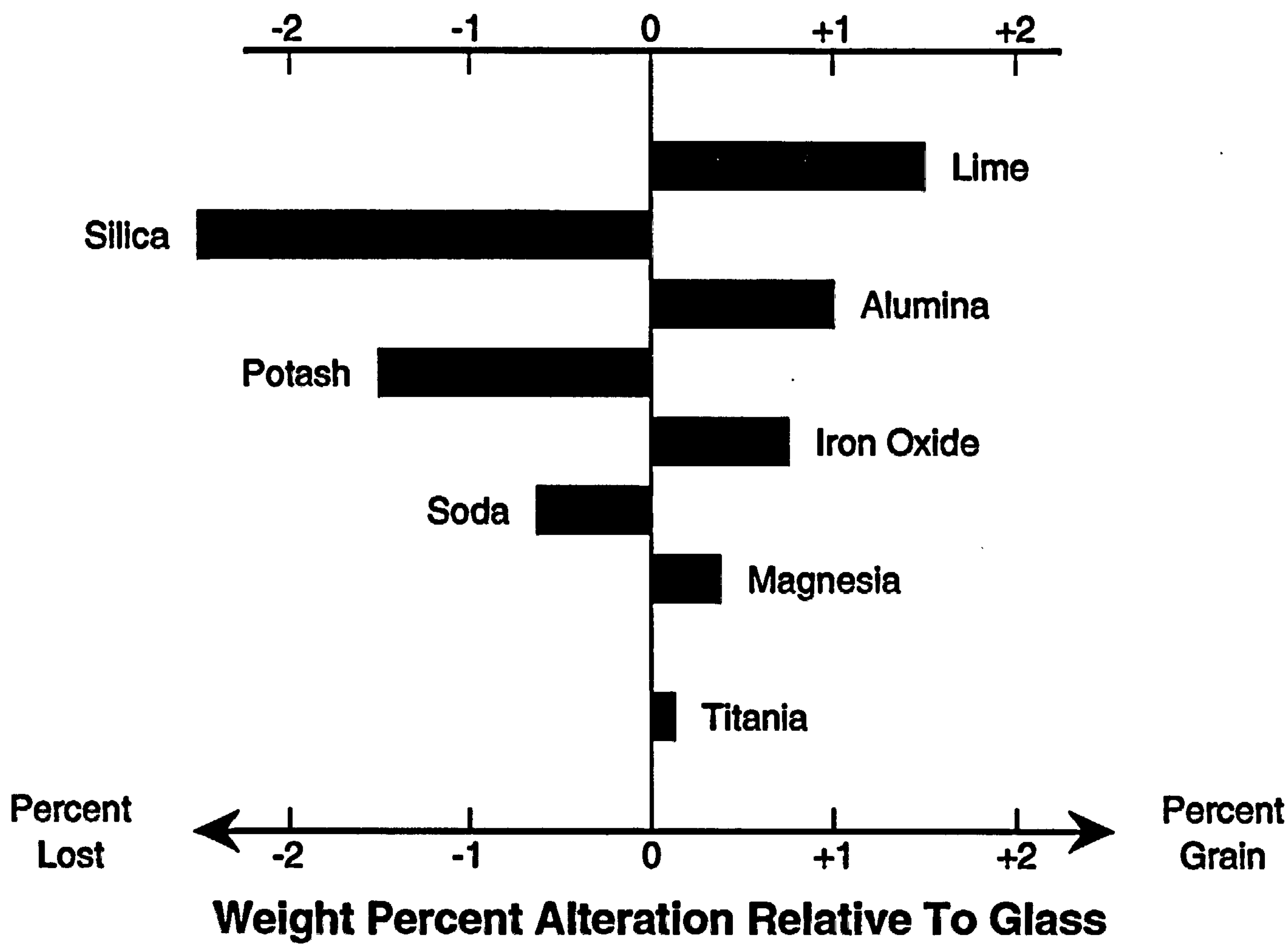


Figure 7. Representative alteration on concentration of components of whole-rock drill core samples from Yucca Mountain. Data from Livingston (1992).

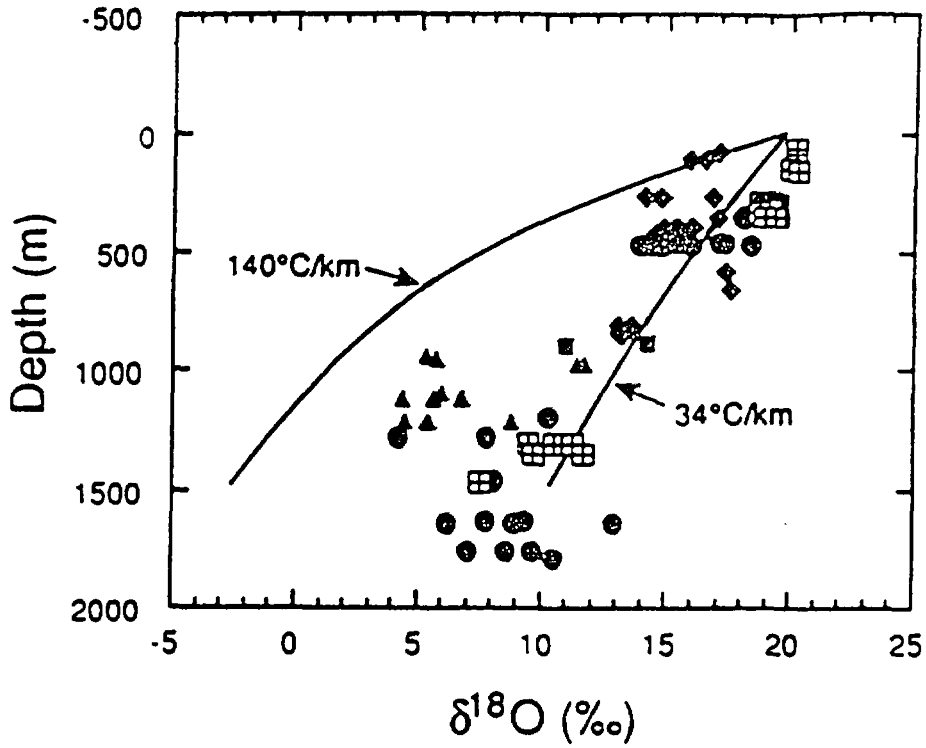


Figure 8. Paleo-geothermal gradients determined by Whelan and Stuckless (1992) from the depth-distribution of isotopic ratios of oxygen-18 and -16 in boreholes USW G-1, G-2, G-3, G-4 and UE-25b#1. Contemporary geothermal gradients measured in these boreholes are 18, 24, 22, 24, and 20° C/km respectively (Sass et al., 1987). Paleo-gradients during crystallization of the calcitic veins were at least 50% greater than the contemporary gradient.

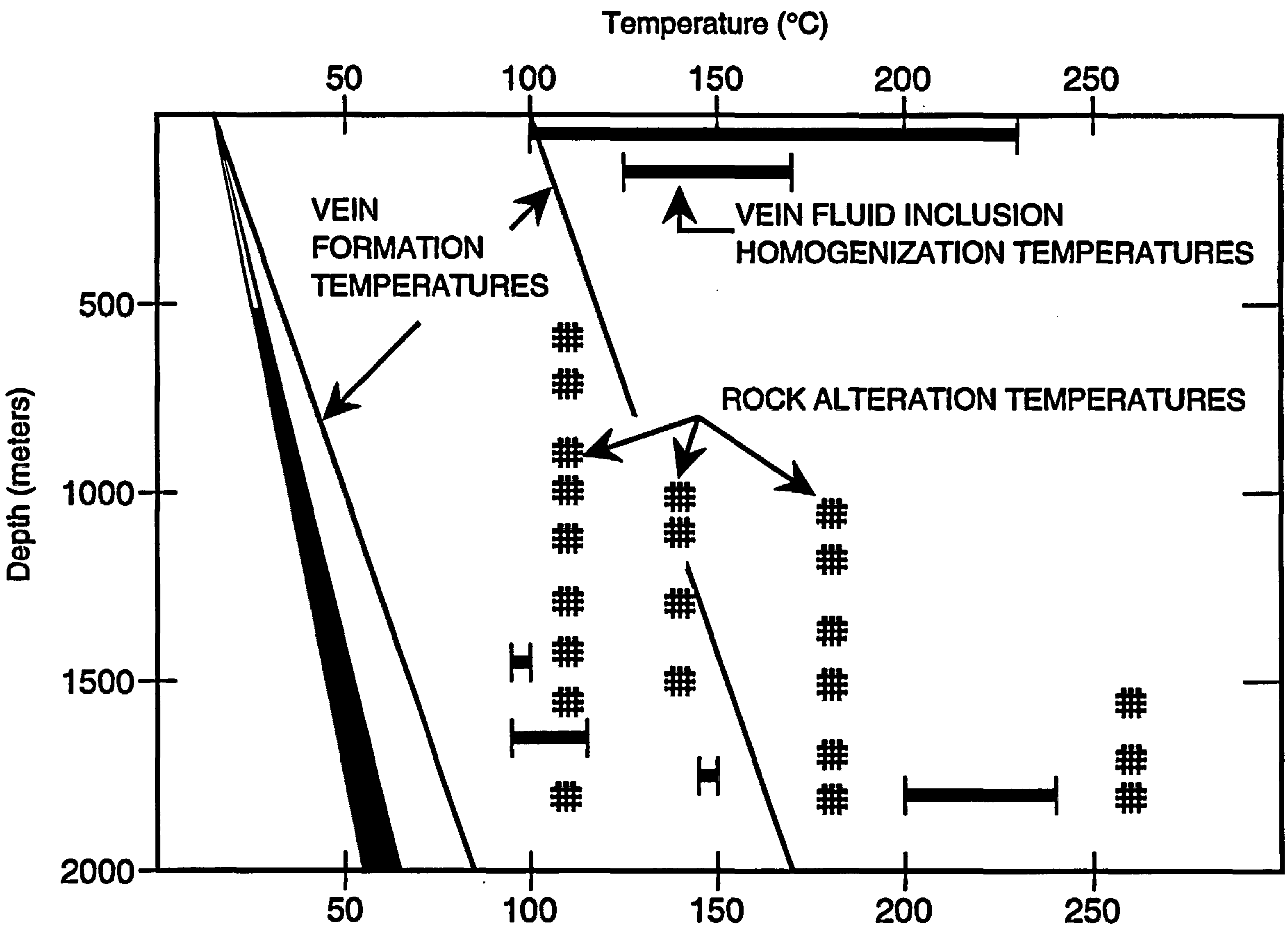


Figure 9. Comparison of contemporary and paleo-temperatures. The minimum paleo-gradient (34/km) determined from oxygen isotopic ratios is illustrated for two arbitrary surface temperatures (ambient and 100° C).

Mineral Enrichment of Vadose-Zone Interstitial Fluids

ELEMENT	ENRICHMENT Ratio *
Magnesium	10
Calcium	8
Nickel	1000
Copper	50
Zinc	45
Rubidium	2
Strontium	30
Yttrium	100
Molybdenum	300
Iodine	20
Tungsten	300
Platinum	**
Gold	**
Titanium	20

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*Data are from borehole UZ#4 (interstitial fluids) normalized by J-12 and J-13 well waters (Smith, 1991).

**Well waters contained no measured gold and platinum. Interstitial fluids contained .2 ppb for both metals.

Figure 10. Mineral enrichment of vadose-zone interstitial fluids relative to well waters residing in ignimbrite fractures.

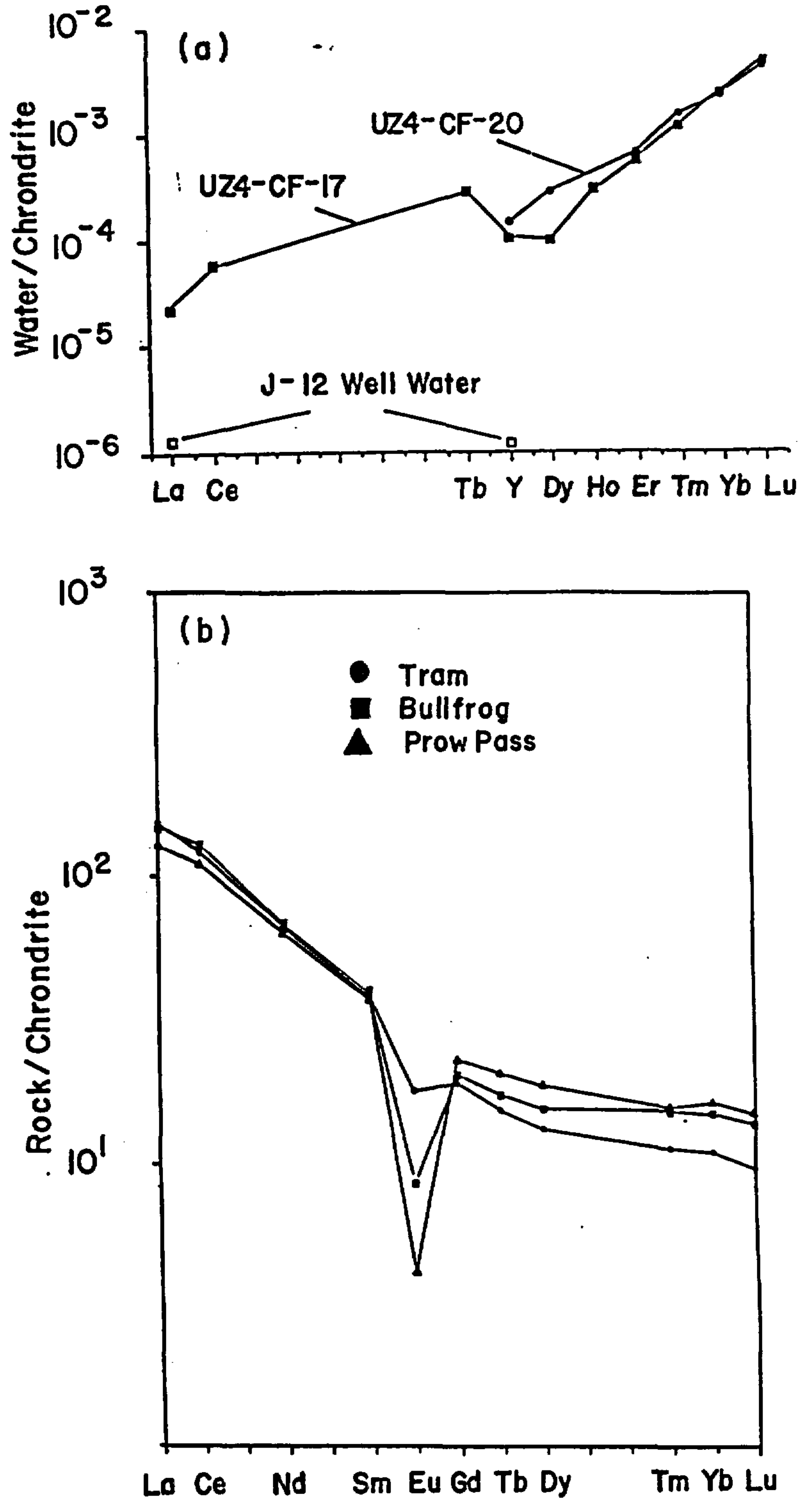

Figure 11. Chondrite-normalized REE abundance patterns. a.) Interstitial fluids and well water residing in ignimbrite fractures: data from Smith (1991). b.) Crater Flat ignimbrites: data from Scott and Castellanos (1984). Heavy REE enrichment for interstitial fluids is due to high CO_2 pressure.

Mineral Enrichment of Breccia Cement

ELEMENT	ENRICHMENT			
	TIVA CANYON LITHOPHYSAL TUFF FROM EXILE HILL *	MEDIAN, TRENCH #14 BRECCIA CEMENT *	MAXIMUM, TRENCH #14 BRECCIA CEMENT *	INTERSTITIAL FLUIDS **
Ag	2	2	16	
As	1	3.6	36	
Au	<1	2	5	
Cu	.25	1	4	50
Mo	7	18	650	300
Pb	14	65	610	1-5
Sb	<1	25	100	
Zn	44	90	33	45
Bi	<1	<1	<1	

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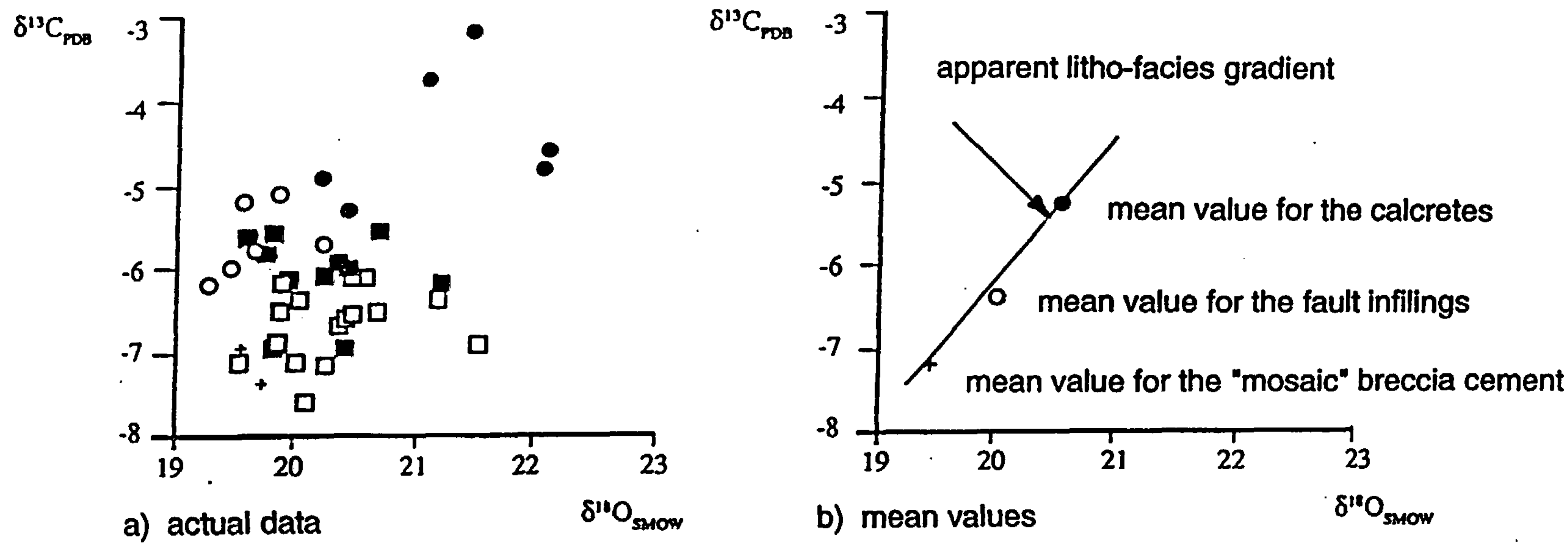
*Data from Weiss (1990); enrichment relative to average concentrations for the Yucca Mountain area (Castor et al., 1989).

**Data from Smith (1991); enrichment relative to well water (See Figure 10).

Figure 12. Mineral enrichment of breccia cement: results for lithophysal tuff and interstitial fluids are shown for comparison.



Explanation:

■ - Trench 14 calcretes

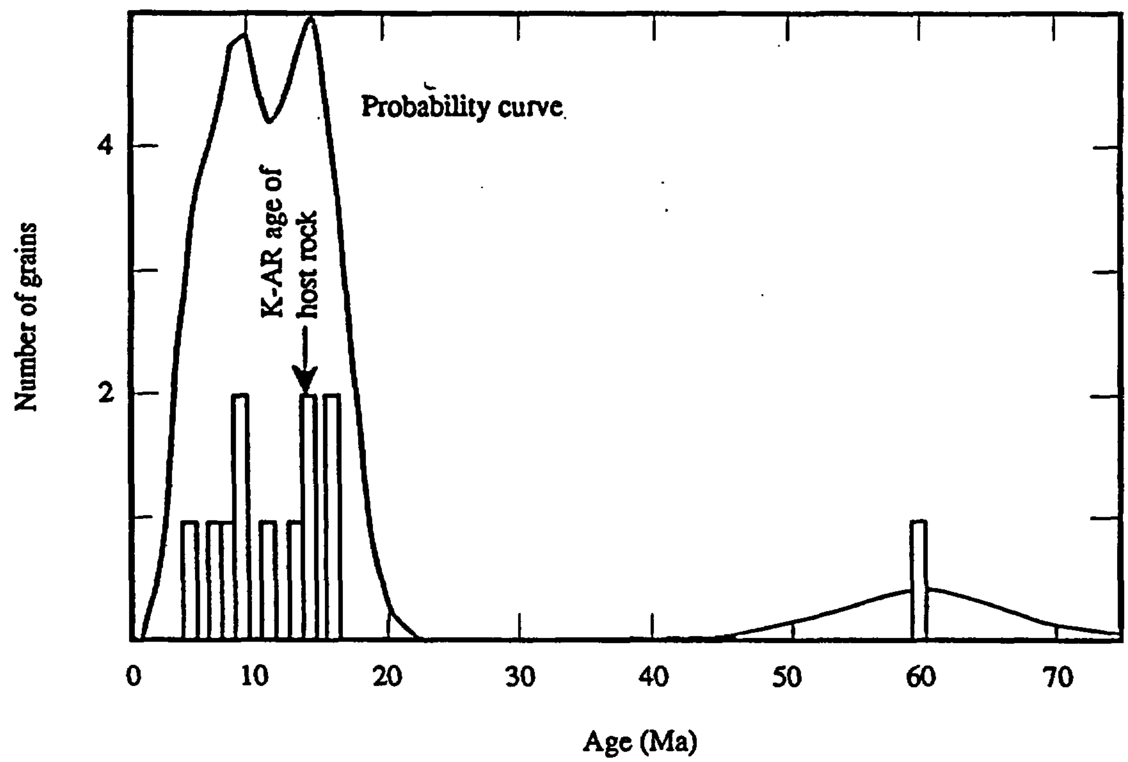
● - Busted Butte calcretes

□ - Trench 14 fault infiling

○ - Busted Butte fault infiling

+ - Trench 14 and Busted Butte "mosaic" breccia

<u>Figure 13.</u> Comparison of the isotopic signatures of carbon and oxygen in samples of "mosaic" breccia cement, surficial veins, and local calcretes (Whelan and Stuckless, 1990). The isotopic gradients are consistent with precipitation from rising, cooling solutions.



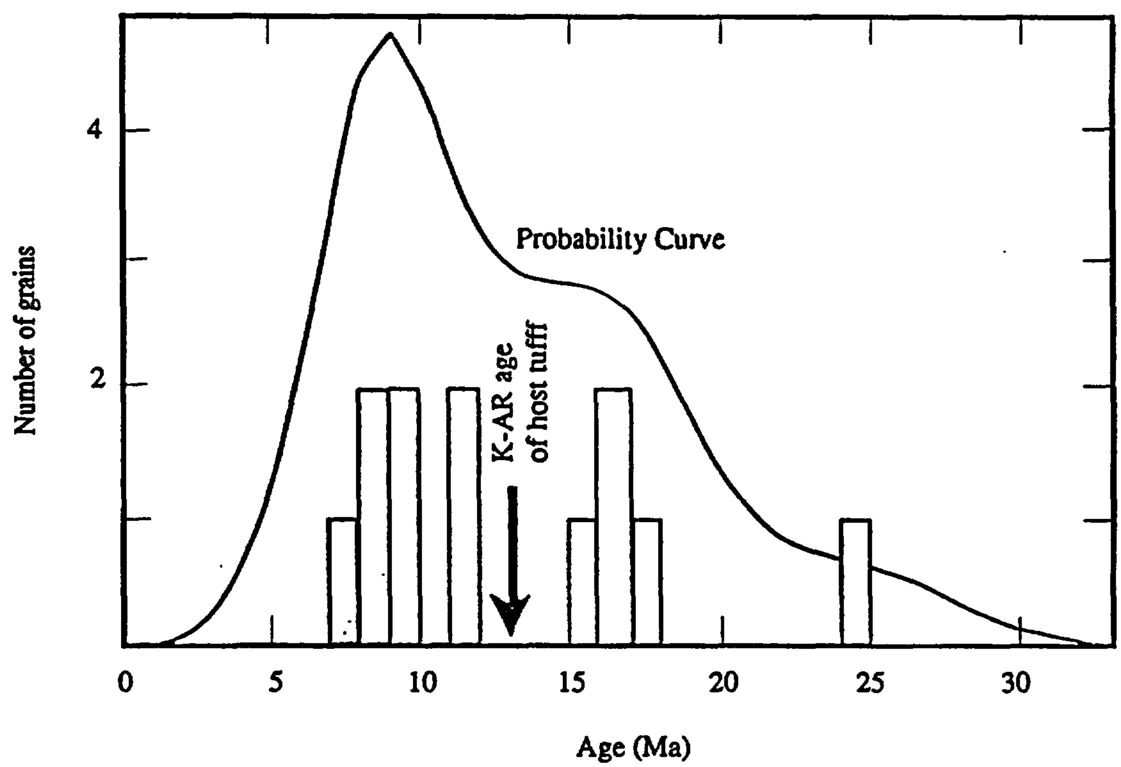


Figure 14. Fission track ages of zircons from breccias at Busted Butte (top) and Trench #14 (bottom). From Levy and Naeser, 1991.

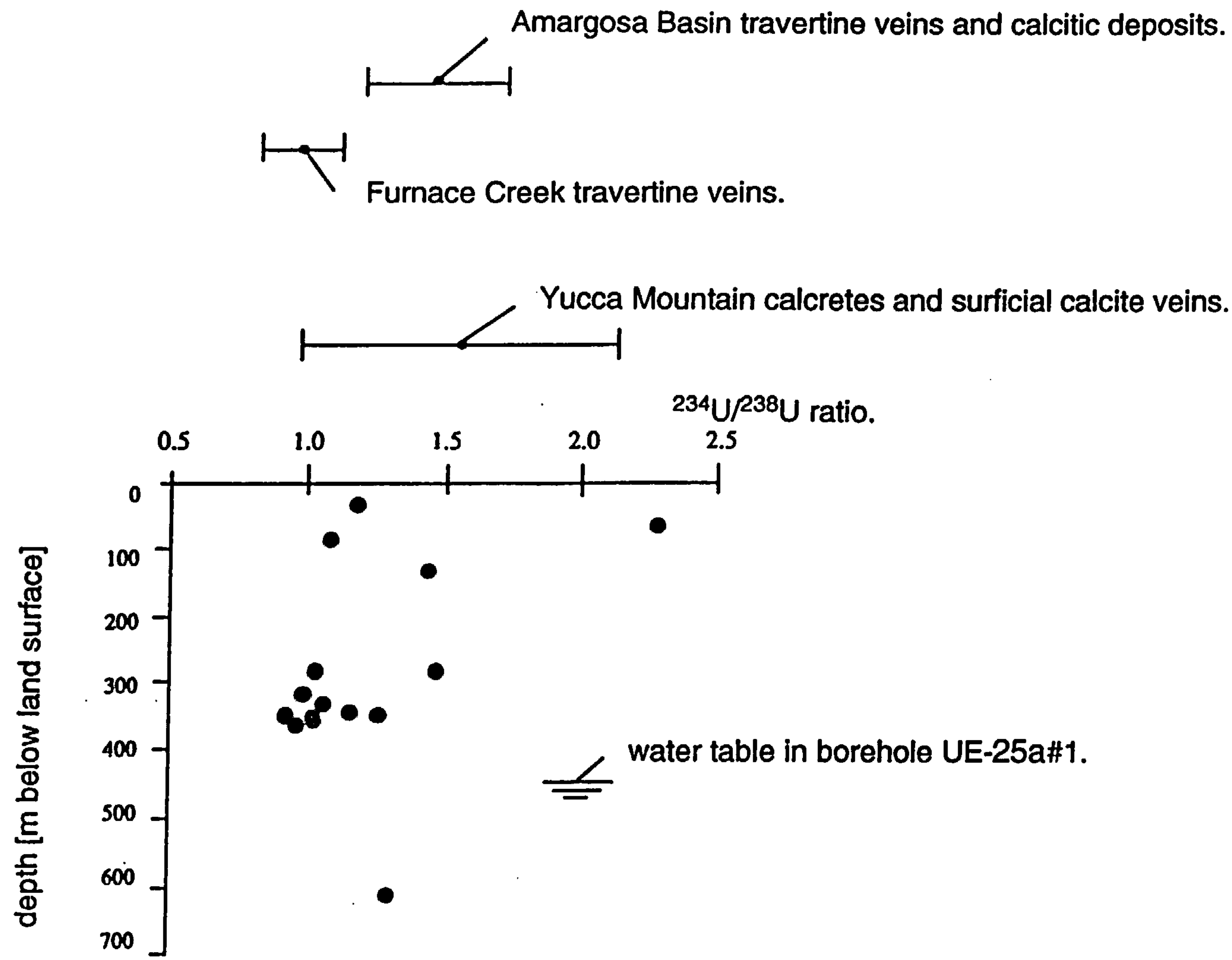


Figure 15. Comparison of uranium isotopic ratios for regional thermal analogs (Szabo and O'Malley, 1985), Yucca Mountain calcretes and surficial veins (Szabo et al., 1981; Szabo and O'Malley, 1985) and subsurface veins (Szabo and Kyser, 1985). From Szymanski (1992).

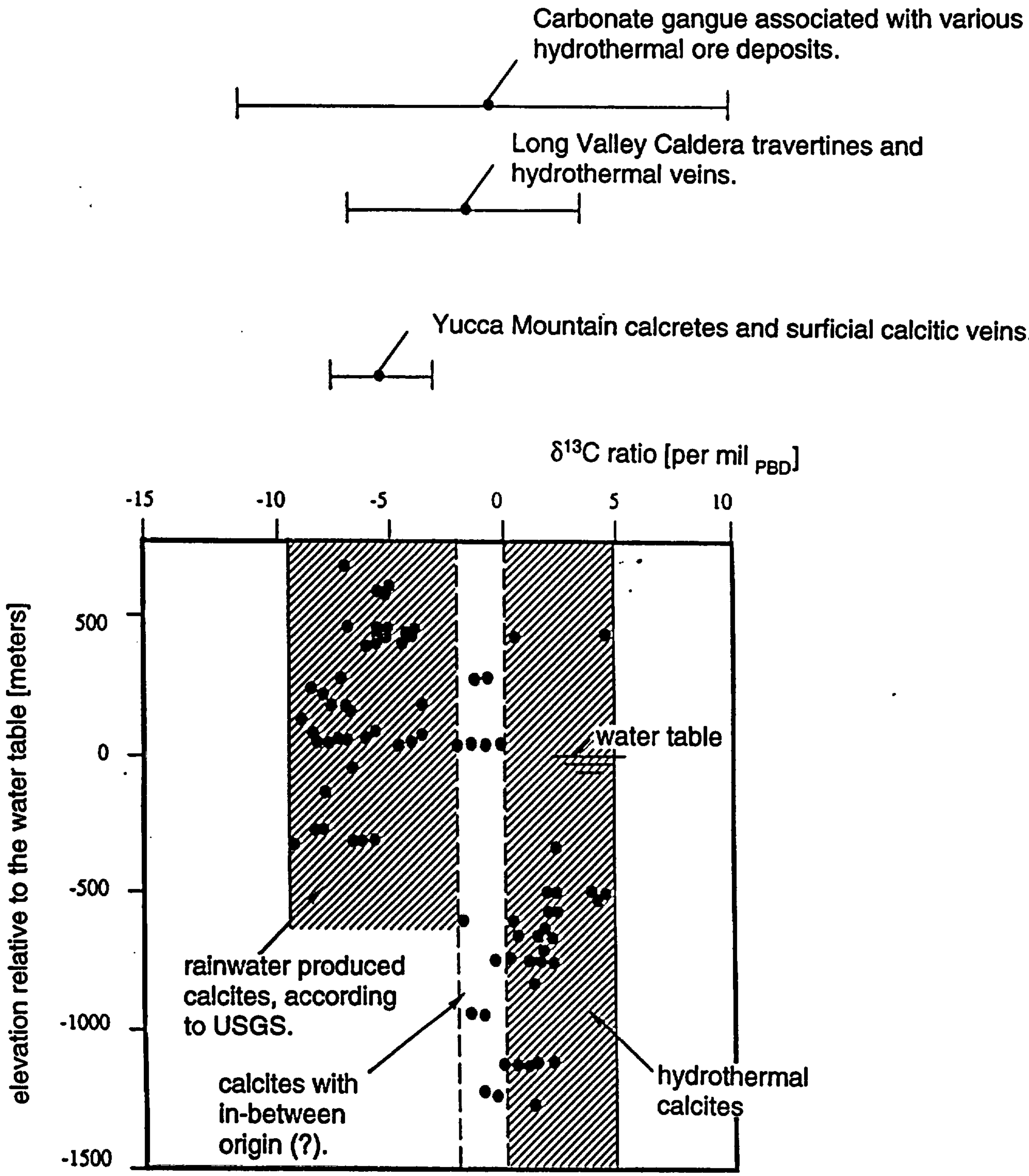


Figure 16. Comparison of carbon isotopic ratios for thermal analogs (Hoefs, 1987; White et al., 1990), Yucca Mountain calcretes and surficial calcitic veins, and subsurface veins (Whelan and Stuckless, 1991). From Szymanski (1992).

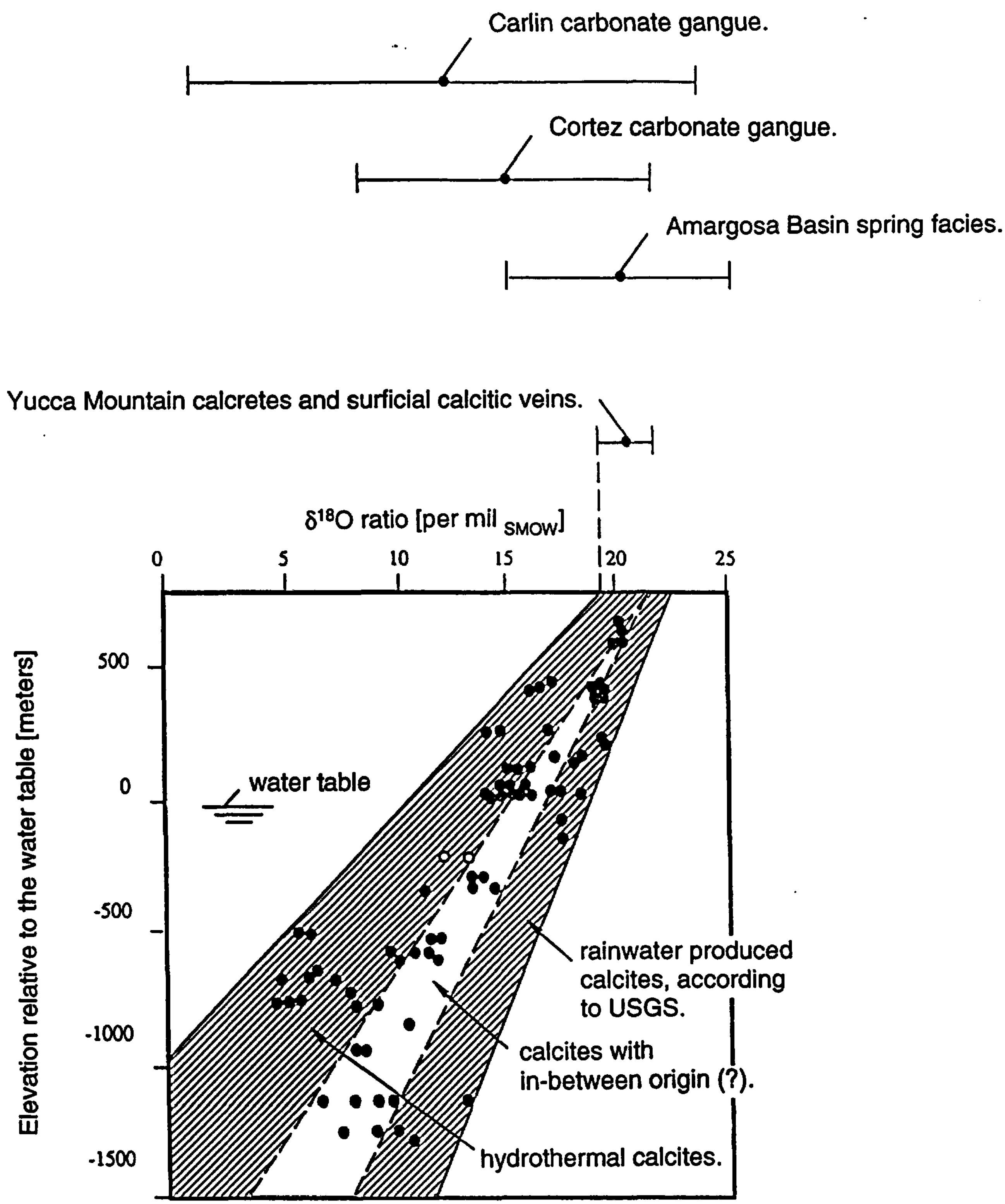


Figure 17. Comparison of oxygen isotopic ratios for thermal analogs (Rye, 1985; Hay et al., 1986), Yucca Mountain calcretes and surficial calcitic veins, and subsurface veins (Whelan and Stuckless, 1991; Broxton et al., 1986). From Szymanski (1992).

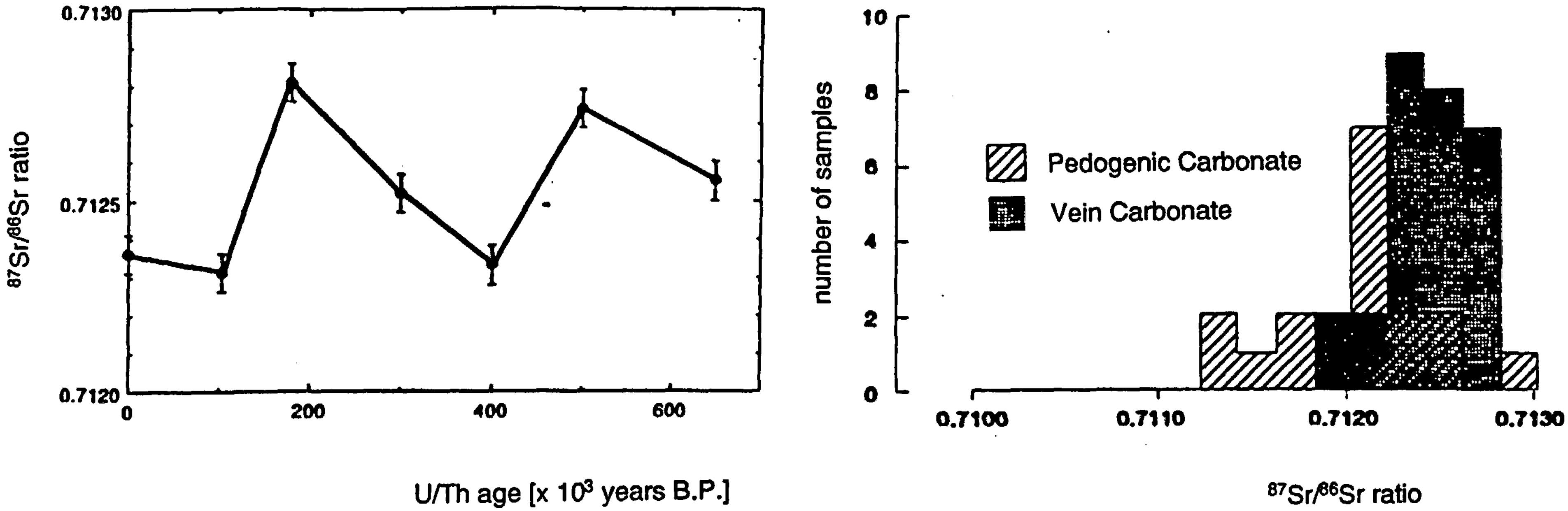


Figure 18. Comparison of strontium isotopic ratios for a nearby thermal analog (left, Devil's Hole; Marshall et al., 1990) and Yucca Mountain (right; Stuckless, 1990). Calcitic veins from Devil's Hole and Yucca Mountain are indistinguishable in terms of strontium isotopic ratio.

Location	Rock Type	$^{87}Sr/^{86}Sr$	Source	Note
Unaltered Ignimbrites				
Long Valley Caldera	Inyo Domes Rhyolites	0.70630	Goff et al. (1990)	mean of 3 samples
do	do	0.70606	do	mean of 7 samples
do	Mafic and Intermediate	0.70630	do	mean of 3 samples
do	Moat Rhyolites	0.70601	do	mean of 6 samples
do	Early Rhyolites	0.70665	do	mean of 2 samples
do	do	0.70716	do	hydrothermally alt
do	do	0.70742	do	do
do	Bishop Tuff	0.7070	do	mean of 2 samples
do	do	0.70713	do	mean of 6 samples
do	do	0.70645	do	sanidine seperates
do	do	0.70745	do	hydrothermally alt
do	Pre-caldera Volcanic	0.70610	do	mean of 3 samples
representative mean value: 0.70667				
Paleozoic Carbonates				
Spring Mountains	Limestone	0.70913	Peterman (1990)	outcrop
do	do	0.70823	do	do
do	do	0.70837	do	do
Ash Meadows	do	0.70990	do	do
Rock Valley	do	0.70934	do	do
representative mean value: 0.70899				
The Precambrian Basement				
Round Vly. Peak, CA	Schist	0.71656	Goff et al. (1990)	PC-derivative
do	Hornfels	0.72201	do	do
do	Sandstone	0.71126	do	do
Dish Hill, CA	Granodiorite	0.7177	Peterman et al (1970)	xenolith
representative mean value: 0.71688				

Figure 19. Strontium isotopic ratios of unaltered ignimbrites, paleozoic carbonates and Precambrian rocks of the western Basin and Range Province. The high strontium isotopic ratio (> 0.71) of Yucca Mountain alteration products and calcite veins is indicative of a deep crustal source.

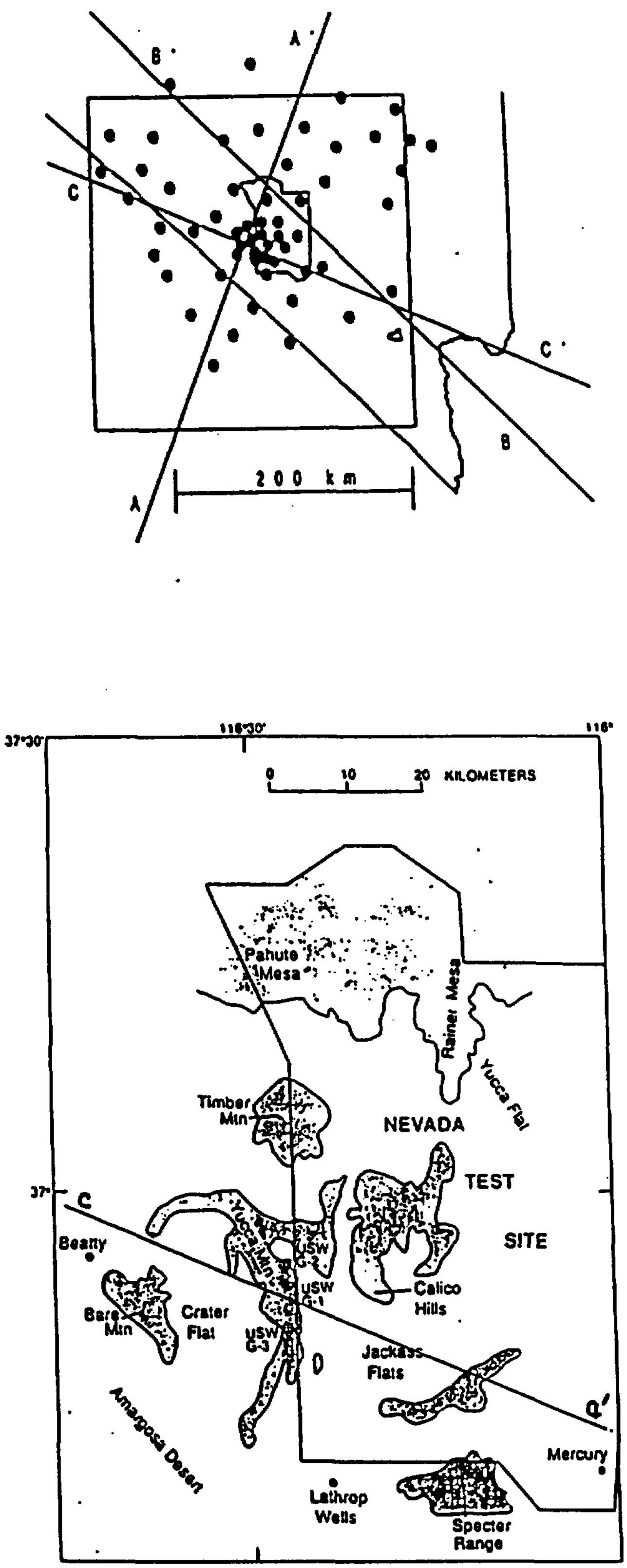


Figure 20. Maps of the seismic station distribution and principal topographic features in the Yucca Mountain and Nevada Test Site areas. Tomographic sections showing the structure at depth along the profiles AA', BB' and CC' were obtained by Evans and Smith, 1992.

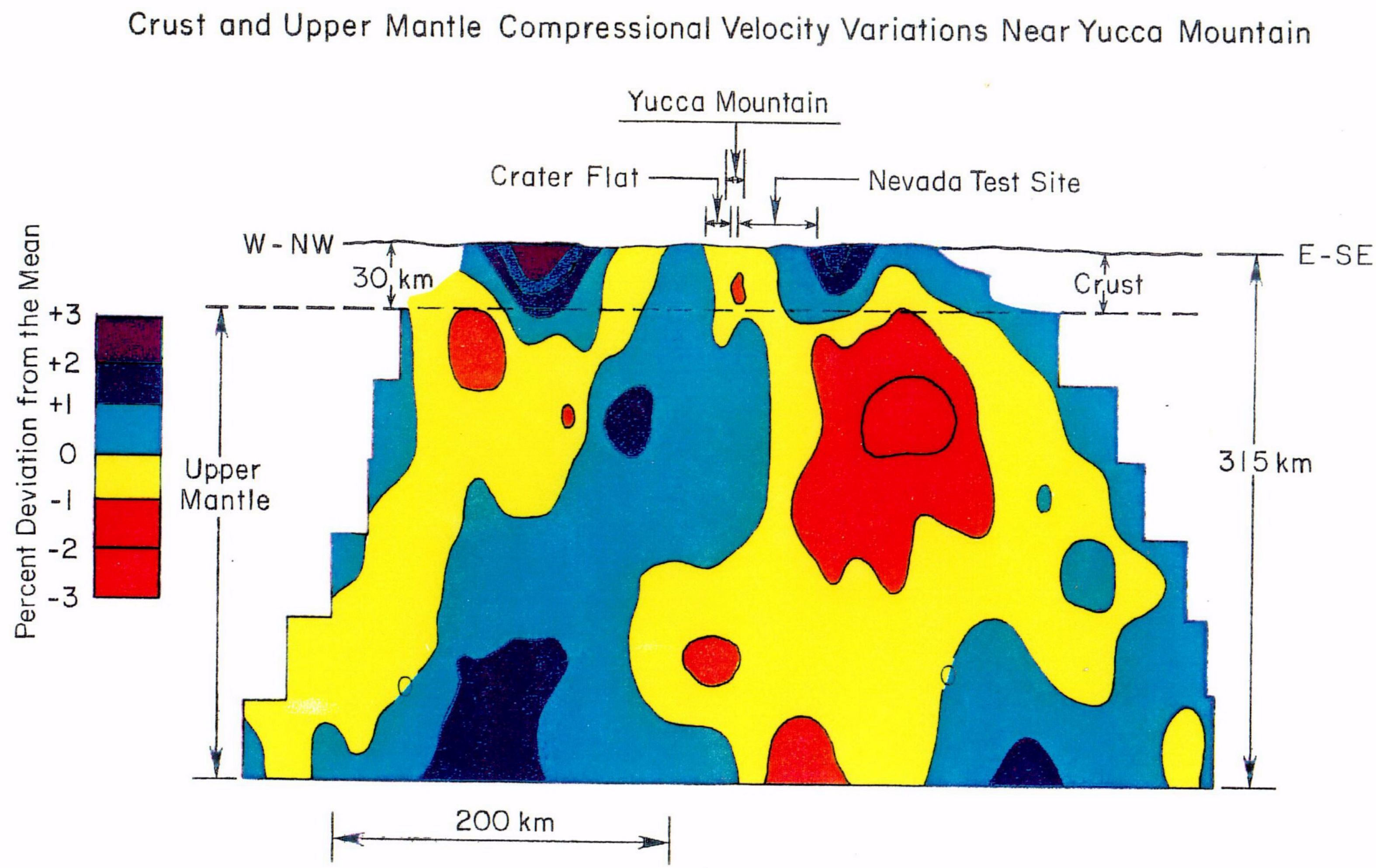


Figure 21. **Tomographic depth section** (profile CC") showing seismic velocity variations (in percent of deviation from the horizontally averaged mean) in the crust and upper mantle beneath and near Yucca Mountain. Details of velocity variations in the crust are not well resolved. The low velocity zone in the Upper Mantle most probably represents partial melting and a source of volcanism. Lower crustal zone heating and possible partial melting may be indicated by the Low Velocity Zone (LVZ) directly beneath Yucca Mountain. (From: Evans and Smith, USGS, 1992)

Crustal Compressional Velocity Variations at Yucca Mountain

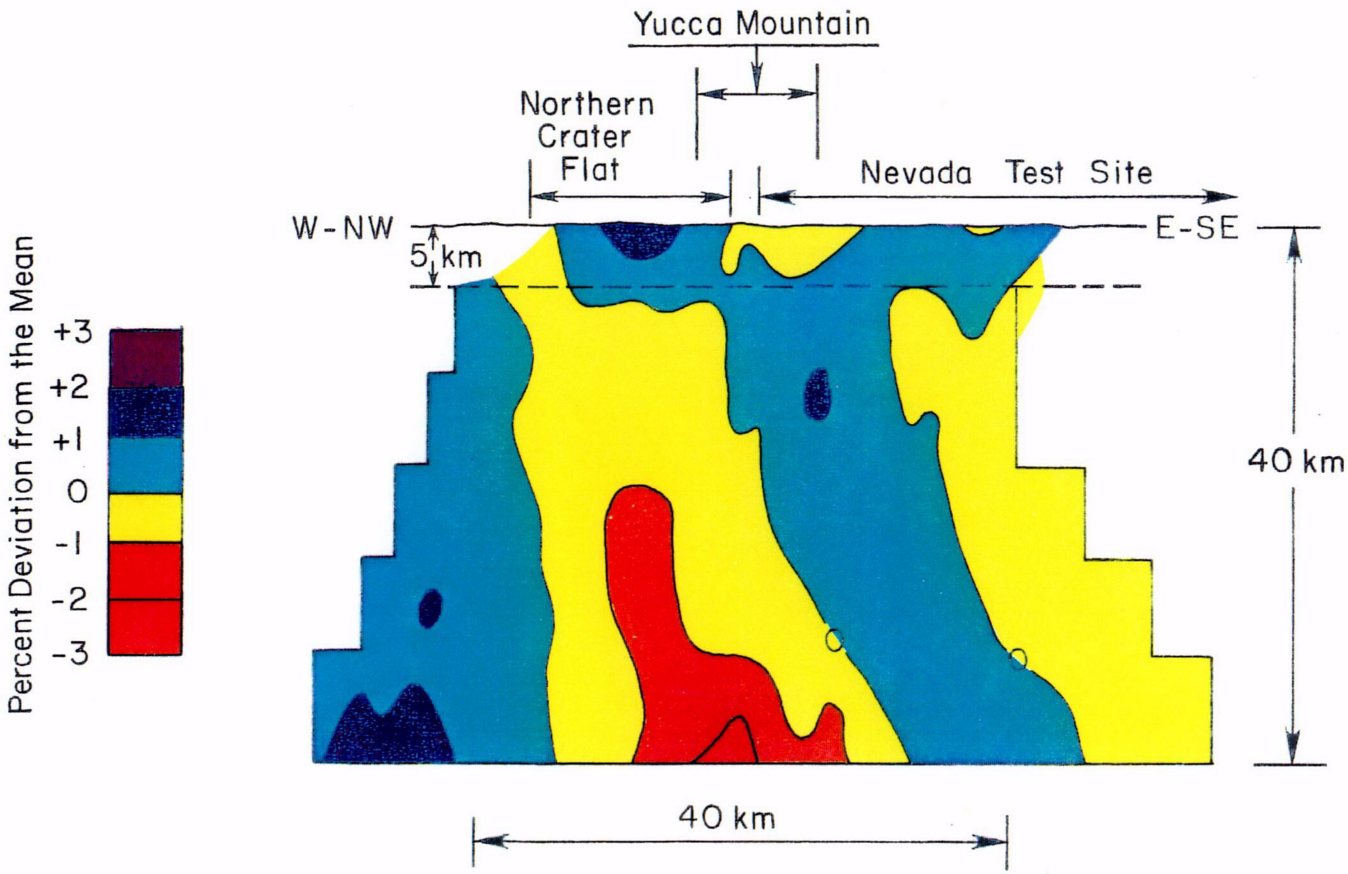


Figure 22. **Tomographic depth section** (profile CC") showing seismic velocity variations (in percent of deviation from the horizontally averaged mean) in the crust beneath and near Yucca Mountain. Velocity variations in the top 5 km are more uncertain than those at larger depths. The low velocity zone beneath Crater Flat and Yucca Mountain may represent crustal heating and a source of new volcanism. (From: Evans and Smith, USGS, 1992).