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REVIEW OF USGS OFR 92-516

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INTRODUCTION

Our subject is a report entitled: *Safety of Proposed Yucca Mountain Nuclear Repository as Regards Geological and Geophysical Factors: Evaluation of Minority Report by Archambeau and Price*, by Jack F. Evernden of the United States Geological Survey.

Controversy was inevitable when the DOE selected a seismically and volcanically active terrain as a candidate repository site for the nation's high-level radioactive waste. At the time, in the late seventies, earth scientists were only dimly aware of the geologic hazards. OFR 92-516 takes us back to a time when it was possible to believe that "the area is essentially tectonically dead" (p. 20), if one could possibly regard the young volcanic cones flanking Yucca Mountain to the west and south as dying gasps.

By the time the Nuclear Waste Policy Act was amended (1987), leaving Yucca Mountain as the only candidate for the repository, site investigations had produced diverse evidence conflicting with the notion of tectonic and hydrologic quiescence. Faults and travertine veins in the faults were found to be youthful, wholesale metasomatic alteration of the ignimbrite rocks of Yucca Mountain was documented, aberrant gradients in subsurface temperature and hydraulic potential were discovered, and rocks were found to fracture under the load of drilling fluids.

The scientist at DOE responsible for formulation and early resolution of potential licensing issues, J. S. Szymanski, grew apprehensive and challenged the notion of a quiescent steady-state description of the site. He proposed a conceptual model wherein

the hydrogeologic system, responding to a variety of tectonic processes and disturbances, can exhibit diverse behavior including discharge of upwelling fluids at the ground surface and inundation of the proposed repository horizon. Neither an internal peer group nor an external review panel convened by DOE resolved the controversy. The external review panel issued majority and minority reports, the latter being the subject of USGS OFR 92-516.

At the request of DOE, the National Academy of Sciences' National Research Council (NAS/NRC) established a Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain. The Panel issued a report in 1992 that again left the controversy unresolved. While committed to assessing the likelihood that the ground water level could rise to the level of the repository by any plausible geological process, the Panel did not consider a gamut of available geochemical data, and inappropriately discounted hydrothermal systems as a potential mechanism for raising the water table level in the Yucca Mountain area. Among the issues not considered by the Panel are: (a.) the origin of surficial breccia cements that exhibit hydrothermal mineralization and contain zircons with young fission-track annealing ages; (b.) the origin of young zeolites within and below the unsaturated zone; (c.) the occurrence in the vadose zone of calcite veins with high fluid inclusion temperatures and of interstitial fluids with hydrothermal mineralization signatures; (d.) the presence and origin of aberrant strontium isotopic ratios of surficial and subsurface calcites; and (e.) high paleogeothermal gradients reconstructed from oxygen isotopic data for calcites.

In response to a report detailing these issues, the President of NAS declined to question the NRC report's conclusions, based in part on their corroboration by USGS OFR 92-516. However, only two of the issues are addressed in OFR 92-516 (1.) the high paleogeothermal gradient reconstructed from calcite oxygen isotopic data and (2.) the aberrant strontium isotopic ratios of calcites. The oxygen isotopic data are dismissed, and the aberrant strontium isotopic ratios are listed as a remaining problem.

Under the misapprehension that Yucca Mountain is "essentially tectonically dead" (p. 20), the author of OFR 92-516 discounts the hydro-tectonic model by Szymanski (1989) in the following terms:

Of course, the trouble with this model is that all evidence re tectonic activity in the area is unequivocal in establishing the lack of any adequate tectonic activity over the past few million years. (p. 49)

The facts demonstrate otherwise, for example:

Extension in the Yucca Mountain area has been episodic, at times probably involving approximately concurrent slip on several faults and coeval volcanic eruptions in or near Crater Flat. Calcium carbonate and silica were locally deposited from ground water or meteoric water moving into and through fissures previously formed during faulting. Extensional episodes at Yucca Mountain during the late Pleistocene and Holocene apparently had an average period of not greater than 75,000 years. (Fox and Carr, 1989)

Reliance on outdated information would be less objectionable if the author of OFR 92-516 did not presume to represent the views of all scientists, for example:

Everybody who writes about the geological history of SW Nevada agrees that large scale tectonic activity essentially ceased 10-12 Ma ago. (p. 21)

The purpose of this review is to discuss significant data missing from OFR 92-516, so that misinformation does not cloud the controversy and does not contribute to elimination of the legitimate licensing issues and concerns from further consideration.

SAFETY AS EVALUATED BY OFR 92-516

OFR 92-516 represents Yucca Mountain as a site untrammelled by tectonic processes over the past several million years. Essential elements of this viewpoint include the following propositions.

1. Hazards posed by fault activity are negligible, given the "total lack of evidence of Holocene, or even Pleistocene scarps in the area" (p. 19).
2. Even in the event of a magnitude 7 earthquake the rupture "probably will not reach the surface" (p. 23) and disturb the vadose zone. Such an event could not cause significant hydrologic effects because "the physical phenomena associated with a magnitude 7 event in Nevada are those associated with a magnitude 6 event in western California" (p. 22), "putting the Nevada earthquake in a size range where no data of which I know indicate there to be changes in water flow in local streams at the time of the earthquake related to any process." (p. 57)
3. In any case, hydrologic disturbance of the vadose zone from below is prevented by the presence of an impermeable stratum of unfractured rocks, the Calico Hills tuffs, underlying the proposed repository horizon, so that "the mountain has been essentially sealed to upward vertical transport of water for the past 10 Ma." (p. 31)
4. Thermal disturbance of the geohydrologic regime at Yucca Mountain is out of the question because hydrothermal activity was "complete 10-11 Ma ago, with there being no evidence of later significant diagenetic alteration of the tuffs" (p. 29). "There are no available data that support the case for high temperature gradients

under Yucca Mountain in the last few million years." (p. 61)

This evaluation is wrong on all counts. Much of the missing data is documented in DOE reports, including the Site Characterization Plan. The following discussion of the relevant data is based mainly on these reports..

SEISMIC AND FAULT RUPTURE POTENTIAL

DOE (1988) documents Quaternary offsets along four faults in the immediate site vicinity (within 3 km): the Paintbrush Canyon, Bow Ridge (misnamed as Bow Spring in OFR 92-516, p. 21), Solitario Canyon, and Windy Wash faults. Of these faults, the Windy Wash has the most detailed displacement chronology. The apparent vertical offset of Pliocene basalts dated at 2.5-3.7 Ma is 40 meters (Ramelli et al., 1991). Four episodes of displacement over the past 270 ka have been documented, the youngest displaced stratum being a Holocene eolian silt dated by thermo-luminescence method at 3.0-6.5 ka (Whitney et al., 1986). Holocene offset has also been documented on the Solitario Canyon and Black Cone faults (Ramelli et al., 1991) using the radiocarbon accelerator mass spectrometry method.

In light of this data, there is only one obvious inference that can be drawn from these

OFR 92-516 remarks:

There is no reason I know of for hypothesizing the potentiality of even minor surface rupturing along this zone within the next 10,000 years. (p. 22)

...the faulting/earthquake threat along the west side of Yucca Mountain imagined in the Minority Report is nonexistent. (p. 22)

Though earthquakes with rupture lengths of a few tens of kilometers appear on

occasion to result in significant modification in spring and stream flow rates in the immediate area above the rupture, this fact has no bearing on expected events at Yucca Mountain there is no prospect of such an earthquake within the next 10,000 years. The argument used by Szymanski to support the case for such an earthquake within 100 years has no merit. (p. 20)

This inference is that, the author of OFR 92-516 is unfamiliar with the site-specific data which have direct relevance to evaluations of the seismic and fault rupture potentials. Having been familiar with such data, he may have concluded that; far from excluding the potentiality of minor surface rupturing, the evidence is, instead, indicative of distributive faulting characteristic of major earthquakes ($m \sim 7$). In that regard, for example, Ramelli et al. (1991) state:

Multiple lines of evidence suggest that recent surface faulting has involved concurrent rupture of multiple faults, and that surface faulting may accompany local basaltic volcanism. Evidence supporting this hypothesis include the high degree of fault interconnection, similarities in scarp morphology, similarities in ages and amounts of recent offset along multiple faults, and presence of basaltic ash within vertical fractures formed in fault-filling carbonate exposed in trenches across four faults.

The presence of basaltic ash within fault zone fractures is one of the stronger lines of evidence of concurrent rupture of multiple faults (Swadley et al., 1984; Fox and Carr, 1989; Shroba et al., 1990).

Because the ash-filled fissure in the Windy Wash fault cuts all surficial strata except the youngest, a Holocene silt, the ash probably came from an eruption of the Lathrop Wells volcanic center. The Lathrop Wells center, situated 15 km south of the proposed repository site, is the youngest basaltic cone in the area. Two separate Lathrop Wells basalt lavas have been dated by Turrin and Champion (1991) at 144 ± 35 and 183 ± 21 ka (arithmetic means of $^{40}\text{Ar}/^{39}\text{Ar}$ ages), and 119 ± 11 and 141 ± 10 ka (combined weighted means of K/Ar and Ar/Ar ages). Wells et al. (1990) infer that three additional

events have occurred within the past 20 ka, based on soil stratigraphy of eolian sand and silt containing tephra.

The fact that the volcanic ash found in fault-zone fissures is uncemented bears on the origin of carbonate-silica veins that are ubiquitous in the fault zones. It would appear that the supergene process involving rainwater, advocated in OFR 92-516, has not been operational at Yucca Mountain for many thousands of years. Likewise it would appear that the seismic event or events that produced the fissures did not cause groundwater discharge at the four trench sites sufficient to cement the volcanic ash. However, it is possible that groundwater was injected into the vadose zone at Yucca Mountain and precipitated vein calcites that have been dated by Szabo and Kyser (1985) using the uranium series method. Calcites with U-series ages in the range 100-200 ka were obtained from drill hole GU-3 at a depth of 63 meters and from drill hole G-2 at depths of 346.7, 348.7, 348.8 and 359 meters. Adjusted downward by 47% (Schlesinger, 1985) to take into account the alpha-recoil related effect, the ages are respectively 155, 129, 97, 116, and 126 ka, with standard errors of about 20 ka. Younger calcites with adjusted ages of 17 and 20 ka, and standard errors of a few ka, were obtained from drill hole GU-3 and depths of 131 and 331 meters. Thus, hydrologic disturbance of the vadose zone by the event or events associated with the fracture-fillings can not be discounted as being irrelevant to evaluating safety over the next 10 ka.

The distributive faulting evidenced at Yucca Mountain in the late Quaternary has a significant implication as to the maximum earthquake potential. dePolo et al. (1991)

documented the distribution of surface ruptures caused by 11 historic earthquakes in the Basin and Range. All nine events that ruptured multiple geometric or structural segments had magnitudes 6.8 and greater. In another study directed toward determining the highest magnitude of earthquakes not producing surface rupture, dePolo (1991) studied 21 historic Basin and Range earthquakes of magnitude 6 to 7 since 1920. The largest event that did not rupture the surface had magnitude 6.6. The historic record of Basin and Range earthquakes therefore indicates that (1.) at Yucca Mountain, the magnitude of largest late Quaternary earthquake was 6.8 or greater and (2.) all earthquakes of magnitude greater than 6.6 can be expected to produce surface rupture.

POTENTIAL GEOHYDROLOGIC EFFECTS OF CREDIBLE SEISMIC EVENTS

OFR 92-516 misconceives the hydrologic effects of earthquakes, principally in the belief that water can be discharged only from the very shallow crust. This misconception accounts for repeated assertions as to the absence of tectonic stress, and invulnerability to stress change, of the shallow crust. For example, "Yucca Mountain and the depths immediately below are not at measurable tectonic stress" (p. 20) and "any typical Nevada earthquake of magnitude 7 at normal depths will be associated with insignificant stress changes at or within a few kilometers of the surface" (p. 24). These assertions, aside from being false, are misdirected in terms of the phenomena involved in producing water outflows from the source zones of large normal-faulting earthquakes in the Basin and Range.

As stated in the Minority Report, a large part of the volumetric strain associated with a normal-faulting event involves the closure of fractures to considerable depth, at least 5 km, and expulsion of water. The results reported by Wood and King (1992) for the 1959 Hebgen Lake and 1983 Borah Peak earthquakes have no alternative explanation. The events, of magnitude 7.3 and 7.0 respectively, produced within a year outflows of 0.5 and 0.3 km³. These outflow volumes are commensurate with crustal volume strains causing water to be expelled from depths of at least 5 km, and are comparable with the storage capacity of a large water impoundment reservoir.

Outflows of similar scale are inferred from qualitative information (Wood & King, 1992) to have occurred following other major normal-faulting earthquakes in the Basin and Range (the 1982 Sonora, 1915 Pleasant Valley, and 1954 Dixie Valley events) and in the Apennine Chain in Italy. Normal fault earthquakes of lesser magnitude in the Basin and Range have also produced widespread increases in groundwater elevations and outflows. Among these are the 1901 Milford, UT, 1925 Helena, MT, 1933 southern Utah, 1934 Hansel Valley, UT, and 1935 Helena, MT earthquakes (Wood & King, 1992). These events, with magnitudes in the range 6 to 6.6, did not produce primary surface rupture, and only one, the magnitude 6.6 Hansel Valley earthquake, produced secondary rupture (de Polo, 1991).

Outflow of water caused by release of upper crustal strain, as documented for the Hebgen Lake and Borah Peak events, appears to be characteristic of normal-faulting earthquakes. This phenomenon is very likely responsible for the extraordinarily

prolonged and prolific aftershock sequences that are characteristic of the Basin and Range, for example, the aftershock sequence of the 1915 Pleasant Valley earthquake is still in progress. Similarly, earthquake-induced effects on groundwater are likely responsible for the prolific aftershock sequence of the magnitude 5.6 earthquake of June 29, 1992 at Little Skull Mountain, located 20 km southeast of the proposed repository.

In terms of quantitative evaluation of hydrologic effects based on empirical data, the evidence is unequivocal in placing recent paleoseismicity at Yucca Mountain in the same category as the Hebgen Lake and Borah Peak earthquakes, i.e. events producing distributive normal faulting at the surface. For both of the historic events, the outflow was equivalent to the earthquake-induced volumetric strain accumulated to a depth of 5 km. There is no reason to believe that this would not be the case at Yucca Mountain. For Yucca Mountain, where the vadose zone is 0.5 km deep and the proposed repository is 0.3 km deep, the issue is the effect of the outflow into the vadose zone.

OFR 92-516 offers three lines of defense against the possibility of repository flooding. First, the presence of an impermeable, unfractured stratum of rocks, the Calico Hills tuffs, underlying the proposed repository horizon, would divert upwelling water away from the vadose zone. The plausibility of this notion is evaluated later. Second, "the earthquake required to make such deeply derived flow credible in any minds has no possibility of occurrence within the next 10,000 years" (p. 22), a statement that is in sharp conflict with the paleoseismicity of the site. Third, even if a magnitude 7

earthquake were to occur, the rupture "probably will not reach the surface" (p. 23), and "the physical phenomena associated with a magnitude 7 event in Nevada are those associated with a magnitude 6 event in western California, an inadequate event as regards the phenomena of importance to the Minority Report" (p. 22). This third line of defense betrays a remarkable misunderstanding of the problem.

To begin with, absence of surface rupture associated with a magnitude 7 event in the Basin and Range would be unprecedented. As noted above, all historic events of magnitude greater than 6.6 have produced surface rupture, and all nine events of magnitude 6.8 and greater have caused rupture of multiple faults. However, these observations are not considered by the author of OFR 92-516, who chooses to estimate rupture length by working backward from the seismic intensity distributions of historic earthquakes, a scheme ill-suited to a sparsely-populated area with plentiful scarps of past earthquake ruptures. Using this scheme, the author obtains Modified Mercalli Intensity 6.3 (threshold of architectural damage) at Yucca Mountain for a magnitude 7 earthquake directly below (p. 25). This result is discordant with the fact that the magnitude 5.6 Little Skull Mountain earthquake of June 29, 1992 produced structural damage (Intensity VIII) to DOE's Field Operations Center of the Yucca Mountain Project, a building on NTS located a few km from the earthquake epicenter.

In regard to documented hydrologic effects, the author's comparison of a magnitude 7 event in Nevada with a magnitude 6 event in western California would be appropriate if the events were interchanged. As noted by Wood and King (1992) "Strike-slip, and

oblique-slip fault movements are associated with a mixture of responses but appear to release no more than 10% the water-volume of the same sized normal fault event." Evidence supporting this conclusion includes the observation of a discharge of only 0.025 km³ of water following the magnitude 7.5 oblique thrust earthquake in Kern County in 1952, as compared with 0.5 and 0.3 km³ recorded for the normal-faulting events at Hebgen Lake and Borah Peak. The observed mechanism-dependence of post-seismic hydrologic effects confirms the volumetric-strain model of Wood and King (1992).

If it were true, as claimed by OFR 92-516 (p. 22), that rupture lengths of Nevada earthquakes are five times shorter than those of western California events of the same magnitude, this would make matters even worse for the proposed repository because the outflow of water would have much greater spatial concentration. Allowing that down-dip widths of normal ruptures in the Basin and Range are about twice the rupture widths of western California earthquakes, the fault displacement of the Nevada event would be 2.5 times greater than for a western California earthquake of the same moment, and the volumetric strain, and hence, water outflow from the source zone would be correspondingly more concentrated.

PROPERTIES OF THE CALICO HILLS TUFFS

OFR 92-516 calls upon the Calico Hills tuffs to seal the vadose zone against upward flow of groundwater resulting from a tectonic event (seismic and/or thermal). The sealing quality of the Calico Hills tuffs is deduced from water yield as a function of depth

in well UE-25p#1 (p. 29), and the statement that calcite is absent from the zeolitized tuffs of Calico Hills (p. 30). The latter statement does not appear to be true, as calcite is reported to occur in the Calico Hills, for example at a depth of 468.6 meters in drillhole USW G-3 (Bish and Chipera, 1989).

Fracture frequencies have been measured for the Calico Hills tuffs both at the surface, where they outcrop at Prow Pass, and in drillholes USW-G-1, USW G-3, USW G-4, and UE-25a#1 (DOE, 1988, P. 1-36). Fracture frequencies were found to be 1.2 per cubic meter at Prow Pass, and from 0.2 to 2 per cubic meter in the drillholes. While these fracture frequencies are several times lower than in other tuffs, the Calico Hills tuffs can not be described accurately as fracture-free.

Stock et al. (1985) show televiewer images of examples of fractures in the Calico Hills tuffs in drillhole USW G-2, both steeply dipping subparallel fractures in the interval 594.4-602.0 meters and shallowly dipping fractures in the interval 609.3-617.2 meters. Images of drilling-induced hydrofractures are shown for the interval 660-668 meters: these are very high angle, nonthroughgoing fractures that are prominent in the depth interval 526-678 meters. Stock et al. describe these as "an echelon subparallel fractures merging into one another along a strike of N25°E to N30°E" and infer that the axis of minimum compressive stress is oriented N60°W. These are interpreted as drilling-induced hydrofractures because some of the corresponding core sections are unfractured. While stress measurements in this section were not conducted because of the complete loss of circulation, results obtained nearby show that "the measured stresses at Yucca Mountain are near the limit of those required to cause slip on

favorably oriented pre-existing faults" (Stock et al., 1985). The loss of drilling fluid into opening fractures in the Calico Hills tuffs is inauspicious for a formation regarded as an impermeable seal.

From the characterization of the Calico Hills tuffs as "a zone essentially impermeable to upward movement of groundwater from depth" (p. 30), one might expect temperature gradients in the Calico Hills tuffs to be free of the aberrations afflicting geotherms in other ignimbrite formations, however, this is not the case. Eight geotherms measured by Sass et al. (1988) over a 2.5 year interval in drillhole USW G-2 show that the lower Calico Hill tuffs, in the depth range 620 to 800 meters, are essentially isothermal at 32°C. Above the Calico Hills tuffs there is a modest geothermal gradient and the conductive heat flow is 44 mW/m². Below the Calico Hills tuffs the geothermal gradient is much steeper, and the conductive heat flow is 71 mW/m².

No unique interpretation of the USW G-2 geotherm is offered by Sass et al. (1988). In one case, the difference in heat flow between the unsaturated and saturated zones is attributed to downward percolation of groundwater at 20 mm/year. In another case, the high geothermal gradient at depth is explained as a transient chilling effect of water moving vertically downward through the isothermal lower part of the Calico Hills tuffs, or moving laterally with a downward component of velocity. In any case, water is moving through the Calico Hills tuffs.

The direction of water flow is important to the case in OFR 92-516 because the author

claims that the Calico Hills tuffs are impermeable only to upward vertical flow of water (p. 30-31). A novel current-rectifying quality is attributed to the permeability. Downward vertical flow of water is needed to explain the crystallization of "pedogenic" carbonates, those with low concentrations of carbon-13, found 300 meters below the present water table in drillhole USW G-4. According to OFR 92-516, during a "transient lowering of the WT" (p. 36), rainwater with the right dissolved constituents percolated vertically downward through the Calico Hills tuffs and crystallized calcites in veins in the underlying Crater Flat tuffs.

Fortunately, there is an alternative and much less demanding explanation for the carbon isotopic characteristics of calcite-silica veins present hundreds of meters below the present water table, namely the source of the carbon isotopically "light" is igneous CO₂. This explanation can also account for the carbon-13 depleted calcites in the vadose zone, the high homogenization temperatures of fluid inclusions contained therein, and the texture and mineralization of breccias, described by Hansen et al. (1987) as "hydrothermal eruption breccias" found in fault zones at Yucca Mountain.

Within the Calico Hills tuffs there are zeolites whose presence is inexplicable in the framework of the notion that "the mountain has been essentially sealed to upward vertical transport of water for the past 10 Ma" (OFR 92-516, p. 31). Potassium-argon ages have been obtained for six clinoptilolites from the Calico Hills tuffs, and these range from 1.99 to 4.64 Ma (WoldeGabriel, 1991). The clinoptilolites bear evidence of recent flow of hot (50-100°C) alkali-earth solutions through the Calico Hills tuffs. Five of

the dated samples are from the vadose zone in drillholes USW G-1, USW G-2, and USW G-4, and the sixth was obtained more than 200 meters below the water table in drillhole USW G-2. It is perplexing that OFR 92-516 makes mention of K/Ar ages of illites (10.9 ± 0.6 Ma) from drillholes USW G-1 and USW G-2 without mentioning the clinoptilolite ages, particularly because WoldeGabriel (1991) reports ages both for illites and clinoptilolites from USW G-2. After citing the illite ages, OFR 92-516 claims that "No available data suggest a later period of elevated temperature and associated diagenesis" (p. 28) referring to the Timber Mountain hydrothermal episode 10 Ma ago. This statement can not be supported in terms of the rules of evidence traditionally applied in the licensing of nuclear facilities in the United States. Further, the term "diagenesis" does not properly characterize the post-Timber Mountain alkali-earth metasomatic alteration of Yucca Mountain.

PALEOGEOTHERMOMETRY AND MINERALIZATION OF THE VADOSE ZONE

OFR 92-516 treats paleogeothermal data on Yucca Mountain in much the same way as it treats the paleoseismic data, by flat denial:

There are no available data that support the case for high temperature gradients under Yucca Mountain in the last few million years. (p. 61)

The presence of young zeolites within and below the vadose zone is just one of several lines of evidence for high temperature gradients in the last few million years. Unlike the alkali zeolitization of the Timber Mountain hydrothermal episode, the younger zeolitization represents alkali earth metasomatic alteration. This can be ascertained by comparing zeolite and whole-rock chemistry with that of the original glass. The data, in

Table 1, from Broxton et al. (1986), are for the sample containing the clinoptilolite dated at 4.64 Ma, discussed previously, from the Calico Hills tuffs at a depth of 740 meters in drillhole USW G-2.

Table 1

	<u>Weight Percent</u>			
	MgO	CaO	Na₂O	K₂O
Glass, Calico Hills (25 samples)	< .01	0.48 ±.05	3.29 ±.13	5.14 ±.23
Whole-Rock, USW G-2 2430	0.41	1.98	1.68	3.95
Clinoptilolite, USW G-2 2430	0.36 0.31	2.77 3.08	0.64 0.72	2.81 2.71

The high degree of exchange of alkali earth for alkali elements shows that the alteration is metasomatic, not diagenetic. Another important difference between the young alkali-earth zeolitization and the alkali Timber Mountain zeolitization, which is pervasive throughout the lower part of the stratigraphic section, is that it occurs in aureoles around fractures in the upper part of the stratigraphic section. The alkali-earth zeolitization is not uniform spatially: it is shallower to the northwest and deeper to the southeast of Yucca Mountain. Szymanski (1992) has pointed out the conceptual difficulties involved in explaining this space-differential alkali-earth metasomatism in terms of the downward percolation of rainwater. Instead, he explains this fracture-based alteration in terms of tectonic events on the Stagecoach Road fault, whose trace lies a few kilometers

southeast of the proposed repository, and which is regarded as the master fault of a system that includes the Paintbrush Canyon, Bow Ridge, Ghost Dance, Solitario Canyon, and Windy Wash faults. Contrary to the claims of OFR 92-516, there is overwhelming evidence of episodic post-Timber Mountain metasomatic alteration of tuffs within and below the vadose zone. The evidence for post-Timber Mountain alkali-earth metasomatism can not be dismissed lightly as supergene in origin because it comprises countless millions of tons of rocks at Yucca Mountain.

Further evidence of elevated temperatures subsequent to the Timber Mountain hydrothermal episode has been obtained from fission-track ages of zircons found in breccia cements at Trench #14 and at Busted Butte, within the Bow Ridge and Paintbrush Canyon faults, respectively. The zircon ages date the most recent annealing of fission tracks, at temperatures above about 200°C, and establish upper bounds on the breccia ages. Levy and Naeser (1991) reported ages for twelve zircon crystals in samples from each of the two fault zones, and concluded:

The spread of ages from each samples 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.

The most recent annealing of fission tracks in zircons may have been caused by hydrothermal solutions that produced the post-Timber Mountain alkali earth zeolitization and carbonatization of Yucca Mountain. This inference is supported by the results of mineral assays of Trench #14 breccias (Weiss et al., 1990) showing significant enrichment in base and noble metals relative to the stratigraphically equivalent background.

The third set of paleogeothermal data missing from OFR 92-516 are homogenization temperatures of fluid inclusions in vein calcites from drill cores. In drillhole USW G-3, homogenization temperatures exceeding 100°C were obtained for calcites from depths of 31 and 131 meters (Bish, 1989). Although Bish suggested that these inclusions probably formed during initial deposition or cooling of the tuffs, this seems unlikely in view of young uranium-series ages obtained for nearby calcite specimens in USW G-3. Ages reported by Szabo and Kyser (1985) for specimens obtained at depths of 19, 40, 97 and 101 meters are 227 ± 20 , 26 ± 2 , >400 , and 30 ± 4 ka, respectively.

The fourth set of paleogeothermal data missing from OFR 92-516 are the results of chemical analyses of intersitial fluids from the Yucca Mountain vadose zone. Samples of water residing in pore space have been separated from volcanic rock cores from two shallow dry-drilled boreholes in the unsaturated zone (the rock above the water table where the repository would be situated) (Smith, 1991). Chemical analysis of water shows that it is mineral water, which welled up from the carbonates and other Precambrian rocks underlying the volcanics (Szymanski, 1992). Mineral enrichment of this water, relative to water residing in fractures in volcanic rocks below the water table, is illustrated in Figure 11 of Somerville et al., (1992). This water resembles water residing in carbonate fractures, as indicated by the ten-fold enrichment of calcium and magnesium. The enrichment in trace elements, including the rare earth elements and base and noble metals, indicates a hydrothermal source. In addition to the overall enrichment in rare earth elements (REE), there is an unusual enrichment of heavy REE relative to light REE (Smith, 1991). In contrast, the host volcanics have the usual

relative enrichment of light REE (Scott and Castellanos, 1984). Enrichment of heavy REE is observed for hydrothermal solutions that are concentrated and rich in carbon dioxide. The heavy REE enrichment mechanism is believed to involve carbonate anion complexing. This observation supports the interpretation of the role of CO₂ in forming the mosaic breccias. Infiltrating rainwater cannot explain either the enrichment of trace elements or the enrichments of REE found in the interstitial fluids above the water table. The only reasonable explanation is that the interstitial fluids are remnants from the previous invasion(s) of the repository horizon by waters of hydrothermal origin.

Finally, the only paleogeothermal results considered in OFR 92-516 are rejected by the author. The results are oxygen isotope data for calcites, reported by Whelan and Stuckless (1992), which they interpret in terms of a minimum paleogeothermal gradient of 34°C/km. This is approximately 50% higher than the present-day gradients of 18-24°C/km measured by Sass et al. (1988) in the drillholes yielding the calcites analyzed for oxygen isotopes. The author of OFR-92-516, to his credit, perceives the difficulty in reconciling the high paleogradient obtained from the calcites with the belief that they crystallized from infiltrating rainwater. However, it is difficult to accept his solution to the dilemma, namely to reject the paleogradient results:

Thus, the overall suggested interpretation given by Whelan and Stuckless must almost certainly be wrong. (p. 37)

One rationale given for rejecting the paleogradient results consists of (1.) removing from consideration calcites more than 200 meters below the water table by assuming that they are 10.5 million years old and therefore unrelated to the recent carbonatization of Yucca Mountain and (2.) stating that there are then too few remaining data to resolve

the paleogradient at shallower depths. A second rationale given for discounting the significance of the 34°C/km paleogradient is its presumed transience:

The persistence of such a high gradient seems doubtful as the normal gradient in the Basin and Range area is only 20°C/km. (p. 37)

The problem with this statement is that it does not distinguish correctly between normal and aberrant temperature gradients in the Basin and Range. The paleogradient of 34°C/km is normal for the Basin and Range (DOE, 1988), while the present-day gradient of about 20°C/km at Yucca Mountain is abnormally low, constituting a pronounced anomaly of conductive heat flow (Sass et al., 1988). To rephrase the OFR 92-516 statement:

The persistence of such a low gradient seems doubtful as the normal gradient in the Basin and Range is 30-40°C/km. (p. 37)

It is precisely the transience of the thermal regime, and the hydrologic and stress regimes, that prompts concern about the suitability of the Yucca Mountain site to safely accommodate a high level nuclear waste repository, Szymanski (1989) and Archambeau and Price (1991).

STRONTIUM ISOTOPIC RATIOS

The first of the two issues that OFR 92-516 lists as remaining problems is the strontium isotopic ratio of calcites in Trench #14. This problem is listed as "source of dust" (p. 63), with the premise being that the calcites crystallized from rainwater that had dissolved calcereous dust, presumably derived from the local Paleozoic carbonates. The difficulty is to explain the crystallization of calcites with a strontium isotopic ratio ($^{87}\text{Sr}/^{86}\text{Sr}$) of 0.7125 from rainwater that has dissolved Paleozoic carbonates with a strontium isotopic ratio of 0.709. The problem as posed by OFR 92-516 is to discover an "atmospheric"

"process" that solves this isotopic discord. OFR 92-516 is correct in identifying Precambrian material as the missing ingredient. The problem is the availability of the "Precambrian dust thrown in for good measure" (p. 64).

This problem vanishes if, instead of appealing to the atmosphere for the source of strontium, one appeals directly to the source in the Precambrian basement underlying Yucca Mountain. This, of course, involves accepting a hypogene origin of the calcites.

GRADIENT OF HYDRAULIC POTENTIAL

The second issue that OFR 92-516 lists as a remaining problem is the potentiometric gradient in northern Yucca Mountain, where the water table rises some 300 meters in elevation between drillholes USW G-1 and G-2. The author frankly admits his inability to contribute to the resolution of the problem. It seems unlikely that the problem can be resolved in the framework of the author's "tectonically dead" model of Yucca Mountain. The prospects of resolution are better if one admits inhomogeneous tectonic strain accumulation (Szymanski, 1989).

CONCLUSION

While this review has not covered all the points made in OFR 92-516, it has addressed several of the topics on which the author asserts his strongest convictions, reinforced by repetition. As we have seen, these convictions are at variance with the relevant data compiled by DOE (1988) and other project documents. Concerns as to site suitability, as expressed in both the Minority Report and the report to the President of NAS, are in

no way allayed by OFR 92-516. On the contrary, the revisionism of OFR 92-516 relative to project data causes yet graver concern, as does the National Research Council's use of OFR 92-516 in its attempt to dismiss the Minority Report and to defend its own report, *Ground Water at Yucca Mountain: How High Can It Rise?*

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