Title
Response to "Analysis of the Treatment, by the U.S. Department of Energy, of the FEP Hydrothermal Activity in the Yucca Mountain Performance Assessment" by Yuri Dublyansky

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Response to "Analysis of the Treatment, by the U.S. Department of Energy, of the FEP Hydrothermal Activity in the Yucca Mountain Performance Assessment" by Yuri Dublyansky (Risk Analysis, Volume 27, Issue 6, Pages 1455–1468, December 2007)

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Abstract

This paper presents a rebuttal to Dublyansky (2007), which misrepresents technical issues associated with hydrothermal activity at the proposed Yucca Mountain nuclear waste repository and their importance to the long-term performance of the repository. In this paper, questions associated with hydrothermal activity are reviewed and the justification for exclusion of hydrothermal activity from performance assessment is presented. The hypothesis that hydrothermal upwelling into the present-day unsaturated zone has occurred at Yucca Mountain is refuted by the unambiguous evidence that secondary minerals and fluid inclusions in the unsaturated zone formed in an unsaturated environment from downward percolating meteoric waters. The thermal history at Yucca Mountain, inferred from fluid inclusion and isotopic data, is explained in terms of the tectonic extensional environment and associated silicic magmatism. The waning of tectonic extension over millions of years has led to the present-day heat flux in the Yucca Mountain region that is below average for the Great Basin. The long time scales of tectonic processes are such that any effects of a resumption of extension or silicic

magmatism on hydrothermal activity at Yucca Mountain over the 10,000-year regulatory period would be negligible. The conclusion that hydrothermal activity was incorrectly excluded from performance assessment as asserted in Dublyansky (2007) is contradicted by the available technical and regulatory information.

Introduction

The subject paper named above misrepresents technical issues associated with hydrothermal activity at the proposed Yucca Mountain nuclear waste repository and their importance to the long-term performance of the repository. The paper describes purported inadequacies in analyses presented in early versions of technical reports prepared by the repository program, and in the *Yucca Mountain Science and Engineering Report* prepared for the Yucca Mountain site recommendation (DOE, 2001). The response below shows that the conclusions of the subject paper are not consistent with the available technical and regulatory information.

The potential for upwelling waters at Yucca Mountain in the next 10,000 years has been the subject of several investigations (as examples: Quade and Cerling, 1990; Stuckless et al., 1991; Vaniman et al., 1994; and Whelan et al., 2002). A previous exchange on the origin of secondary minerals from the unsaturated zone and from near-surface deposits near Yucca Mountain is documented in the literature (Hill et al., 1995; Stuckless et al., 1998; Hill and Dublyansky, 1999). The origin of near-surface deposits was also considered by an independent, expert peer review (National Research Council, 1992), which found little technical merit in the idea of upwelling waters at Yucca Mountain.

More recently, the interpretation of fluid inclusion data as evidence for hydrothermal activity in the geologic past was investigated in a research program funded by the U.S. Department of Energy that was supported by scientists from the University of Nevada and other institutions (Wilson et al., 2003). The results continue to show no evidence for upwelling fluids of hydrothermal origin in the unsaturated zone at Yucca Mountain.

Dr. Dublyansky states that the repository risk assessment "…must be based on a thorough understanding of the relevant processes that may affect repository performance and on site-specific information…" (Dublyansky, 2007, Section 1), but does not discuss the regulatory and technical understanding that must be used to determine which processes are included in the quantitative risk assessment. While a thorough understanding of the relevant processes that may affect repository performance is certainly needed, there is not a requirement for a mathematical model of all historical geological events and processes that have occurred at Yucca Mountain for millions of years (NRC, 2003, p. A-4). Rather, the risk assessment focuses on those features, events, and processes (FEPs) that have may have a significant impact on the future performance of the repository. After thorough evaluation, the resumption of hydrothermal activity at Yucca Mountain was excluded from the risk assessment on the basis that it would not significantly change estimates of the future performance of the repository (DOE, 2008, Table 2.2-1; SNL, 2008a, FEP 1.2.06.00.0A; 10 CFR 63.113).

Each of these points and supporting information is addressed in more detail in the following sections. These sections are organized around: (1) description of the hydrothermal activity process that was excluded from performance assessment, (2) justification for exclusion, (3) evidence for the downward movement of water through Yucca Mountain, and (4) discussion of the thermal history of Yucca Mountain.

The Hydrothermal Activity FEP

Postclosure risk assessment for the Yucca Mountain repository relies on systematic screening of features, events, and processes (FEPs) to determine which need to be included in the assessment. The analysis of FEPs for Yucca Mountain performance assessment (SNL, 2008a) is the culmination of years of development, and is now available in one volume that supersedes numerous previous reports and revisions. The screening criteria for FEPs are taken directly from the controlling regulation (10 CFR part 63), and allow exclusion of FEPs that are either very unlikely or that would have little or no impact on overall performance. Specifically, a FEP can be excluded from the analysis if it has less than one chance in 10,000 of occurring within 10,000 years. A FEP can also be excluded on the basis of low consequence if there is sufficient evidence that the magnitude and timing of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment, are not significantly changed by its omission.

The hydrothermal activity FEP (SNL, 2008a, FEP 1.2.06.00.0A) is defined as follows: "Naturally occurring high-temperature groundwater may induce hydrothermal alteration of minerals in the rocks through which the high-temperature groundwater flows." As Dr. Dublyansky notes (Dublyansky, 2007, Section 3.1), until 2004 the Yucca Mountain Project's FEP definition included reference to density-driven groundwater flow; however, that is only one process that could drive hydrothermal activity. (Deep groundwater circulation can also be driven by elevation differences at recharge and discharge locations.) Density-driven groundwater flow was deleted in order to emphasize the effects from hydrothermal activity without specifying a hydrogeologic mechanism as the cause of the activity. Justification for exclusion of this FEP was provided by SNL (2008a, FEP 1.2.06.00.0A) including multiple lines of reasoning, and without relying solely or principally on mathematical simulations of the thermal history of Yucca Mountain. Although the FEP description could be interpreted to limit the FEP to hydrothermal mineral alteration, the exclusion justification (SNL 2008a, FEP 1.2.06.00.0A) goes well beyond that to discuss the geological evidence for the thermal history of Yucca Mountain, as well as the origin of secondary minerals and the inferences that may be made from their origins. Thus, the FEP exclusion justification uses a broader interpretation than implied by the subject paper (Dublyansky, 2007, Section 3.1) and addresses all aspects of the FEP that are relevant to repository performance.

Justification for Exclusion of the Hydrothermal Activity FEP

Justification for excluding the hydrothermal activity FEP (SNL, 2008a, FEP 1.2.06.00.0A) is based on: (1) the current state of the unsaturated and saturated zones at Yucca Mountain; (2) interpretation of geologic evidence of past hydrothermal activity; (3) characteristic spatial and temporal scales associated with significant future hydrothermal activity; and (4) indications from fracture mineral analyses of downward moving waters, both from external peer review and results from follow-up investigations by university scientists. Both nonmagmatic and magmatic types of igneous activity are considered as potential sources of heat for hydrothermal processes. There is no “crucially important" assumption concerning a link between hydrothermal activity and silicic magmatism, as asserted in the subject paper (Dublyansky, 2007, Section 6.3).

Hydrothermal activity associated with nonmagmatic heat sources is common in the Basin and Range province, which includes nearly all of Nevada and portions of adjoining states (DOE 2001, Figure 1-7). These hydrothermal systems are strongly correlated with regional heat flow in excess of 80 mW/m^2 (Blackwell et al., 2003, Section 2.3), although other system parameters, particularly permeability, are also important for the development of hydrothermal systems (Blackwell et al., 2003, Section 7). Measured heat flux in the unsaturated zone at Yucca Mountain is on the order of 40 mW/m^2 or less, substantially below 80 mW/m^2, and the typical heat flow of 85 mW/m^2 that is characteristic of the Basin and Range province (Sass et al., 1988, p. 3).

Circulation of hydrothermal waters beneath Yucca Mountain would not result in significant temperature changes in the repository area in 10,000 years, which can be demonstrated by a simple one-dimensional calculation. Hydrothermal systems have been shown to circulate to typical depths of approximately 4 km or greater (Blackwell et al., 2000, p. 30) and localized, high heat-flow areas of the Basin and Range province have rates in excess of 120 mW/m^2 (Flynn et al. 1996, p. 11). Using rock heat capacity of approximately 1,000 J/kg-K, bulk rock density of approximately 2,000 kg/m^3, and a local average heat flux of 200 mW/m^2, the time required to heat a 4 km thick column of rock representing a conduit for hydrothermal upwelling by 10 degrees Celsius can be computed (SNL, 2008a, FEP 1.2.06.00.0A). The result is more than 10,000 years, or longer if heat dissipates laterally. Thus the thermal expression of hydrothermal systems takes a long time to develop, compared to the 10,000-year performance period for the repository. This time scale is comparable to results from simulations of transient geothermal systems in the Basin and Range (McKenna and Blackwell, 2004, Figure 8). Repository temperatures are predicted to be in the range 25ºC to 60ºC at 10,000 years as a result of waste-generated heat (SNL, 2008b, Figure 6.3-76[a]). A temperature rise of 10ºC would have a negligible influence on repository temperatures; therefore, the effects on radionuclide transport in 10,000 years resulting from future hydrothermal activity caused by nonmagmatic heating are expected to be negligible (SNL, 2008a, FEP 1.2.06.00.0A).

The FEP exclusion justification reviews the history and effects from silicic magmatism that formed the tuffs of Yucca Mountain, and related eruptions that occurred during the Miocene epoch. Silicic magmatic activity and eruptions in the region coincided with a major period of crustal extension that occurred between approximately 14 and 9 Ma (Sawyer et al. 1994, Figure 4). The southwestern Nevada volcanic field, which includes Yucca Mountain, ceased silicic eruptive activity with the formation of the Black Mountain caldera about 9 Ma (Sawyer et al., 1994). A later, more distant episode of silicic magmatism produced the Stonewall Mountain volcanic center about 7.4 Ma (BSC 2004a, Section 6.2).

The Timber Mountain caldera (11 to 10.5 Ma) is near Yucca Mountain and represents the last significant heating event for the site (Whelan et al., 2008, Section 6.3). The Timber Mountain event produced peak fluid-inclusion homogenization temperatures near 90ºC, occurring at more than 9 Ma (Whelan et al., 2008, Figure 8 and Table 4).

The current FEP exclusion justification reviews the geologic evidence for hydrothermal activity at Yucca Mountain, including thermal history information derived from fluid-inclusion and isotopic characteristics of fracture mineral coatings. The available evidence consists of: (1) stable-oxygen isotopic analyses of fracture-lining calcite, which indicate temperature of mineral formation; (2) homogenization temperatures for fluid inclusions, which indicate the temperatures at which the fluids were trapped; and (3) uranium and lead isotope ratios in opal associated with calcite (Whelan et al., 2008, Section 5.2.2 and Figure 8), which constrain the ages of deposited minerals. All together, these data show that temperatures in the unsaturated zone decreased over time from approximately 90ºC at 9 Ma or earlier, to near-ambient at approximately 2 Ma. As reported by DOE (2001, p. 4–402) fluid inclusion temperatures for all but the earliest calcites range from 35° to 75°C, and most of these temperatures were determined for calcite that is clearly older than 4 to 5.3 million years. The chemical composition of calcite changed between 2.8 and 1.9 million years ago to include a few percent magnesium, and this calcite lacks two-phase inclusions, thereby indicating precipitation at ambient temperatures (Wilson et al. 2003).

Additional evidence of elevated paleo-temperatures at Yucca Mountain comes from observations of thick-twinned calcite in older, minor faults intercepted in the exploratory tunnels at Yucca Mountain (Gray et al., 2005). Whereas such twinning indicates elevated secondary formation temperatures, estimated to be above 170ºC (Ferrill et al., 2004), these samples may have resulted from much earlier, higher-temperature activity associated with emplacement and devitrification of the tuffs. Gray et al. (2005) note that such twinning was not observed in the more recent block-bounding faults, which would be good candidate pathways if water upwelling were to occur. A general absence of indications of hydrothermal mineralization in the Yucca Mountain tuffs indicates that large-scale hydrothermal activity has not occurred.

Basaltic volcanism commenced during the period of silicic magmatic activity and has been declining since about 7 Ma. Small-volume intrusive and extrusive basaltic events continued into the Quaternary, and this is considered the only plausible type of igneous activity that could affect the repository. Although basaltic volcanism could occur at Yucca Mountain during the next 10,000 years, the associated hydrothermal effects would be limited in scale and duration, as shown by natural analogue observations (SNL, 2008a, FEP: 1.2.04.02.0A). The effect from hydrothermal activity associated with basaltic volcanism on radionuclide transport in the unsaturated and saturated zones at Yucca Mountain is therefore expected to be negligible.

Supporting Evidence for Downward Moving Waters

Secondary minerals sampled from the unsaturated zone near Yucca Mountain resulted from downward percolating meteoric waters and not from upwelling groundwaters (Wilson et al., 2003, Sections 7.3 and 8; National Research Council, 1992, p. 3). Evidence for precipitation in vadose conditions includes: (1) only 1% to 40% of the lithophysal cavities are mineralized with calcite and opal coatings in a given area, whereas precipitation in a saturated environment would predict that most, if not all sites would be mineralized (Marshall et al., 2003, Section 2); (2) mineralization is restricted to the floors of cavities and footwalls of fractures (Marshall et al., 2003); (3) the fluid inclusion assemblage of all liquid, all vapor, and liquid and vapor in variable proportions is most consistent with a vadose environment (DOE, 2001, p. 4-402; Whelan et al., 2008, Section 7); and (4) trace element composition of the Tiva Canyon unit (overlying the repository host rock) shows that meteoric processes prevailed after initial cooling, and there is no evidence for hydrothermal alteration (Marshall et al., 1996).

As discussed in the Yucca Mountain *Science and Engineering Report* (DOE 2001, p. 4-402) the Nuclear Waste Technical Review Board (NWTRB; Cohon, 1998) reviewed a group of reports submitted by the state of Nevada, including one that cited fluid inclusion studies which the authors claimed indicated a high-temperature origin for secondary calcite sampled from the exploratory tunnels at Yucca Mountain (Dublyansky and Reutsky, 1995). The NWTRB concluded that the fluid inclusion data are consistent with the explanation of downward percolating meteoric waters and do not indicate upwelling waters. This result is consistent with the conclusions of an earlier peer review by the U.S. National Academy of Sciences (National Research Council, 1992).

The NWTRB also recommended further fluid-inclusion studies to be performed in conjunction with radiometric age determinations. In response, the DOE sponsored research at the University of Nevada, Las Vegas (UNLV) and the U.S. Geological Survey (USGS) on radiometric age and thermal history indicated by fluid inclusions. Representatives of the state of Nevada participated in the sampling program, and in biannual meetings to review and interpret the data. The general conclusions reached by the USGS and UNLV researchers were that the fluid inclusions formed from downward percolating meteoric water in a vadose environment, and that there is no evidence for mineral precipitation at elevated temperatures (above ambient) during the past 1.9 My (DOE, 2001, p. 4-402).

Other evidence for mineral precipitation in a vadose environment includes the isotopic composition of secondary calcite, as summarized by DOE (2001, p. 4–402). Also, strontium in samples of calcite collected underground at Yucca Mountain is more radiogenic (greater $^{87}Sr/^{86}Sr$ ratio) in successively younger calcite, which is consistent with an origin of downward moving, meteoric water reacting with rocks so that deeper units accumulate radiogenic strontium (Marshall and Whelan, 2000). Stable carbon isotopic ratios ($^{13}C/^{12}C$) in calcite also show trends that can be related to past changes in the plant community at the ground surface, reflecting known changes in climate (Whelan and Moscati, 1998).

Discussion of the Thermal History of Yucca Mountain

The main eruptions that created the units comprising the unsaturated zone at Yucca Mountain occurred from approximately 13.3 to 11.4 Ma (Sawyer et al., 1994; rounded to the nearest 0.1 Ma). As stated above, the Timber Mountain volcanic center was the last significant thermal event to affect Yucca Mountain. Large-scale hydrothermal alteration found in the saturated zone, primarily north of the proposed repository site, has been linked to long-lasting thermal effects from the Timber Mountain event. Bish and Aronson (1993, p. 155) found evidence of illite/smectite reactions with ages as recent as 9 to 10 Ma, associated with Timber Mountain, and which could have persisted for 1 My or longer. Later work examined $\delta^{18}O$ in illite/smectite clays and clinoptillolite (Feng et al., 1999), and corroborated the saturated zone and Timber Mountain associations of the hydrothermal signature. Three-dimensional characterization of the zeolitization of vitric tuffs at Yucca Mountain (Bish et al., 2003) shows similar trends, with a marked south-to-north trend in alteration of the Calico Hills unit, and alteration of only deeper strata to the south and west, consistent with a deep hydrothermal mechanism. All of this evidence for large-scale hydrothermal activity is found only in the saturated zone, or in units altered by the former saturated zone at 10 Ma, and is clearly associated with the remnants of silicic volcanism immediately to the north of Yucca Mountain.

The subject paper (Dublyansky, 2007, Section 4) discusses an early version of a conductive thermal model developed by the USGS (Marshall and Whelan, 2001). This type of mathematical modeling has limitations, particularly in the treatment of uncertainty in regional heat flow and convective processes. A more recent USGS model (Whelan et al., 2008, Section 6) shows how thermal convective and hydrologic processes can also affect interpretation of paleo-temperature data. While this model supplements our interpretation of site geologic history, its use is only corroborative and is not the basis for excluding the hydrothermal activity FEP.

The southwestern Nevada volcanic field is associated with crustal extension, and long-lasting, higher regional heat flow. This provides yet another explanation for the history of the unsaturated zone at Yucca Mountain, as indicated by observed fluid-inclusion temperatures and radiometric dating. Significant tectonic extension in the central Basin and Range began prior to eruptive volcanic activity in the southwestern Nevada volcanic field, approximately 16 Ma (Snow and Wernicke, 2000, Figure 12 and p. 704). Extension rates rapidly increased from 16 to 13 Ma and have been decreasing since 13 Ma to the present. The thermal history at Yucca Mountain has been affected not only by nearby magmatic activity, but also by the regional heat flux caused by this tectonic extension, acting over a larger spatial scale and a longer time frame. Areas of increased heat flux in the Basin and Range province are strongly linked to trends in lithospheric thickness and rates of tectonic extension (Lachenbruch and Sass, 1978, pp. 243–244). Crustal extension is associated with stretching and thinning of the lithosphere, which results in magmatic upwelling from the asthenosphere, intrusion of basaltic dikes into the lithosphere, and accretion of basaltic material at the base of the lithosphere (Lachenbruch and Sass, 1978, Figure 9-8). Mathematical models of crustal heat flow that include the effects from extension and upwelling of the asthenosphere have been compared with observations of heat flux and relative extension rates from the Basin and Range, to develop quantitative relationships between extension and heat flux (Lachenbruch and Sass, 1978, Figure 9-14). Applying the history of extension at Yucca Mountain over the last 16 million years from Snow and Wernicke (2000, Figure 12) with the correlations between extension and heat flux from Lachenbruch and Sass (1978, Figure 9-14), the history of geothermal heat flux at Yucca Mountain can be assessed. The history of extension shows a steady decline from 13 Ma to the present, and the corresponding heat flux decreases steadily from more than 300 mW/m^2 during the time of silicic magmatism, to less than 100 mW/m^2 at present. This long-term behavior of heat flux is an important factor that helps explain paleo-temperature indications from the unsaturated zone at Yucca Mountain.

The subject paper also discusses the merits of an alternative explanation: that elevated paleo-temperature in the unsaturated zone at Yucca Mountain was caused by the presence of additional overburden (Dublyansky, 2007, Section 4.2). It was estimated that the overburden was approximately 100 m higher and has subsequently eroded. The paper asserts that an additional 1100 m of overburden would be required for simulation results to match observations. However, this assumes present-day heat flow and thermal conductivity of 1.3 W/m-K for the overburden tuffs. Where they have been intercepted by drillholes (Geslin and Moyer, 1995), the post-Tiva Canyon (overburden) tuffs in the region are tens of meters thick and mostly nonwelded, higher-porosity facies similar to the existing nonwelded vitric units at Yucca Mountain (Moyer et al., 1996). Such facies have a thermal conductivity that is approximately half the value used by Dublyansky and Polyansky (2007, Table 2; see BSC, 2004b, Table 6-13). Therefore, a plausible explanation for the thermal history at Yucca Mountain, as represented in the fluid inclusion and radiometric age data, can be made on the basis of known tectonic extension and silicic magmatism over the same time period. The long time scales of these processes are such that any effects of tectonic extension or silicic magmatism on hydrothermal activity at Yucca Mountain over the next 10,000 years would be negligible.

In summary, the repository host rock in the unsaturated zone at Yucca Mountain was subjected to early alteration during cooling of the ash flow and devitrification, followed by large-scale hydrothermal effects associated with nearby magmatism, and finally the longer-term cooling and elevated heat flow associated with gradually decreasing rates of crustal extension. There is no indication that nonmagmatic, deep water circulation has driven any hydrothermal activity at Yucca Mountain, and the subject paper offers no plausible geologic mechanism through which nonmagmatic, deep circulation could start in the next 10,000 years consistent with current understanding of regional geology. The current local thermal regime at Yucca Mountain has been associated with the Eureka Low, a region where heat flux is below the average for the Great Basin (Sass, 1988, pp.

31–35). This low heat flux is inconsistent with hydrothermal activity linked to deep water circulation.

Finally, Dr. Dublyansky states that the USGS thermal history model was part of the technical basis for the site recommendation (Dublyansky, 2007, Section 6.3). In fact, that model was produced in late 2001 and is not cited by the *Yucca Mountain Science and Engineering Report* (DOE 2001), nor by the other reports that supported the site recommendation. References to the original, conductive, USGS thermal model as corroborating information were introduced into the FEP screening justification after the site recommendation. The information relied on in 2001 to exclude the FEP was based principally on the NWTRB report (Cohon, 1998), which confirms that secondary minerals in the unsaturated zone precipitated in a vadose zone environment.

Summary and Conclusion

This response describes the current basis for screening of the FEP on hydrothermal activity and identifies technical problems with the criticisms in the subject paper (Dublyansky, 2007). There is no evidence for any large-scale hydrothermal activity in the unsaturated host rock at Yucca Mountain, since eruption of the tuffs comprising the host rock units. Secondary mineralization indicates that ambient temperatures (similar to present-day) have prevailed for approximately the past 2 My. Available evidence, supported by peer review and independent scientific investigations, shows that fracture minerals were precipitated from downward percolating meteoric waters, rather than from upwelling hydrothermal waters (Wilson et al., 2003, Sections 7.3 and 8; DOE, 2001, p. 4-402; NWTRB; Cohon, 1998). Evidence for past, large-scale hydrothermal activity is found only for saturated-zone conditions and associated with silicic magmatism older than 10 Ma. Any igneous activity that occurs at the site during the next 10,000 years would be basaltic, with hydrothermal effects that are quite limited in duration and magnitude. Future, large-scale hydrothermal activity would be limited by the availability of geothermal heat flow, and therefore would take longer than 10,000 years to develop significant effects on repository performance.

Much discussion here is given to whether fracture minerals precipitated from upwelling or downward percolating waters, and to interpretation of the thermal history of Yucca Mountain. However, while hydrothermal activity occurred at Yucca Mountain in the geologic past, there is no evidence that the *effects* of past hydrothermal activity, beyond the mineralization that is already *included* in the performance assessment, are significant to repository performance. And there is no evidence that future hydrothermal activity (not presently active) could be significant.

Section 7 of the subject paper stipulates several corrective actions that, given the supporting information used in FEP screening as described here, would be inappropriate. The definition of the hydrothermal activity FEP was changed in 2004, making it applicable to a broader range of hydrologic conditions. The FEP screening justification is not limited to mineral alteration, but also includes qualitative analysis of evidence for downward percolating waters, and of the thermal history of Yucca Mountain. A quantitative, phenomenological model for past hydrothermal activity at Yucca Mountain is not critical for exclusion of the FEP. Rather, the FEP is excluded because the evidence for hydrothermal activity indicates that, to the extent this process occurs in the next 10,000 years, it will have a negligible effect on the performance of the repository, i.e., that hydrothermal activity poses a low consequence. This exclusion can be made whether the supposed source of the hydrothermal activity is magmatic or deep water circulation. Accordingly, the subject paper incorrectly criticizes the basis and technical validity of the FEP screening justification, and no "error" was made in the FEP screening justification process.

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References

10 CFR 63. 2007. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada.

Bish, D. L. and Aronson, J. L. 1993. "Paleogeothermal and Paleohydrologic Conditions in Silicic Tuff from Yucca Mountain, Nevada." *Clays and Clay Minerals, 41,* (2), 148-161. Long Island City, New York: Pergamon Press.Bish, D. L., Vaniman, D. T.,; Chipera, S. J., and Carey, J. W. 2003. "The Distribution of Zeolites and their Effects on the Performance of a Nuclear Waste Repository at Yucca Mountain, Nevada, U.S.A."

American Mineralogist, 88, ([11-12, Part 2]), 1889–1902. [Washington, D.C.: Mineralogical Society of America].

Blackwell, D. D., Wisian, K. W., Richards, M. C., and Steele, J. L. 2000. *Geothermal Resource/Reservoir Investigations Based on Heat Flow and Thermal Gradient Data for the United States*. DOE/ID/13504. Washington, D.C.: U.S. Department of Energy.

Blackwell, D. G., Wisian, K. W., Richards, M. C., Leidig, M., Smith, R., and McKenna, J. 2003. *Geothermal Resource Analysis and Structure of Basin and Range Systems, Especially Dixie Valley Geothermal Field, Nevada*. Department of Geological Sciences, Southern Methodist University, Dallas, Texas. Prepared for the U.S. Department of Energy, DOE Idaho Operations Office Financial Assistance award DE-FG07-01ID13886.

BSC (Bechtel SAIC Company) 2004a. *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada*. ANL-MGR-GS-000001 REV 02. Las Vegas, Nevada: Bechtel SAIC Company.

BSC (Bechtel SAIC Company) 2004b. *Thermal Conductivity of Non-Repository Lithostratigraphic Layers*. MDL-NBS-GS-000006 REV 01. Las Vegas, Nevada: Bechtel SAIC Company.

Cohon, J. L. 1998. Nuclear Waste Technical Review Board Review of Reports by Jerry Szymanski and Harry Swainston. Letter from J.L. Cohon (NWTRB) to L.H. Barrett (DOE/OCRWM), July 24, 1998, with attachment.

DOE (U.S. Department of Energy) 2001. *Yucca Mountain Science and Engineering Report*. DOE/RW-0539. [Washington, D.C.]: U.S. Department of Energy, Office of Civilian Radioactive Waste Management.

DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application.* DOE/RW-0573, Rev. 0. Las Vegas, Nevada: U.S. Department of Energy, Office of Civilian Radioactive Waste Management.

Dublyansky, Y. 2007. "Analysis of the Treatment, by the U.S. Department of Energy, of the FEP Hydrothermal Activity in the Yucca Mountain Performance Assessment." *Risk Analysis, 27,* (6), 1455-1468. [McLean, Virginia]: Society for Risk Analysis.

Dublyansky, Y. V. and Reutsky, V. N. 1995. *Preliminary Data on Fluid Inclusions in Epigenetic Minerals from Tunnel Excavated Under Yucca Mountain*. Novosibirsk, [Russia]: United Institute of Geology, Geophysics and Mineralogy, Russian Academy of Sciences, Siberian Branch.

Dublyansky, Y. and Polyansky, O. 2007. "Search for the cause-effect relationship between Miocene silicic volcanism and hydrothermal activity in the unsaturated zone of Yucca Mountain, Nevada: Numerical modeling approach." *J. Geophys. Res.*, *112*, *B09201*, doi:10.1029/2006JB004597.

Feng, X., Faiia, A. M., WoldeGabriel, G., Aronson, J. L., Poage, M. A., and Chamberlain, C. P. 1999. "Oxygen isotopic studies of illite/smectite and clinoptilolite from Yucca Mountain: implications for paleohydrologic conditions." *Earth and Planet. Sci. Lett.*, 171, 95-106.

Ferrill, D. A., Morris, A. P., Evans, M. A., Burkhard, M., Groshong, R. H.,Jr., and Onasch, C. M. 2004. “Calcite Twin Morphology: A Low-Temperature Deformation Geothermometer.” *Journal of Structural Geology*, 26, (8), 1521-1529. New York, New York: Elsevier.

Flynn, T., Buchanan, P., Trexler, D., Shevenell, L., and Garside, L. 1996. *Geothermal Resource Assessment of the Yucca Mountain Area, Nye County, Nevada*. BA0000000-03255-5705-00002. Las Vegas, Nevada: University and Community College System of Nevada.

Geslin, J. K. and Moyer, T. C. 1995. *Summary of Lithologic Logging of New and Existing Boreholes at Yucca Mountain, Nevada, March 1994 to June 1994.* Open-File Report 94-451. Denver, Colorado: U.S. Geological Survey.

Gray, M. B., Stamatakos, J. A., Ferrill, D. A., and Evans, M. A. 2005. “Fault-Zone Deformation in Welded Tuffs at Yucca Mountain, Nevada, USA.” *Journal of Structural Geology*, 27, ([10]), 1873-1891. [New York, New York]: Elsevier.

Hill, C. A. and Dublyansky, Y. V. 1999. “Response to Stuckless and Others (1998) on ‘Overview of Calcite/Opal Deposits at or Near the Proposed High-Level Nuclear Waste Site, Yucca Mountain, Nevada, USA: Pedogenic, Hypogene, or Both?’” *Environmental Geology*, 38, (1), 77-81. [New York, New York]: Springer-Verlag.

Hill, C. A., Dublyansky, Y. V., Harmon, R. S., and Schluter, C. M. 1995. “Overview of Calcite/Opal Deposits at or Near the Proposed High-Level Nuclear Waste Site, Yucca

Mountain, Nevada, USA: Pedogenic, Hypogene, or Both?" *Environmental Geology*, 26, 69-88. New York, New York: Springer-Verlag.

Lachenbruch, A. H. and Sass, J. H. 1978. "Models of an Extending Lithosphere and Heat Flow in the Basin and Range Province." Chapter 9 of *Cenozoic Tectonics and Regional Geophysics of the Western Cordillera*. Smith, R.B. and Eaton, G.P., eds. Memoir 152. pp. 209-250. Boulder, Colorado: Geological Society of America.

Marshall, B. D., Kyser, T. K., and Peterman, Z. E. 1996. *Oxygen Isotopes and Trace Elements in the Tiva Canyon Tuff, Yucca Mountain and Vicinity, Nye County, Nevada*. Open-File Report 95-431. Denver, Colorado: U.S. Geological Survey.

Marshall, B. D., Neymark, L. A., and Peterman, Z. E. 2003. "Estimation of Past Seepage Volumes from Calcite Distribution in the Topopah Spring Tuff, Yucca Mountain, Nevada." *Journal of Contaminant Hydrology*, 62-63, 237-247. [New York, New York]: Elsevier.

Marshall, B. D. and Whelan, J. F. 2000. "Isotope Geochemistry of Calcite Coatings and the Thermal History of the Unsaturated Zone at Yucca Mountain, Nevada." *Abstracts with Programs - Geological Society of America, 32,* (7), A-259. Boulder, Colorado: Geological Society of America.

Marshall, B. D. and Whelan, J. F. 2001. "Simulating the Thermal History of the Unsaturated Zone at Yucca Mountain, Nevada." *Abstracts with Programs—Geological Society of America, 33,* (6), A-375. Boulder, Colorado: Geological Society of America.

McKenna, J. R. and Blackwell, D. D. 2004. "Numerical Modeling of Transient Basin and Range Extensional Geothermal Systems." *Geothermics*, 33, 457-476. [New York, New York]: Pergamon.

Moyer, T. C., Geslin, J. K., and Flint, L. E. 1996. *Stratigraphic Relations and Hydrologic Properties of the Paintbrush Tuff Nonwelded (PTn) Hydrologic Unit, Yucca Mountain, Nevada*. Open-File Report 95-397. Denver, Colorado: U.S. Geological Survey.

National Research Council. 1992. *Ground Water at Yucca Mountain, How High Can It Rise? Final Report of the Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain*. Washington, D.C.: National Academy Press.

NRC (U.S. Nuclear Regulatory Commission) 2003. *Yucca Mountain Review Plan, Final Report.* NUREG-1804, Rev. 2. Washington, D.C.: U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards.

Quade, J. and Cerling, T. E. 1990. "Stable Isotopic Evidence for a Pedogenic Origin of Carbonates in Trench 14 Near Yucca Mountain, Nevada." *Science*, 250, 1549-1552. Washington, D.C.: American Association for the Advancement of Science.

Sass, J. H., Lachenbruch, A. H., Dudley, W. W., Jr., Priest, S. S., and Munroe, R. J. 1988. *Temperature, Thermal Conductivity, and Heat Flow Near Yucca Mountain, Nevada: Some Tectonic and Hydrologic Implications.* Open-File Report 87-649. [Denver, Colorado]: U.S. Geological Survey.

Sawyer, D. A., Fleck, R. J., Lanphere, M. A., Warren, R. G., Broxton, D. E., and Hudson, M.R. 1994. "Episodic Caldera Volcanism in the Miocene Southwestern Nevada Volcanic

Field: Revised Stratigraphic Framework, {superscript 40}Ar/{superscript 39}Ar Geochronology, and Implications for Magmatism and Extension." *Geological Society of America Bulletin, 106,* (10), 1304-1318. Boulder, Colorado: Geological Society of America.

SNL (Sandia National Laboratories) 2008a. *Features, Events, and Processes for the Total System Performance Assessment: Analyses*. ANL-WIS-MD-000027 REV 00. Las Vegas, Nevada: Sandia National Laboratories.

SNL (Sandia National Laboratories) 2008b. *Multiscale Thermohydrologic Model*. ANL-EBS-MD-000049 REV 03 AD 02. Las Vegas, Nevada: Sandia National Laboratories.

Snow, J. K. and Wernicke, B. P. 2000. "Cenozoic Tectonism in the Central Basin and Range: Magnitude, Rate, and Distribution of Upper Crustal Strain." *American Journal of Science*, 300, (9), 659-719. New Haven, Connecticut: Yale University, Kline Geology Laboratory.

Stuckless, J. S., Peterman, Z. E., and Muhs, D.,R. 1991. "U and Sr in Ground Water and Calcite, Yucca Mountain, Nevada: Evidence Against Upwelling Water." *Science*, 254, 551-554. Washington, D.C.: American Association for the Advancement of Science.

Stuckless, J. S., Marshall, B. D., Vaniman, D. T., Dudley, W. W., Peterman, Z. E., Paces, J. B., Whelan, J. F., Taylor, E. M., Forester, R. M., and O'Leary, D. W. 1998. "Comments on 'Overview of Calcite/Opal Deposits at or Near the Proposed High-Level Nuclear Waste Site, Yucca Mountain, Nevada, USA: Pedogenic, Hypogene, or Both' by C. A.

Hill, Y. V. Dublyansky, R. S. Harmon, and C. M. Schluter." *Environmental Geology*, 34, (1), 70-78. New York, New York: Springer-Verlag.

Vaniman, D. T., Chipera, S. J., and Bish, D. L. 1994. "Pedogenesis of Siliceous Calcretes at Yucca Mountain, Nevada." *Geoderma*, 63, 1-17. Amsterdam, The Netherlands: Elsevier.

Whelan, J. F. and Moscati, R. J. 1998. "9 M.Y. Record of Southern Nevada Climate from Yucca Mountain Secondary Minerals." *High-Level Radioactive Waste Management, Proceedings of the Eighth International Conference, Las Vegas, Nevada, May 11-14, 1998*, pp. 12-15. La Grange Park, Illinois: American Nuclear Society.

Whelan, J. F., Neymark, L. A., Moscati, R. J., and Marshall, B. D. 2008. "Thermal History of the Unsaturated Zone at Yucca Mountain, Nevada, USA." *Applied Geochemistry*, 23, 1041-1075. New York, New York: Elsevier.Whelan, J. F., Roedder, E., and Paces, J. B. 2001. "Evidence for an Unsaturated-Zone Origin of Secondary Minerals in Yucca Mountain, Nevada." "Back to the Future - Managing the Back End of the Nuclear Fuel Cycle to Create a More Secure Energy Future," *Proceedings of the 9th International High-Level Radioactive Waste Management Conference (IHLRWM)*, Las Vegas, Nevada, April 29-May 3, 2001. La Grange Park, Illinois: American Nuclear Society. Whelan, J. F., Paces, J. B., and Peterman, Z. E. 2002. "Physical and Stable-Isotope Evidence for Formation of Secondary Calcite and Silica in the Unsaturated Zone, Yucca Mountain, Nevada." *Applied Geochemistry*, 17, ([6]), 735-750. [New York, New York]: Elsevier.

Wilson, N. S. F., Cline, J. S., and Amelin, Y. V. 2003. "Origin, Timing, and Temperature of Secondary Calcite–Silica Mineral Formation at Yucca Mountain, Nevada." *Geochimica et Cosmochimica Acta*, 67, (6), 1145-1176. [New York, New York]: Pergamon.